MELTWATER CHARACTERISTICS AS INDICATORS OF THE HYDROLOGY OF ALPINE GLACIERS

by

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Hydrological, hydrochemical and sedimentological observations were undertaken in the catchments of Feevispa (Feegletscher), Findelenbach (Findelengletscher) and Gornera (Gornergletscher), Swiss Alps, in an attempt to use meltwater characteristics as indicators of the nature and functioning of glacial hydrological systems.

Annual and seasonal hydrographs of the Feevispa allowed calculation of catchment water balance. Considerable annual variation resulted from excess icemelt over snow accumulation giving greater outputs than inputs. Diurnal hydrograph analysis showed that large quantities of water are stored in Feegletscher and Gornergletscher.

Rapid erratic fluctuations of subglacial sediment supply caused involutions in daily clockwise suspended sediment concentration-discharge hysteresis loops in the Gornera. During draining of the Gornera, exceptionally high discharges evacuated large quantities of sediment from beneath Gornergletscher, but bequeathed no lasting impact on conduit capacity. Close interval sampling and continuous monitoring of sediment concentration permit interpretation of the nature of ice-meltwater-sediment interactions on Alpine glacier beds.

Chemical composition of meltwaters emerging from the glacier portals was monitored during several ablation seasons. Electrical conductivity, a surrogate measure of ionic content, was continuously recorded and Na^{+}, K^{+}, Ca^{2+} and Mg^{2+} determined by atomic absorption spectrophotometry. Meltwaters from glacier surfaces have low solute contents, of atmospheric origins, whereas after passage through internal conduits; meltwaters become chemically enriched from lithospheric contact. Marked diurnal variations (clockwise hysteresis) of solute concentration in portal meltstreams reflect the mixing in varying proportions through time of waters of different compositions, delimiting trapezoidal solute concentration-discharge relationships.

Two components of discharge through Findelengletscher and Gornergletscher were separated on the basis of chemical composition using a simple mass-balance mixing model. A large proportion of total flow passes rapidly through major moulin-arterial canal networks. For basal flow, two contrasting regimes were discriminated, both independent of (Findelengletscher) and interlinked with (Gornergletscher) cavity storage at the ice-bedrock interface.

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1. INTRODUCTION

1.1 Aims

Englacial and subglacial water is of considerable interest from both scientific and practical viewpoints. In addition to intrinsic interest in the structure and functioning of internal drainage systems, the circulation of water within glaciers is of importance in the dynamics of Alpine glaciers. Problems in which water plays a significant part include ice movement by plastic deformation and basal sliding, conditions at the ice-bedrock interface, basal erosional processes, internal distribution of heat and the formation of runoff draining to the glacier portal. The collection of meltwaters from Alpine glaciers for hydroelectric and water resources purposes at both subglacial and proglacial sites requires a good knowledge of hydro-glaciological processes and has stimulated investigation of the hydrology of glaciers.

On the glacier surface, water from melting snow percolates downwards in the accumulation area, but in the ablation area during the summer melt season, many streams of various sizes flow over the ice, to enter the internal hydrological system through moulins, cracks and crevasses. Meltwaters reappear at the glacier snout when they emerge from the portal, often in the form of a single large stream. Supraglacial meltwaters are clear and are almost free of sedimentary material, yet portal meltstreams transport large quantities of sediment. Also, in a reconnaissance survey at Chamberlin Glacier, Alaska, Rainwater and Guy (1961) determined that surface meltwaters contained very little dissolved material, but after passage through the glacier, they had become chemically enriched. As there have been few direct observations at depth, studies of the internal drainage of glaciers have relied on indirect observations and theoretical considerations, in attempts to determine the structure, location and behaviour of the hydrological system.

The purpose of this study is to evaluate the use of water quality characteristics of meltwaters as an indirect method of attempting to answer the question 'What happens to meltwater between where it disappears into surface moulins and where it emerges from the portal of an Alpine glacier?' Observations of the quantity and quality of meltwaters draining from glacier portals are used as a means of determining the nature, location and functioning of the internal drainage network. In particular, the observations are intended to permit separation of components of total discharge taking different routes with varying transit times through the glacier. The study also provides basic data concerning hydrochemistry of Alpine meltwaters during the ablation season, and presents observations of sediment concentration in meltwaters draining from a large valley glacier. There have been few previous measurements of water quality in the European Alps (Eidg. Amt für Wasserwirtschaft, 1976).

The investigation was designed as an intensive series of observations of the total environment of meltstreams to allow analysis of the relationships between discharge, sediment concentration and chemical characteristics. It was intended to identify environmental variables affecting glacier discharge, and runoff hydrochemistry and sedimentation. Information concerning characteristics of the Alpine meltwater runoff system is required both for an understanding of physical processes and as an aid to the development of distributed catchment models for forecasting in water resources planning.

Since meltwaters carry a fair amount of sediment, it can be inferred that subglacial streams are located at the glacier bed. Meltwaters effectively sample conditions at the glacier bed, integrated over a considerable area, acquiring their quality characteristics as they pass through the internal hydrological network. This study aims to utilise water quality data to provide detailed information concerning the interaction of meltwaters at basal sites with sources of solutes and sedimentary material, as a contribution to knowledge of conditions at the ice-bedrock interface. In this respect, measurements of sediment transport in meltwater streams have been used to permit calculation of annual rates of glacial erosion (Østrem, 1975).

The following specific questions were posed during the investigation:

1. Does the flow within glaciers occur in channels, as a sheet or in interlocking cavities?
2. Do major arterial conduits in the glacier discharge most of the meltwater?

3. Are the waters discharged along the glacier bed?
4. Are the drainage lines stable through time in capacity and location?
5. What are the sources of sediments and solutes?
6. Is water stored within glaciers in englacial pockets or sub-glacial cavities?
7. What are the hydrological and chemical conditions at the ice-bedrock interface?

These specific questions remain among the significant outstanding problems in hydro-glaciology. Since flow and quality characteristics of waters in meltstreams can only be explained in terms of glacier internal hydrological systems, this investigation is based on the premise that some knowledge of input and a thorough knowledge of output characteristics should permit a better understanding of the intermediate modifying processes.

1.2 Study areas

Observations were made in three glacierised catchments in the massif of Monte-Rosa and the Mischabel chain of the Pennine Alps, canton Wallis, Switzerland. The catchments were selected on the criteria of (1) extensive glacier cover, (2) meltstreams gauged throughout the year close to the glacier portal, (3) only one meltstream draining from the portal, (4) the meltstream could be easily accessed, (5) size and velocity of the stream would not prohibit representative sampling of the cross-section for solute and sediment content of meltwaters. Criteria were initially rated in order of decreasing importance: 5, 4, 2, but with further field experience, 5 and 4 became less important, 3 more important, and 2 relaxed to summer months only. In 1971 and 1972, the investigation was based at the two meltstreams draining the Nordzunge of Feegletscher, in 1974 and 1975 on the Gornera, the only stream emerging from the portal of Gornergletscher, and in 1977 at Findelenbach, draining Findelengletscher. The locations of the glaciers are shown in Figure 1.1, and characteristics of their catchment areas in Table 1.1.

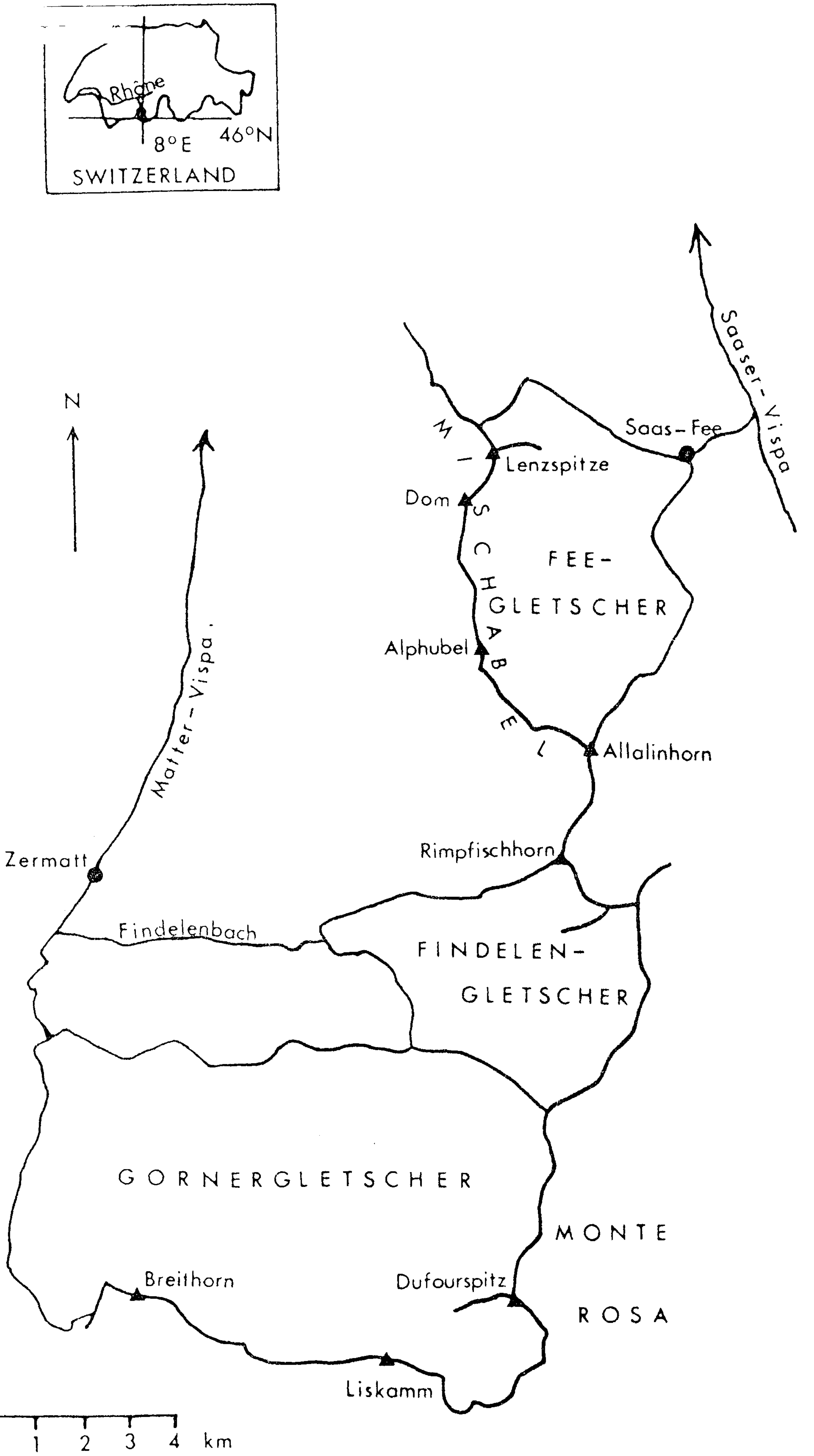


Figure 1.1 Map showing the locations of the catchments of Feegletscher, Findelengletscher and Gornergletscher in the Massif of Monte Rosa and Mischabel chain, Switzerland.

TABLE 1.1 CHARACTERISTICS OF THE CATCHMENTS OF THE GLACIERS SELECTED FOR STUDY

Characteristic		Glacier: Feegletscher	Findelengletscher	Gornergletscher
Catchment area	km^2	35.3	24.9	82.0
Glacierised area	km^2	16.7	19.1	68.9
Percentage glacierisation	%	53.7	76.7	83.7
Maximum length of glacier	km	5.1	9.3	14.1
Glacier altitude range				
Snout	m a.s.l.	2040	2520	2120
Highest elevation	m a.s.l.	4360	4190	4600
Mean	m a.s.l.	3260	3300	3220
Catchment elevation				
Gauging station	m a.s.l.	1761	2500	2005
Highest elevation	m a.s.l.	4535	4190	4634

1.2.1 Feegletscher

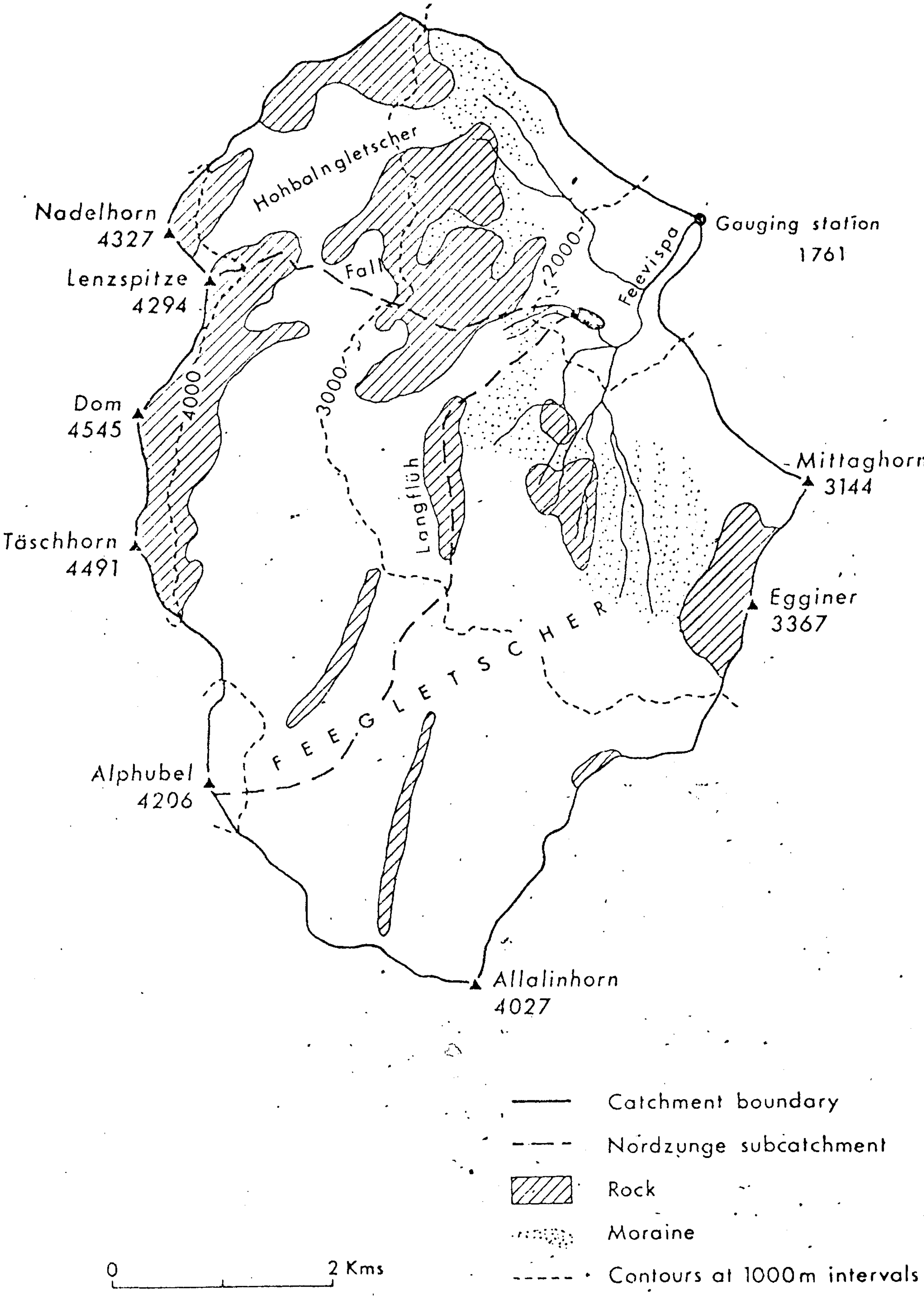
A catchment area of 35.3 km^2 drains to a gauging station on the Feevispa in the village of Saas-Fee at 1761m a.s.l. (Fig. 1.2). The limnigraph, operated by Forces Matrices de Mattmark, S.A., is located immediately upstream of a hydro-electric adduction gallery. Continuous measurements of discharge have been recorded since 1965 all the year round, permitting calculations of total annual runoff. Because the weir is about 1.8 km from the nearest part of the glacier, a large non-glacierised area (currently 46.3 per cent of the catchment) is tributary to the gauge. Feegletscher is fed from high snowfields to the east of Alphubel (4206m a.s.l.) and north of Allalinhorn (4027m). About 50 per cent of the glacier surface lies in the ablation zone at the end of the summer (Müller and others, 1976). A long rocky ridge, Langflüh, separates the lower part of the glacier into two parts. The Nordzunge descends to the lower elevation, where the snout terminates in debris from a large recent rockslide. Two meltstreams emerge from beneath the rock debris to flow to a meltwater lake at about 1905m a.s.l., dammed by small moraines inside the large left lateral moraine of a former, thicker and longer Nordzunge. The southern terminus of Feegletscher is irregular and extends across 2.5 km of steep rocks. It is drained by several meltstreams which coalesce to form two torrents which descend to meet the outflow stream of the lake. In addition to the Feegletscher (16.66 km^2), the catchment contains Hohbalngletscher (1.96 km^2) and Fallgletscher (0.32 km^2).

The catchment area has a vertical extent of 2784m, rising to the peaks of the Mischabel chain, many of which have summits above 4000m a.s.l., the highest being Dom, 4545m. The basin is underlain by metamorphic rocks, the Nordzunge subcatchment being predominantly muscovite-gneiss and -schist, and micaschist, with an outcrop of calcarious schist and amphibolite on the ridge of Langflüh. The remaining area is based on amphibolite and greenschists, both low grade metamorphic rocks (Lütschg and others, 1950).

Annual runoff for the hydrological year 1 October - 30 September averaged 1385mm, with a range from 1055-1528mm for the years 1966-7 to 1975-6, being the equivalent of a mean annual discharge of 48.87 x $10^6 m^3$ (range 37.25 - 53.97 x $10^6 m^3$).

1.2.2 Findelengletscher

The catchment of the Findelenbach, the only proglacial meltwater



<u>Figure 1.2</u> Map of the Feegletscher catchment, Pennine Alps.

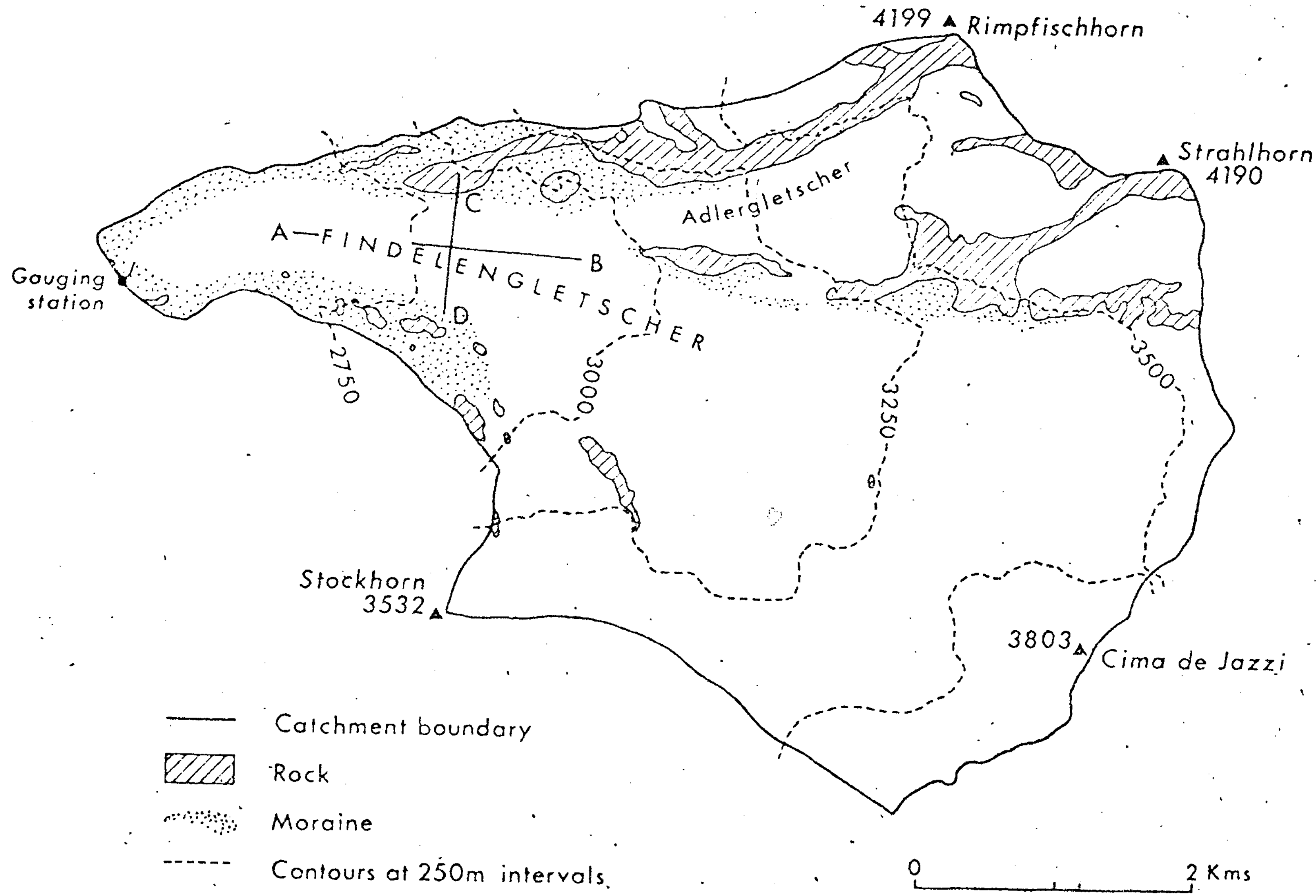
stream emerging from Findelengletscher, extends over 24.9 km^2, 76.7 per cent of which is currently glacierised. The stream discharge at a point 0.4 km from the glacier snout can be determined from measurements of flows in hydro-electric adduction galleries and restitution to the Findelenbach made by Grande Dixence, S.A. between May and September. Findelengletscher is of relatively simple structure (Fig. 1.3) with a wide accumulation basin bounded by Adlerhorn (3988m a.s.l.), Strahlhorn (4190m), and Cima di Jazzi (3803m). From Rimpfischhorn (4199m) a small tributary glacier, Adlergletscher, joins the main Findelen icemass. To the south-east the catchment has a common boundary with that of Gornergletscher. Again, approximately 50 per cent of the glacier surface lies in the ablation zone in summer (Müller and others, 1976).

Bedrock underlying the catchment is of igneous and metamorphic origins, gneiss, schists, serpentine and granite (Lütschg and others, 1950). Bedrock configuration beneath the ice has been determined by seismic sounding for an area of about 1 km^2 (2650-2950m a.s.l.) (Süsstrunk, 1960). The glacier descends a series of rounded steps (Fig. 1.4). It is thicker to the north side, reaching a maximum of about 180m in the area studied. A basal morainic layer, 15-20m thick in general but increasing to over 50m towards the right margin of the glacier (Fig. 1.5), was indicated by seismic reflections.

1.2.3 Gornergletscher

Gornergletscher also drains to one proglacial meltwater stream, the Gornera, which is gauged between May and September by Grande Dixence, S.A., at a well-developed limnigraph station, prise d'eau (2005m a.s.l.) about 1 km from the glacier snout. At present, 83.7 per cent of the 82 km^2 catchment area is covered by permanent ice and snow. The basin extends through 2629m from the prise d'eau to the highest point, Dufourspitz(4634m a.s.l.). The trunk Gornergletscher receives several tributaries from the southern watershed (for example, Unterer Theodul, Zwillings, Schwärze and Grenzgletscher: see Fig. 1.6). The glacier descends to 2120m, and about 50 per cent of the glacier surface area lies in the ablation zone in summer (Müller and others, 1976). The catchment is surrounded by peaks rising over 4000m a.s.l. on the southern divide, but the northern boundary is delimited by the low ridge of Gornergrat (3135m a.s.l.).

The bedrock underlying the catchment is composed of similar igneous and metamorphic facies as at Findelen, granite, gneiss and schists, all



<u>Figure 1.3</u> Map of the catchment of Findelengletscher, Mischabel chain, Pennine Alps. Lines AB and CD show the positions of seismic traverses.

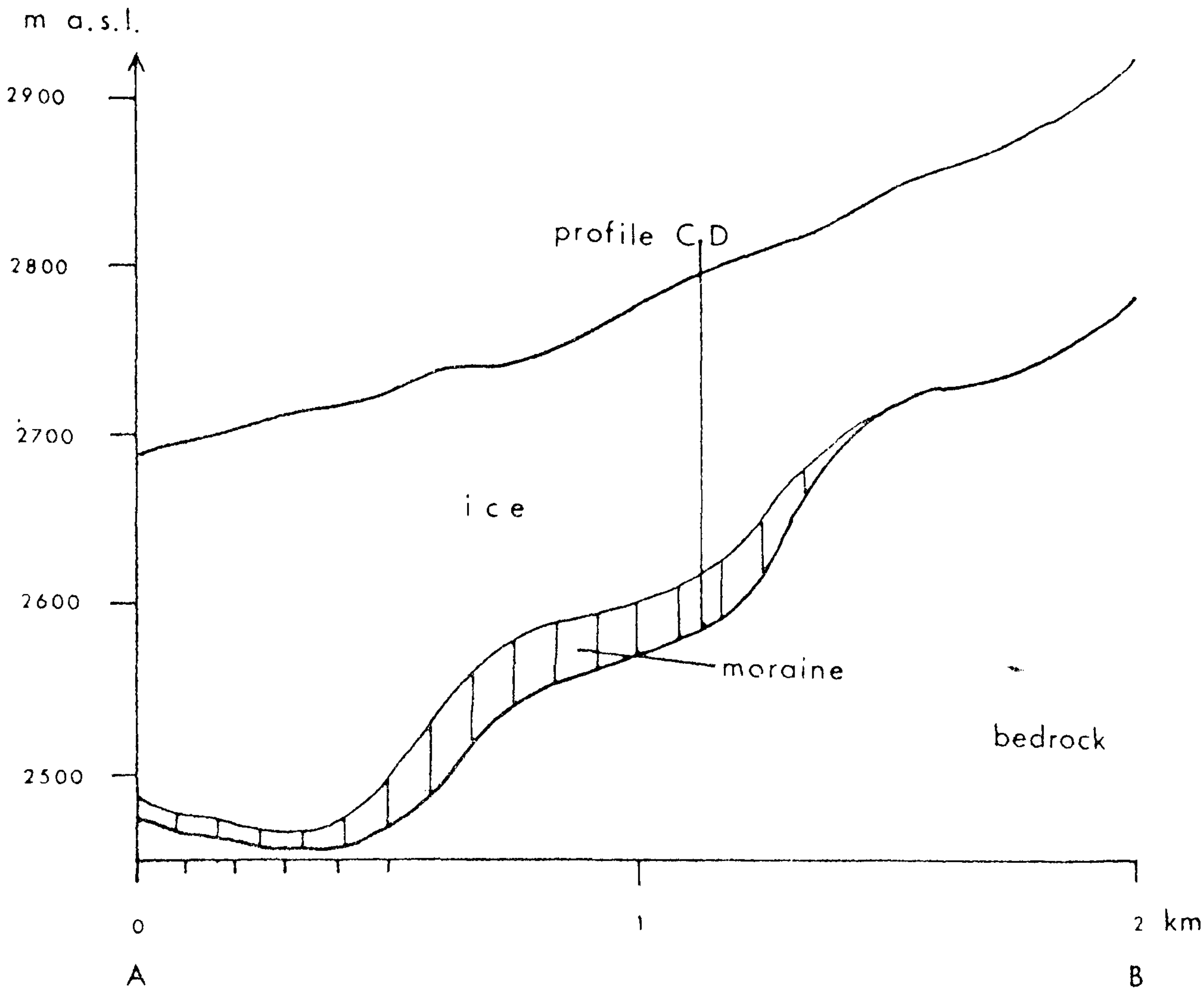


Figure 1.4 Long profile AB of Findelengletscher, as determined by seismic survey (Süsstrunk, 1960). Vertical exaggeration x3.3 .

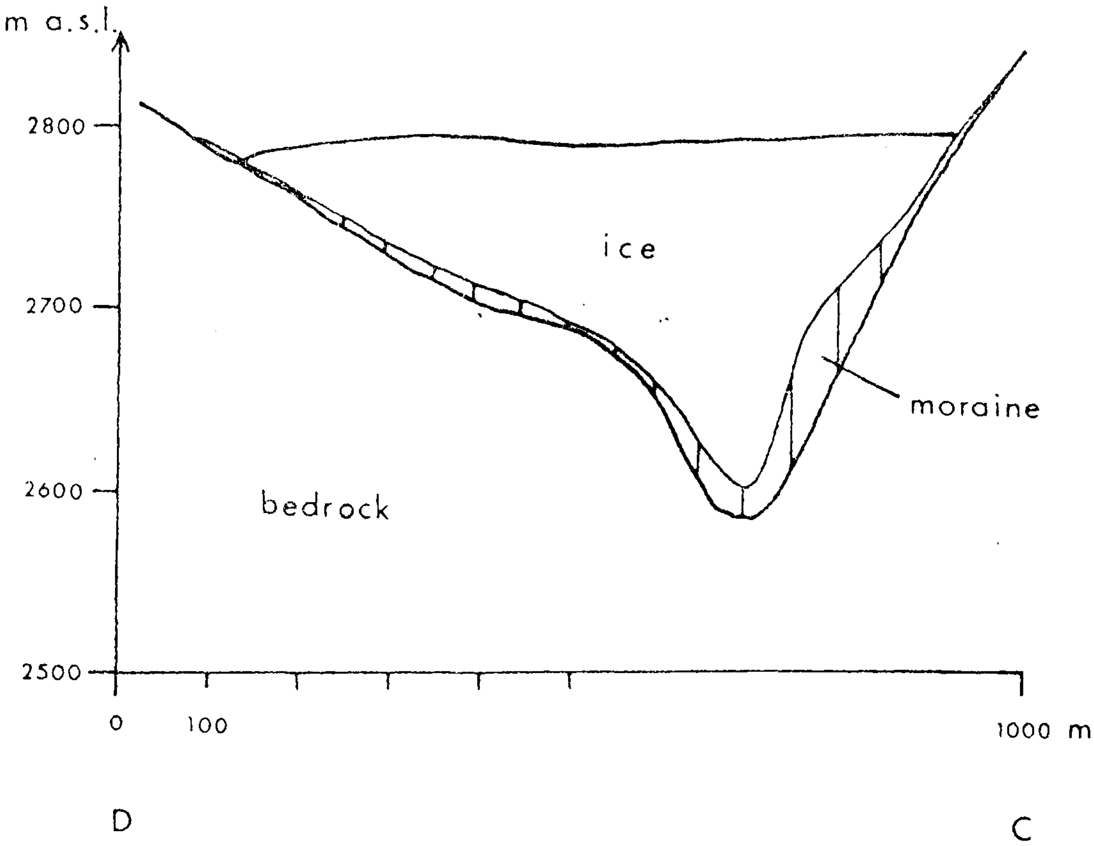


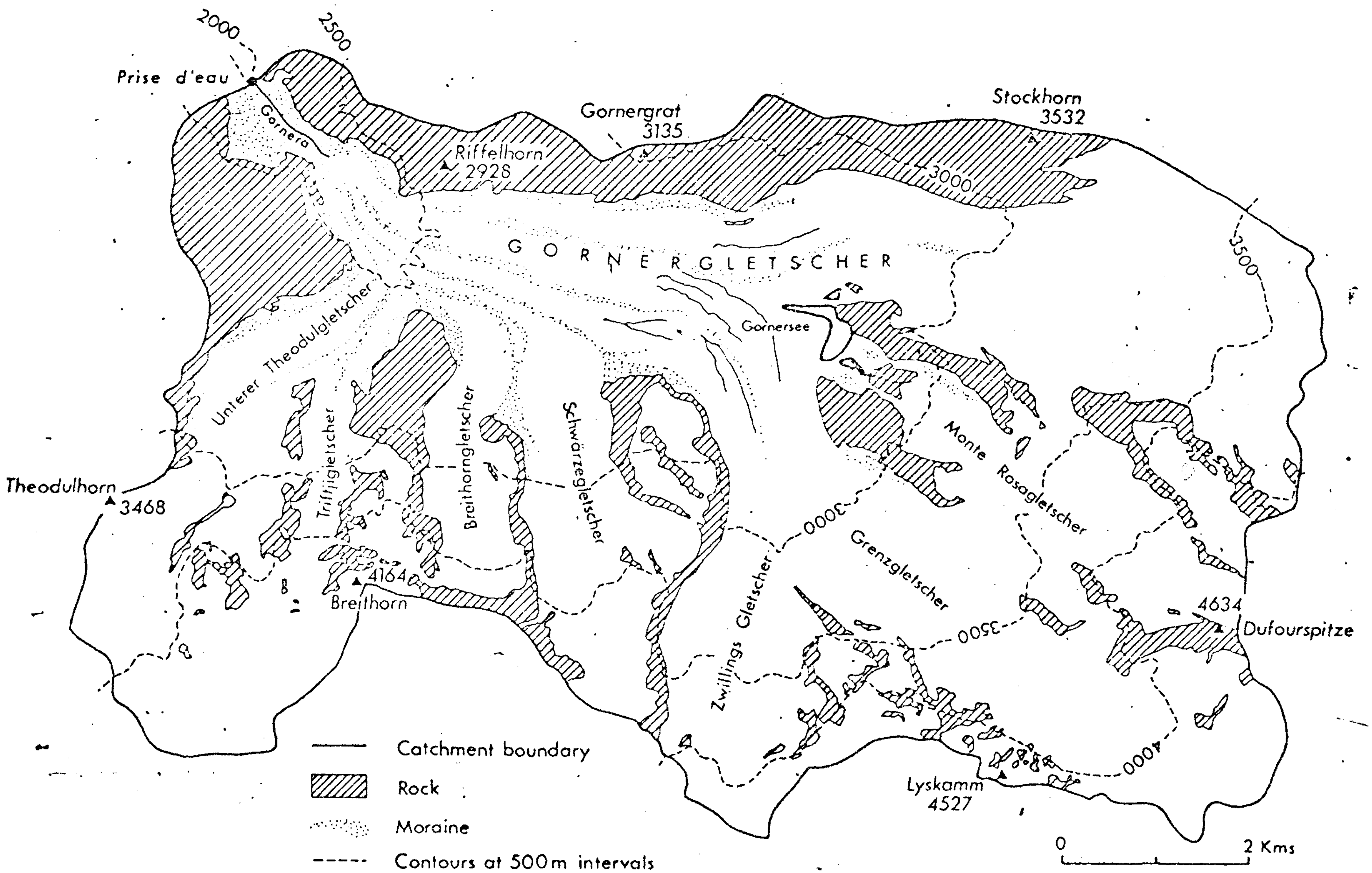
Figure 1.5 Cross profile CD of Findelengletscher, as determined by seismic survey (Süsstrunk, 1960). Vertical exaggeration x2 .

of which are impermeable, with a very small outcrop of calcareous rocks around Gornergrat (Bearth, 1953). Bedrock topography in the ablation area is known in great detail from seismic soundings (Süsstrunk, 1951) and from drilling to prove bedrock (Bezinge and others, 1973). Two closed depressions exist in the long profile beneath the trunk Gornergletscher in the central valley area (Fig. 1.7). The greatest thickness of ice, about 400m, is attained downstream of the junction of Grenz and Gornergletschers. Towards the glacier portal, a steepsided gorge presumably concentrates runoff from the central valley area into the Gornera meltstream. A basal morainic layer exists between the ice and bedrock, over the width of the glacier in the ablation area. Near the ice margin, it has been shown to be several metres thick by drilling. A discrepancy between the depth of the bedrock determined from seismic sounding, and that proved by drilling upwards from a rock tunnel under the glacier, suggests that the morainic layer may extend to be 50m thick at the centre of the icestream (Bezinge and others, 1973).

Certain aspects of the hydrology of Gornergletscher have also been investigated as a result of the possibilities presented by the development and construction of the Mattertal section of the Dix hydro-electric scheme by Grande Dixence, S.A. Subglacial water pressures have been measured (Bezinge and others, 1973), and discharge limnigraphs at a temporary station close to the glacier snout examined (Elliston, 1973). Measurements of rates of surface ablation and surface ice velocities have been undertaken by Renaud (1952) and Elliston (1963). Previous hydrological interest was centred on 'entonnoirs', surface lakes present on Gornergletscher, yet absent from other Alpine glaciers (Renaud, 1936), which occasionally empty into the ice through moulins in their beds.

An ice-dammed marginal lake, the Gornersee, builds up annually at the apex of the junction of the Gornergletscher and Grenzgletscher. Each summer, it drains through or beneath the glacier to produce flooding in the Gornera, which persists for 2-3 days (Bezinge and others, 1973). Röthlisberger (1972) has referred to the emptying of the Gornersee in a theoretical approach to the internal plumbing of glaciers.

Whilst it is often assumed that Alpine glaciers are temperate, i.e. at pressure melting temperature throughout, observations in tunnels dug in ice on Monte Rosa and on the Breithorn suggest that, in the accumulation area, ice is at a temperature well below 0^{o} Celsius (Fisher, 1953; 1955, 1963). Strongly negative firn temperatures ($-10^{o}C$) at altitudes higher



<u>Figure 1.6</u> Map of the catchment of Gornergletscher, massif of Monte Rosa, Pennine Alps.

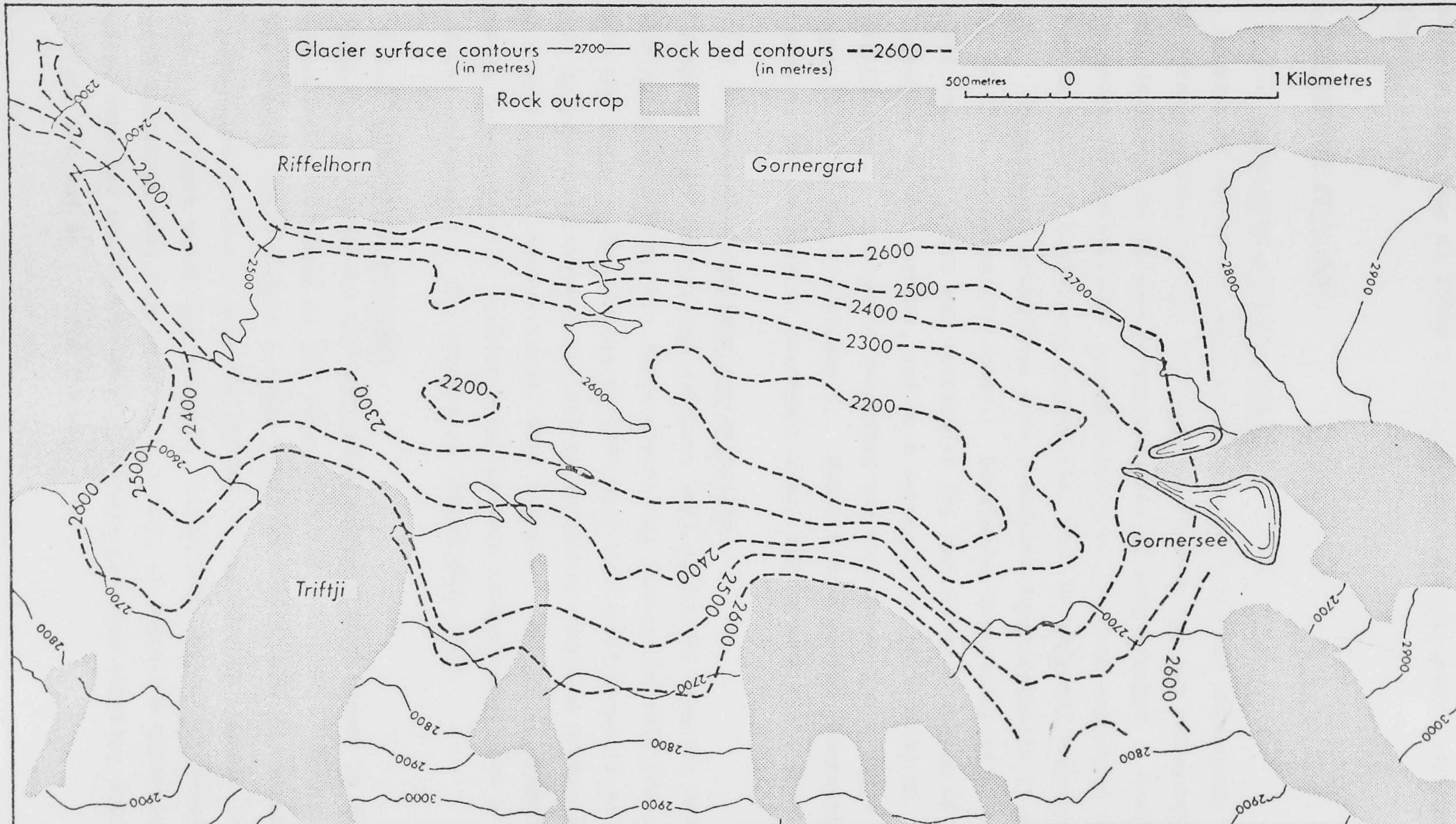


Figure 1.7 Bedrock contours of the Gornergletscher central basin, determined by seismic sounding and drilling (Süsstrunk, 1951; Bearth, 1953).

than about 4000m can explain ice temperatures of -2 to -3°C measured in a borehole 180m deep at 2600m a.s.l. on the Grenzgletscher icestream (Haeberli, 1976).

1.3 Measurement programme

1.3.1 Hydrochemical observations

Samples of meltwaters were collected for field and subsequent laboratory determinations in July and August 1972 from the two meltwater streams draining the Nordzunge subcatchment of Feegletscher. Analysis of the waters and subsequent interpretation of the data suggested inadequacies in terms of analytical procedures, and the temporal sampling design. Measurement techniques were evaluated experimentally in the summer of 1974, at Gornergletscher. Continuous monitoring of hydrochemical characteristics was introduced for the ablation season of 1975 and installed on the Gornera, and on a supraglacial meltstream on Gornergletscher. Continuous recording was undertaken for a short period in August 1977 on the Findelenbach. Other hydrochemical observations were made in the respective catchment areas during each field season.

1.3.2 Suspended sediment concentration

Samples of meltwaters and sediment were collected from the Gornera and subjected to preliminary field processing during the ablation seasons of 1974 and 1975. The samples in 1974 were collected manually as frequently as possible, whereas in 1975 an automatic sampling device produced a more useful short-interval data record. Several experiments with recording photo-electric turbidity meters were unsuccessful, but a short record was obtained for the Gornera in July-August 1977.

1.3.3 Laboratory analysis

Samples of meltwaters and suspended sediment were stored in the field and subsequently returned to the laboratory for analysis. Inevitably, for the waters, non-standard storage times were involved, and experiments were undertaken to investigate the extent of any temporal change in quality. For both water and sediment, laboratory facilities unsuited to field imitation were required. This lack of immediate determinations prevented detailed evaluation of field techniques and sampling designs until after the end of a field season.

1.3.4 Evaluation of measurement programme

The measurement programme undertaken was constrained by financial, logistic and technological limitations, both in field and laboratory. Until 1975, continuous recording and automatic sampling equipment was unavailable to the investigation, although considered to be essential. Periods of fieldwork were short, being restricted to several weeks of actual operation during the months of June-September. Ideally, all the year round continuous or closely-spaced observations would have been desirable. Only two aspects of water quality could be considered on account of limited equipment resources. However, given the concept of a research project of one individual with limited funds and in the Alpine glacial environment, this measurement programme was all that could be done.

2. RUNOFF IN ALPINE GLACIERISED CATCHMENTS

2.1 Introduction

The total discharge of a meltstream draining from an Alpine glacier to a gauge close to the portal is composed of waters arising from different sources or origins, in various source areas and following differing routes across the catchment. Conceptually it is simple to separate waters into components according to their hydrological behaviour within the catchment, but in reality the components must be defined by characteristics which permit their discrimination. Both total discharge and actual quantities and relative proportions of its component flows exhibit diurnal and seasonal temporal variations. Direct measurement of individual component contributions is often difficult because of spatial and altitudinal differences in process operation. Within the glacier itself, knowledge of sources of runoff, routing and behaviour of meltwaters has had to be inferred from indirect observations.

2.2 Sources of runoff in glacier catchments

2.2.1 Source types

The total discharge of a stream draining from an extensively glacierised catchment is made up of waters derived from two source areas:

$$Q_t = Q_g + Q_r \qquad (2.1)$$

where Q represents runoff proportions and the subscripts refer to the glacierised area (g), the area not covered by perennial snow or ice (r) and total discharge from the catchment (t). On ice-free slopes surrounding the glacier, water is derived from two sources:

$$Q_r = Q_k + Q_l \qquad (2.2)$$

where subscript (k) is snowmelt and (l) rainfall. Within the glacier itself, meltwater arises from a variety of origins:

$$Q_g = Q_s + Q_i + Q_q + Q_p + Q_n + Q_m \qquad (2.3)$$

where (s) refers to snowmelt on the glacier surface, (i) surface ice ablation meltwater, (q) subglacial melting, (p) precipitation on the surface of the glacier, (n) subglacial springwater or groundwater, and (m) internally produced meltwater resulting from ice deformation, frictional melting by flowing water, pressure melting and heat conducted down the pressure-melting temperature gradient.

Production of meltwater by snow and icemelt at the glacier surface ($Q_s + Q_i$) is by far the most important source overall, being orders of magnitude greater than the others. Subglacial melting (Q_q) results from geothermal heating and basal sliding. A layer of about 6mm of ice at the pressure melting temperature will be melted per year by a normal geothermal heat flux, and a similar amount may be melted by the heat generated by sliding (Paterson, 1969). Subglacial and englacial melting ($Q_q + Q_m$) together produce about 10mm of water per unit area of bed per year (Shreve, 1972), although in thicker glaciers, deformation alone has been calculated to melt a layer of ice 20mm thick per year (Nye and Frank, 1973).

Subglacial springwater (Q_n) is ultimately derived from supraglacial snow and icemelt, snowmelt from the ice-free areas or from rainfall. Such groundwaters are probably so delayed in runoff to deserve treatment as a source. Winter observations of the small discharges from several glaciers in northern Sweden suggested the importance of fractions derived from groundwater (Stenborg, 1965). In the Swiss Alps, groundwater was also the primary contributor in winter to total discharge with some basal and delayed supraglacial meltwaters (Lütschg and others, 1950). However, the question of the existence of groundwater systems beneath Alpine glaciers, especially on impermeable igneous and metamorphic bedrocks, remains unsettled.

2.2.2 Variable source-area contributions

In spring, snowmelt predominates and runoff is derived from the non-glacierised portion of the catchment (Q_k). As summer procedes, the contributing area of snow decreases as the transient snowline ascends, although the rate of melting will increase. As the area of ice exposed to melting increases, supraglacial melting ($Q_s + Q_i$) becomes more important. The effective contribution of precipitation ($Q_l + Q_p$) to runoff will increase as the snow-free areas of both glacier and surrounding slopes enlarge, although depending on the type of terrain on which rain falls. In summer, the snow-free non-glacierised area contributes to Q_t only following rainfall. Kasser (1954) recognised three zones on an Alpine glacier surface according to the contribution of surface melt to runoff (Fig. 2.1). In the upper part of the accumulation area, surface snowmelt water percolates vertically into firn, refreezing at depth with no lateral runoff component. In the lower part of the accumulation area, lateral movement of meltwater results from the melting of snow and firn. Icemelt in the ablation area, decreasing with increasing altitude, varies according to diurnal and seasonal meteorological changes. The investigation of runoff is complex because of spatial and temporal variations in melting and variable contributing altitude-area distributions of snow and icemelt sources.

2.2.3 Separation of runoff components by source type

Hydrograph components of Q_t may be separated according to origins as snowmelt, icemelt or springwater, using the natural isotope content of meltwaters forming total discharge (Behrens and others, 1971). 'Snow' is assumed to date from post-1952, since when tritium content in precipitation rose steeply following thermo-nuclear testing and subsequently declined, whereas 'ice' is tritium-free. Mixing of snowmelt, icemelt, springwater and contemporary rainfall produced diurnal and seasonal variations of tritium (and deuterium and ^{18}O) in portal meltstreams. Up to 40 per cent of runoff from melting at Hintereisferner (Ötztal Alps, Austria) appears from measurements of tritium and deuterium contents to originate as 'snow' ($Q_k + Q_s$). Further, 40 per cent of the summer runoff of Hintereisferner was calculated from isotope determinations to be contributed from subglacial springs (Ambach and others, 1976). This contribution appears to be exceptionally large, since it might be expected that groundwater flow remains constant throughout the year.

Groundwater was defined by tritium content of winter runoff, which when compared with tritium content of precipitation in previous years, suggested that the mean residence time of base-flow in the catchment was of the order of a few years.

Both Lütschg and others (1950) and Stenborg (1965), in non-quantitative separations of springwater flow, identified the flow of springwater during winter by the high concentration of dissolved load in meltstreams draining from glaciers.

The proportion Q_i/Q_t can be obtained from frequent measurements of surface ablation over a dense stake net, and limnigraph records, on a 2 to 4-daily basis. For Peyto Glacier, Rocky Mountains, Alberta, Canada, the ice component of total flow increased from a mean (1967-74)

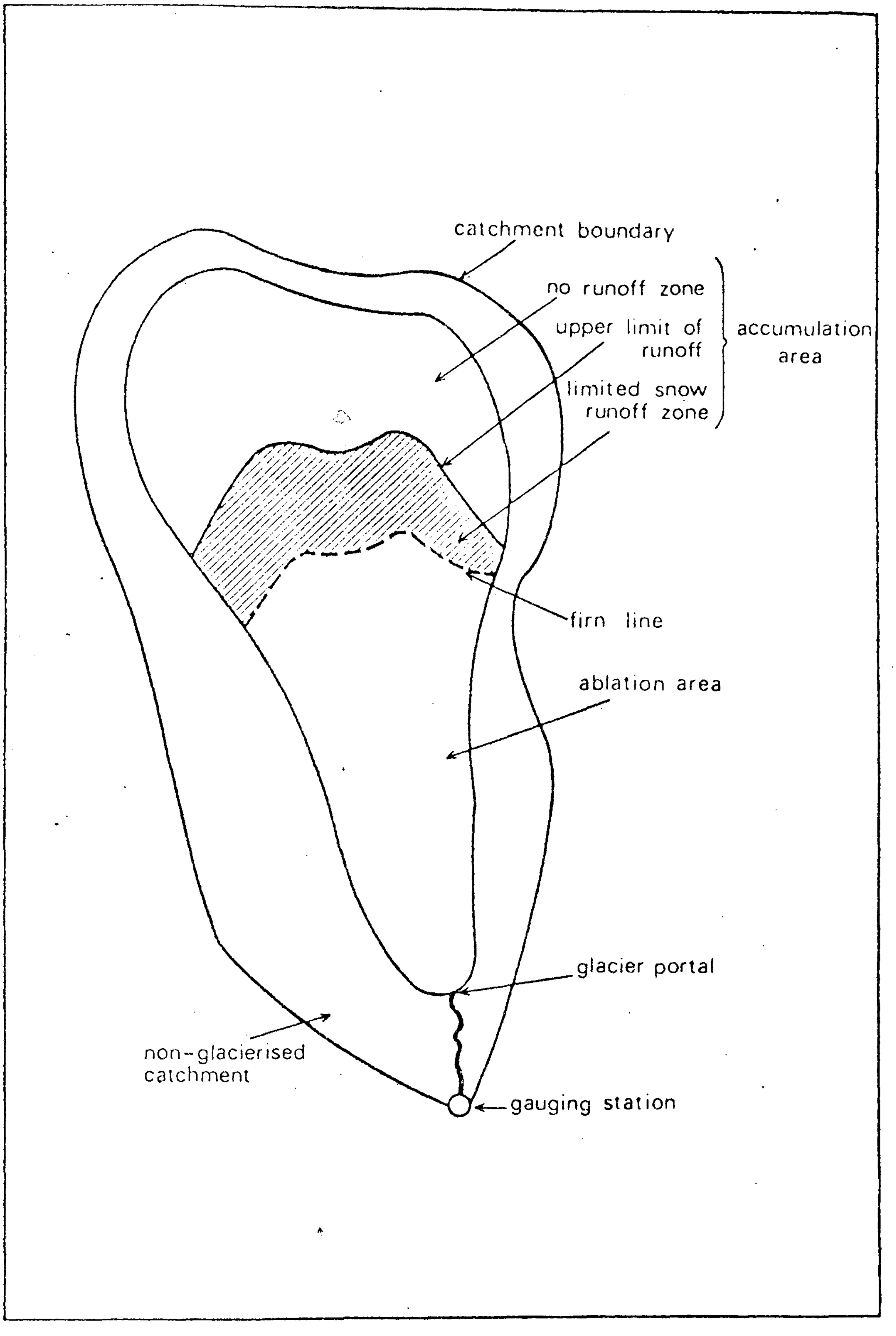


Figure 2.1 Zones on the surface of an alpine glacier contibuting meltwaters to runoff (after Kasser, 1954).

3 per cent in June to 32 per cent in August (Young, 1977). Detailed separation of hydrograph components by source for diurnal variations has not been undertaken, despite the importance of understanding the nature and behaviour of physical processes in the development of short-and-long-term predictive models of Alpine runoff systems.

Diagrammatical temporal variations of inputs to runoff from an Alpine glacier catchment are shown in Figure 2.2. While observations suggest the shapes of the hydrographs of $Q_s + Q_i$, Q_k, and Q_n, the summer performance of $Q_q + Q_m$ is inferred since basal sliding and internal deformation increase in summer.

2.3 Routing of flow components

The total discharge hydrograph Q_t results from varying quantities of flow following different paths at different velocities across a catchment. The nature of flow, volume of discharge and transit times associated with different routes depend on the size, structure and capacity of the network in which flow occurs. Since inputs vary diurnally and seasonally, the network capacity may not always be well adjusted to flow potential. In particular, the internal drainage system of the glacier provides routes for the discharge of most of the meltwater, and is of critical importance in the formation of Alpine runoff.

2.4 Structure of the internal drainage network of an Alpine glacier

The drainage system of an Alpine glacier consists of three distinct but connected networks: supraglacial, englacial and subglacial. The function of the system is to allow removal of meltwaters from all parts of the surface and body of the glacier and to transport increasingly large quantities of meltwater downglacier. Since there are few direct observations at depth, the structure of the network has been inferred from theoretical considerations, or indirect observations.

2.4.1 Supraglacial network

Surface channels readily transmit water across the ablation area beneath the transient snowline, to moulins, cracks and crevasses which lead water into the englacial system. As the englacial system adjusts to take increasing quantities of meltwater, total supraglacial channel length decreases during the ablation season.

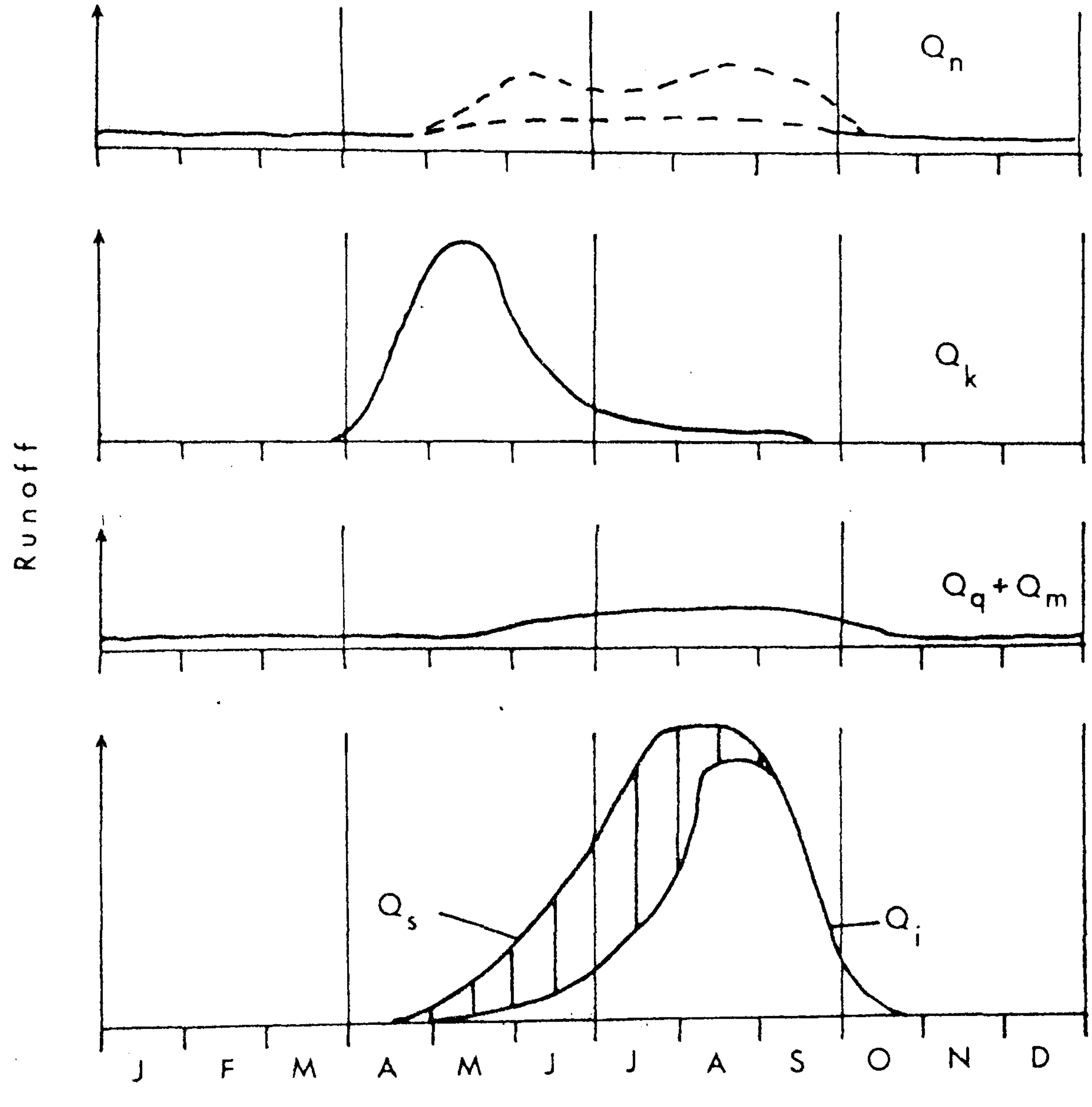


Figure 2.2 Schematic temporal variations of contributing component sources of runoff from an alpine glacierised catchment. Q_i represents meltwater from ice ablation Q_s snowmelt on the glacier surface, $Q_q + Q_m$ internal and subglacial components of icemelt, Q_k snowmelt from the area surrounding the glacier and Q_n ground or spring water. The diagram shows relative annual variation of each component of runoff. No attempt is made to compare relative contributions to total runoff of each of the components.

2.4.2 Englacial vein network

Microscopic investigation of polycrystalline ice has proved the existence of a network of water-filled veins along the three-grain intersections (Nye and Frank, 1973). Meltwater from internal deformation (Q_m) must contribute to vein flow, which also distributes and flushes impurities in the ice. Water descends the vein network under an effective pressure gradient given by $(\rho_w - \rho_i)g$ where ρ_i is density of ice (including water content), ρ_w density of water and g gravitational acceleration. From geometric and flow dynamics considerations, the volume of flow, q, passing through unit area in unit time, is given by

$$q = \frac{(\rho_w - \rho_i)g\ f^2\ a^2}{x\,\mu} \qquad (2.4)$$

where f is the fractional volume occupied by water, a, grain diameter, μ, viscosity of water, and x a constant (associated with geometry). Veins may become blocked by gas bubbles (Raymond and Harrison, 1975), or be deformed out of existence (Lliboutry, 1971), and the theoretical treatment has excluded consideration of the influence of impurities. It is probable that a maximum of about 1m of meltwater per unit area of bed per year can pass slowly through the vein network, taking several months to pass through up to 200m of ice thickness, if the veins consist of capillaries of maximum radius 0.6mm, with favourable capillary end conditions (Nye, 1976).

2.4.3 Englacial and subglacial conduits

Most of the surface input of meltwaters passes beneath the ablation area of the glacier in a network of tunnels either in ice, or at the ice-bedrock interface, the latter seemingly preferentially since water emerges from the portal charged with sediment. Steeply-sloping open moulin-shafts extend to a limited depth of about 30m (Stenborg, 1968; Iken, 1974). At greater depths, conduits in ice tend to close under ice overburden pressure (P), but are kept open, or widened by melting of the walls by frictional heat produced in flowing water and by heat from the waters having a temperature initially slightly higher than that of the ice. Increased water pressure (p) relative to the ambient pressure in ice ($p > P$) may also increase the conduit diameter, as originally suggested by Glen (1954). The mechanics of conduits depend on the capacity of the channel in relation to variations in the flow of water. This determines whether water completely occupies the channel cross section, and whether water pressure builds up in tunnels.

In a hydraulic treatment, Röthlisberger (1972) examined the steady-state constant discharge condition of closed pipe flow under pressure, in a tubular conduit completely surrounded by ice, where conduit water pressure is exceeded by overburden pressure ($P > p$) and channel closure and melt rates are in equilibrium. Water pressure gradient was found to reduce with increasing discharge, which proves that larger streams will drain waters away from smaller ones, so that flow occurs in discrete conduits which join to form major arterial canals. Analysis of vertical hydraulic gradients within the ice suggested that channels can exist both in sub- and englacial locations, the latter at the level of the hydraulic grade line. In summer, water pressure is reduced as discharge increases, since conduits have been widened, whereas in winter water pressure increases as conduits close down in response to reduced flow. Shreve (1972) assumed that water pressure is a function of ice overburden pressure and melting of channel walls at steady state, and flow through conduits occurs down a gradient of the excess of p over P. The amount of heat energy available for melting was calculated to be sufficient to produce significant annual change in the conduit network in the space of a single melt season. In reality, not all heat is used in melting in larger conduits since more flow occurs in relation to tunnel wall area (Mathews, 1973), and diurnal and seasonal variations of temperature in meltwaters at the portal would therefore be expected.

Surface inputs of meltwater to the conduit network are characterised by diurnal fluctuations in summer. Conduit diameters will be adjusted to flow, probably to some mean discharge (Röthlisberger, 1972). Adjustment depends on the time constants by which conduit capacity adapts to new conditions. It is assumed that conduits enlarge quickly during increasing flows of water. Increased discharge following the drainage of glacier-dammed lakes implies that tunnels in ice grow rapidly to accommodate larger flows (Bezinge and others, 1973; Mathews, 1973) as the melting rate dominates over closure allowing adjustment in the space of several hours. Channel closure rate is probably much slower, taking days or years (Röthlisberger, 1972), and is strongly dependent on $(P - p)$. The time (t) necessary for closure of a tunnel of radius r_1 to r_2 is

$$t = \left(\frac{nA}{P - p}\right)^n \ln \frac{r_1}{r_2} \qquad (2.5)$$

where n and A are iceflow parameters in the flow law $\dot{\varepsilon} = A\tau^n$ (Glen, 1958). The value of constant A is also important, and is usually obtained from observations of ice tunnel closure (Nye, 1953; Haefeli, 1970). At about 80m depth ($P - p = 8 \times 10^5$ N m^{-2}), using n = 3.0, A = 1.0, a conduit would suffer five-fold reduction in diameter in 31 days. In a period twice as long, the conduit would reduce to 1/25th of the original diameter. Haefeli (1970) gave rather longer closure times, using different values of A. However, Nye (1976) considers that the rate of plastic closure can be very great, and quite suddenly, occurring in several hours, conduit diameter can reduce if water pressure drops, since the plastic contraction rate is proportional to a high power (27) of the pressure difference (P - p). It is suggested that the assumption that passages will tend to ignore short-term fluctuations of discharge, but follow longer-term ones (Shreve, 1972) such that a particular passage is adjusted to the previous week or weeks mean flow may be incorrect. The actual behaviour of a conduit will depend on its size, its depth in the glacier, interconnections at its ends and the magnitude and rate of variations in the discharges to which it is subjected. What remains to be demonstrated is whether conduits can adapt on a diurnal basis to the rapid fluctuations of discharge experienced in Alpine glaciers during the summer ablation season. There have been few field observations in englacial meltwater streams of actual pressures, necessary for testing of the theoretical postulates. Indeed, the basic premise in theoretical treatments of continuous full occupancy of conduit cross sections by water may not be met.

The existence of en- and subglacial conduits leading to an arterial channel and carrying large quantities of water alongside the network of veins led Shreve (1972) to liken water flow in temperate glaciers to that of groundwater through permeable cavernous limestone. Consequently, water tables might be expected to exist in Alpine glaciers, between the bed and ice surface, which would fluctuate according to conduit discharge/capacity status in relation to the rate of input of surface water.

2.4.4 Water at the glacier bed

Subglacial water is of great importance for the dynamics of Alpine glaciers since it has a pronounced effect on glacier flow, and is involved in theories of glacier sliding (Weertman, 1964; Lliboutry, 1968). The nature of a subglacial hydrological system remains problematical, and thin water layers (Weertman, 1964), water filled cavities (Lliboutry, 1968) and basal conduits (Röthlisberger, 1972; Nye, 1973) have been postulated. The system must fulfil two functions: (1) allow water produced by melting at places with relatively high pressure between sole and bed to zones of low pressure where refreezing occurs and (2) permit the transfer of large quantities of meltwater down-glacier. Nye (1973) calculated the thickness of water film necessary for the regelation process to be 1 μm, whereas Weertman (1962) concluded that if the water layer additionally transfers flow down-glacier it would be considerably thicker (say 1mm), which would prevent operation of the regelation mechanism. The film associated with regelation on a sinusoidal bed would in any case transmit water up- and down-glacier in equal quantities. It is probable therefore that drainage downglacier takes place in a separate channel system. Since conduits incised upwards into ice will suffer closure on meeting upstanding bed-rock protruberances as the glacier moves, Nye (1973) proposed that permanent channels would be cut into bedrock, although there may be temporary tunnels in ice, termed Röthlisberger-channels by Weertman (1972). Calculations show that even during a catastrophic outburst from a glacier-dammed lake, the conduits remain discrete and flooding out into a basal sheet does not occur (Nye, 1976), although Röthlisberger's (1972) analysis strongly suggests 'flooding' of the bed, especially under time-variant discharge.

Water filled cavities probably exist in the lee of bedrock bumps (of size 20-100mm) beneath Alpine glaciers (Lliboutry, 1968). Some cavities will be isolated from water circulation, an autonomous hydraulic regime, but their dimensions will grow until either they coalesce or meet flowing conduits. Some outflow occurs at the pressure of water in the interconnecting conduits in this connected hydraulic regime (Lliboutry, 1976). Eventually the cavities fill with regelation ice, and move with the glacier-sole, allowing new autonomous cavities to develop behind bed-rock obstacles.

Some direct observations of the hydrology of glacier beds have been made in tunnels excavated to capture subglacial torrents for hydro-electric adduction purposes. These observations show that channels can be both incised into bedrock (Østrem and Wold, 1978), or be unstable with stream courses continually changing positions (Vivian and Zumstein, 1973; Vivian, 1977).

2.4.5 Firn hydrology

In the accumulation area, water from snowmelt and rainfall moves irregularly through the non-homogeneous structure of the snowpack. The distinct diurnal meltwater infiltration wave in the upper few centimetres of Alpine firn appears to be attenuated to a more uniform percolation through time at a depth of 3m (Lang and others, 1978). Little is known about the lateral and vertical penetration of meltwater in the zone of limited snow runoff. At the depth of the transition zone, firnification renders firn to increasingly impermeable ice, where a water table is produced,between 14-32m beneath the surface at Ewigschneefeld, Grosser Aletschgletscher, Switzerland. Another firn aquifer has been found in the Upper Vallée Blanche, Mer de Glace, France (Vallon and others, 1976). How such water tables connect to the englacial conduit network is unknown, although crevassing may cause local drainage. Response of the water table to changing conditions of ablation from June-September (Schommer, 1978) suggests that outflow from the firn aquifer always remains much less than surface input and that pressure of stored water does not increase flows, which would enhance melting and so widen passages leading into the glacier.

2.5 Runoff routing in the ice-free area of the catchment

The ice-free areas of Alpine glacierised catchments are usually made up of surfaces of bare rock, which may have thin detrital cover, or limited locally derived morainic deposits. In spring, snowmelt runoff, itself lagged by storage within the snowpack, probably flows across the surface, although some throughflow may occur within morainic material. During the ablation season, streams on the ice-free slopes are maintained by melting snowpack, and flow ceases as the snow is eliminated, except after rainfall, when discharge immediately increases.

2.6 Indirect attempts to determine flow behaviour and structure of glacier drainage systems

2.6.1 Analysis of discharge characteristics

Some indications of the nature and behaviour of the internal hydrological systems of glaciers can be obtained from classical analysis of the distinctive hydrographs of portal meltstreams. Most of the total annual flow occurs between May and September, when diurnal rhythmic fluctuations of discharge are such that peak flow in late afternoon following surface ablation contributes only a fraction of the total daily runoff, being superimposed on a steady background flow maintained throughout 24h. Elliston (1973) suggested that peak discharge results from increased hydrostatic pressure in englacial reservoirs as they are topped up by ablation meltwaters during the day and maintaining flow as they drain at night. In contrast, Golubev (1973) considered that lagged drainage of snowmelt water from storage within the accumulation area contributes much of the steady background flow in summer. Storage somewhere within the glacier is suggested because depletion flow continues for several days after occasions on which summer snowfall prevents surface melting (Elliston, 1973). Towards the end of the ablation season, depletion curves appeared to become steeper, as drainage occurred more rapidly. Elliston thought this was consistent with the hypothesis that as the season progresses, exits from the englacial reservoirs become enlarged by the warmth of descending water, enabling discharge to increase and reducing the time of passage through the glacier. The time at which maximum daily flow occurred was noticed to advance during the season, by 3h in the Matter-Vispa, to which the Gornera is tributary, between June and late September (Elliston, 1973), and similarly for the Massa, Aletschgletscher, Switzerland (Lang, 1973), in spite of reducing discharges in September. The question as to what extent the seasonal variation depends on development of the internal drainage system, or on the nature and extent of contributing melt areas, remains unsettled.

Anomalous discharge events, with no meteorological causation, may be due to conduits tapping subglacial water pockets and suddenly increasing flow (Mathews, 1964a) or reducing flow due to collapse of tunnels.

2.6.2 Relationships between discharge and meteorological parameters

Studies of relationships between discharge and meteorological elements have been undertaken primarily for the purpose of forecasting discharge of proglacial meltwater streams (e.g. Jensen and Lang, 1973). Correlation coefficients calculated between mean daily temperature and mean daily discharge at various lag intervals provide a measure of delays in meltwater runoff (Lang, 1968). The lag at which maximum correlation occurs represents the mean transit time of the passage of all meltwaters through the glacier. At Aletschgletscher, a mean lag of 3d in May - mid-June was reduced to 1d by mid-September (Lang, 1973), again suggesting evolution of the drainage network.

On a seasonal basis, extrapolation of regression equations fitted to relationships between meteorological parameters and discharge in August at Mikkaglaciären, Sweden, to apply to June and July showed that runoff in June to mid-July was lower than would be predicted and run-off in late July somewhat greater (Stenborg, 1970). Taking into account changing surface areas of snow and ice subject to ablation, about 25 per cent of the total summer discharge was found to be delayed in runoff from the early to the middle part of the ablation season. Water is probably stored as slush on the surface of lower parts of the glacier, in firn in the accumulation area, and held up in conduits, crevasses and moulins which have been closed by deformation, glacier movement or freezing during winter, according to Stenborg (1970), although the resumption of flow should readily re-open them.

2.6.3 Natural and experimental labelling of meltwaters

Elliston (1973) commented that waters entering moulins and flowing in large streams may reach the glacier portal rapidly, but that they account for only a small fraction of the total meltwater. Nevertheless, measurements of transit times for flow of individual 'parcels' of water from the surface to the portal can provide useful information about the internal hydrology of glaciers. Diurnal variations of tritium content of meltwaters draining from Hintereisferner show that waters which are tritium-free from the melting of ice in the ablation area reach the portal concurrent with the daily ablation of the surface (Behrens and others, 1971). Experimental labelling of waters draining into moulins has been used to determine point-to-portal transit times, using salt and dye tracers. Within South Cascade Glacier, Washington, U.S.A., mean velocities of 0.29m s^{-1} from moulins to portal suggested that flow beneath the firn line was in large open conduits, since surface stream velocities were 0.17-0.42m s^{-1} (Krimmel and others, 1973). Tracing from the accumulation area suggests a rate of 0.4m h^{-1} through snowpack, but interpretation of transit times from firn to portal depends on whether slow percolation in firn is followed by rapid flow in an arterial conduit, or slow percolation, slow flow in small conduits, temporary storage and quickflow.

At Mikkaglaciären, Stenborg (1969, 1970) used salt tracers to determine contributing areas of glacier surface to the two outlets from the internal drainage system and so deduce the internal network structure. Internal flow velocities between 0.5-0.7m s^{-1} were measured. Decreasing transit times from 3.0h (18 June) to 1.5h (27 August) were observed from the same moulin to the portal of Glacier d'Argentière, Mont Blanc, France (Vivian and Zumstein, 1973).

Detailed tracer studies using the dyes uranine and rhodamine WT at Hintereisferner indicated that the travel time of dye from the same moulin to the glacier portal varied diurnally according to total discharge from the glacier. The usual open channel velocity-discharge routing relationship would account for this behaviour, and calculations of a dispersion coefficient also suggest that the dye tracer flowed largely in an open channel within the glacier (Behrens and others, 1975). Comparison of results between two years suggest that no detectable change pccurred in the structure and behaviour of the internal drainage network (Ambach and others, 1972; Behrens and others, 1975). The flow-through times and dispersion coefficients indicated that no large water-filled cavities exist along the conduits within Hintereisferner.

2.6.4 Borehole measurements

Measurements of water levels and water pressure in glaciers are inconclusive with respect to the internal drainage system since boreholes may or may not penetrate the conduit system. If connection occurs, conduit pressure conditions may be modified locally. The borehole water level may simply reflect the difference between the rates of surface water supply to the hole from water escape at the bed. In the firn area of South Cascade Glacier, water levels in boreholes remained constant at the level of the firn water table, until the drill reached the bed, when the level fell (Hodge, 1976). In the ablation area, water levels oscillated between 100 and 140m above the bed between July and November with periodicity of around 7-10d. No diurnal variations were observed, although large variations of pressure were measured beneath Glacier d'Argentière which occurred in phase with fluctuations of the discharge of the portal meltstream (Vivian and Zumstein, 1973). Diurnal water level variations of 100m per day were observed by Röthlisberger (1976) at Gornergletscher. Mathews (1964b) found steady pressure conditions, interrupted by irregular surges at South Leduc Glacier, British Columbia, Canada. Water pressures measured by manometers inserted in holes drilled up from a tunnel in rock into ice beneath Gornergletscher showed a stable water head from May to July, 60-70m above the bed, which suddenly dropped following a particularly high daily flow from Gornergletscher (Bezinge and others, 1973). Winter pressures higher than summer pressures are suggested both from observations (Vivian and Zumstein, 1973) and theory (Röthlisberger, 1972). Differences between adjacent holes (Hodge, 1976) suggest that uniform height water tables,if they occur,must be extremely localised.

During drilling operations on glaciers, sudden drops of the drill have suggested that boreholes have intersected with englacial and subglacial conduits. In 13 boreholes at South Cascade Glacier, 18 englacial (diameters 0.25 $\pm$ 0.21m) and 2 subglacial (0.65$\pm$1.15m) cavities were penetrated (Hodge, 1976). The englacial cavities or conduits were clustered at one particular depth, as suggested by Röthlisberger (1972). Englacial waterfilled cavities were also discovered on Athabasca Glacier (Savage and Paterson, 1963; Paterson and Savage, 1970) and at Blue Glacier, U.S.A. (Shreve and Sharp, 1970).

2.6.5 Discussion

Considerable amounts of information about the structure and functioning of internal hydrological systems of individual glaciers have been acquired from indirect observations. Individual glaciers with different characteristics, thickness, length, flow velocity, bed configuration and gradient, ratio of accumulation: ablation areas, and area-altitude distribution might be expected to behave hydrologically in different ways. The indirect observations are insufficiently diagnostic to allow separation of individual effects of several variables which may contribute to a general characteristic. For example, hydrograph analysis suggests storage of water within the glacier, but cannot separate individual storage elements by location, in firn, in transit from parts of the conduit system distant from the portal, in subglacial cavities or in englacial water pockets. Similarly, transit times measured with dye tracers average conditions over the length of the path followed by the water, rather than giving separate velocities for firn percolation, small conduit and arterial conduit flows.

In general, observations of borehole water levels, which may or may not be surrogate basal water pressures (Hodge, 1976), support the concept of large quantities of liquid water remaining stored in the body of Alpine glaciers. Simultaneous determinations of mass balance of South Cascade Glacier by glaciological and hydrological methods (Tangborn and others, 1975), show that some liquid water may remain in storage within the glacier over winter. On the other hand, dye tracing experiments suggest that much meltwater can pass freely, without delay, through conduits which are not links between reservoirs or cavities. A network of two components (at least) is suggested, composed of a route through which meltwater may pass quickly, immediately following production to the glacier portal, and another route which only permits much slower flows. The structure, location and functioning of such a system within a glacier, however, remain enigmatic.

While theoretical treatments of flow in englacial and subglacial conduits have been based on the assumption that the channel cross section is completely full of water and flow occurs under pressure, field observations indicate that open channel flow conditions prevail in tunnels under the ablation area between major moulins and the glacier portal. The existence of open channel flow even at high discharges in summer indicates that consideration of rates of plastic closure as the major control on conduit flow capacity may have to be replaced by some other mechanism, possibly operating in a different part of the hydrological network.

2.7 A model of the Alpine glacier runoff system

A conceptual model of the structure of the Alpine glacier runoff system is shown in Figure 2.3. The model is divided into two compartments, the internal hydrological system of the glacier and the catchment area which is assumed to be free of perennial ice and snow. The input to the ice-free catchment area is precipitation, which as snow and rain becomes stored in snowpack to be released as subsequent melt, or as rain after the rise of the transient snowline, may contribute immediately to runoff. Some of the runoff from the ice-free catchment may enter the glacier, some possibly percolates into storage as groundwater should geological conditions favour a groundwater system, and some flows in stream channels to join the portal meltstream downstream of the glacier snout. A groundwater component may be added to the flow of the portal meltstream between glacier and gauging station at the catchment outlet.

Inputs to the internal hydrological system are derived from precipitation, with solid and liquid storage phases in snow and firn in the accumulation area ('snowmelt' contributions) and as ice, snow and slush in the ablation area ('icemelt'). Since it is generally accepted that water flows in networks of englacial and subglacial conduits, these have

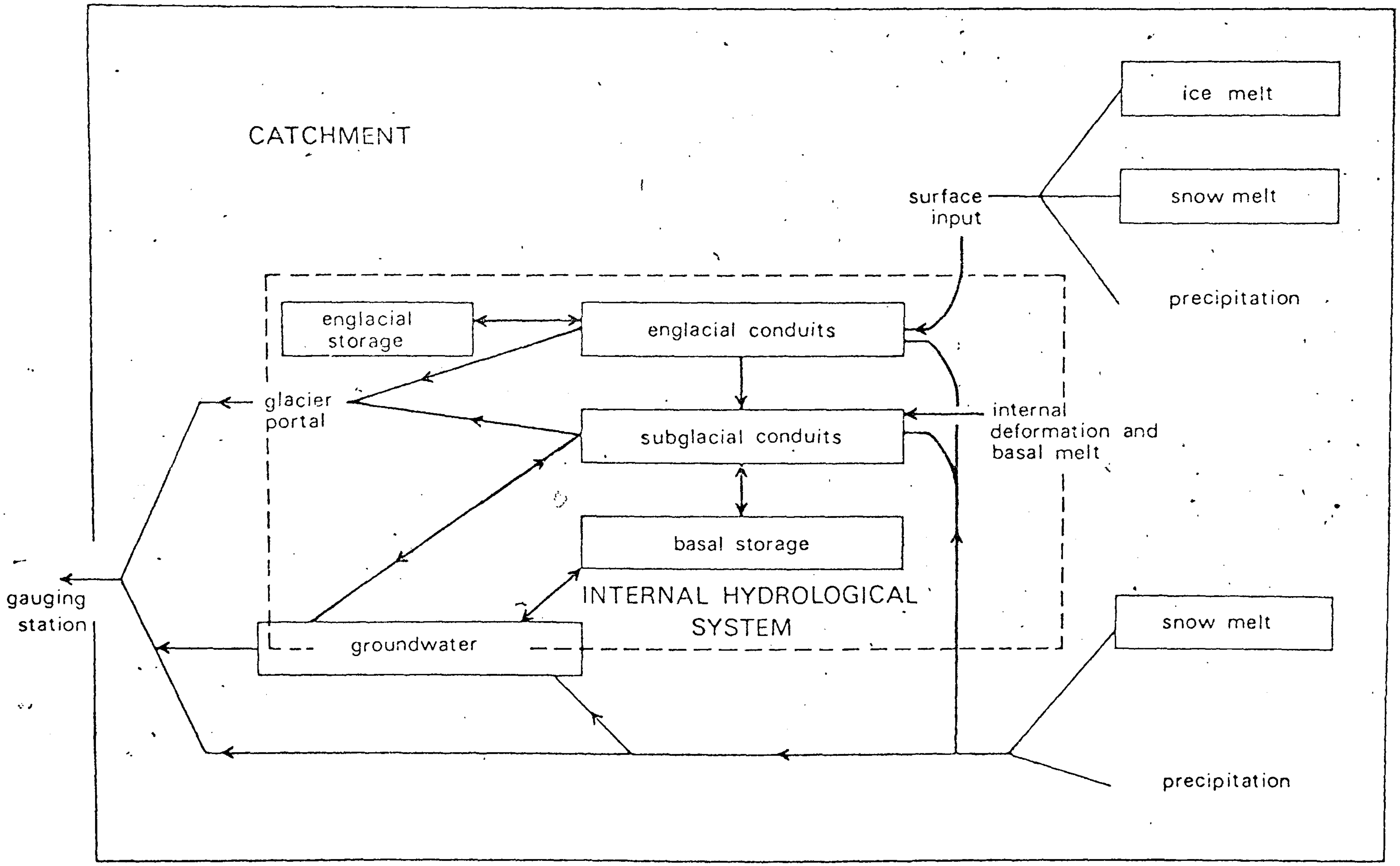


Figure 2.3 Conceptual model of the structure of the alpine glacier runoff system.

been assumed to form the basic structure of the internal plumbing. Veins have been ignored since their volumetric contribution to flow is not substantial. The routing of snowmelt into englacial conduits beneath the accumulation area has not been proved, but in the ablation zone, icemelt enters through moulins, crevasses and cracks. Englacial conduits are assumed to be icewalled tunnels, located away from the ice-bedrock interface. Some of the runoff from the icefree catchment will enter englacial conduits from the ice-margin, the remainder following the bed into subglacial conduits, defined by basal location, and either incised in bedrock, or cast up as tunnels in ice. Water from the englacial system may interact with englacial storage waters either deep in firn or as water pockets in the body of the ice, with net loss or gain to the conduits. A large quantity of water equivalent to the pipe capacity may at any time be stored actually in transit in the englacial conduits. Englacial conduits may conduct a portion of the water to the proglacial meltstream close to the portal, but most of the flow will descend into subglacial conduits which also receive contributions from subglacial melting, and internal deformation melting through the vein network.

Subglacial conduits may interact with basal cavities allowing water both in and out of basal storage. If a groundwater system exists, some water may be lost from conduits and cavities, but some contributed from subglacial springs. Should the subglacial conduits be full, storage of water in transit may occur, equal to the volume of the conduit network. It is probable that the subglacial conduits contribute most of the discharge of the portal meltstream. Flow through a water film at the glacier bed is assumed to be unimportant.

The conceptual model proposed is thought to provide a useful framework for the investigation of the hydrology of Alpine glaciers. It suggests a basic interlinked structure of storages and conduits. More information is required concerning the functioning of the runoff system and seasonal evolution of its behaviour in order to formalise this descriptive simplification into a distributed physical process model. Ideally, a knowledge of what proportion of total flow passes through which routes and which storages would provide considerable insight into the working and structure of the internal plumbing within Alpine glaciers.

3. ANNUAL AND SEASONAL REGIME OF MELTWATER STREAMS

3.1 Introduction

Temporal variations of discharge in portal meltstreams reflect largely meteorological variations. Seasonal discharge variations are of interest because they provide an indication of how glacier drainage systems develop from spring to fall. In addition, they show how run-off responds to precipitation inputs and changing meteorological controls on melting of snow and ice, and also are indicative of conditions within the glacier. Annual fluctuations in runoff result from variations in inputs, which are climatically determined, and which in non-glacierised catchments determine the water balance, but integrate such effects with regulatory effects from climatically controlled changes in glacier mass balance. Studies of storage and release of water from temperate glaciers have become increasingly important in view of the establishment of hydro-electric schemes in Alpine regions. Such studies are important because they show the changing amounts and surface distributions of inputs to glaciers throughout one season and from year to year. The regulatory effect of glaciers reduces winter runoff and releases large quantities of water during spring and summer.

The annual amount of discharge released may be less than, equal to, or greater than the total annual precipitation input. If precipitation amounts remained unchanged for several years, the amount of runoff produced in warmer summers may exceed annual precipitation input, because of extra melting of ice and snow. Cooler summers would produce less runoff, and result in a net increase in the total icemass stored in the glacier. If temperatures were unchanged, increased precipitation may produce more runoff, from snowmelt or summer precipitation, but outflows may be lower than inputs depending on amount of snowfall and its effect on the ablation season and area. Decreased inputs will result in loss of glacier mass and discharge may decline absolutely but still be greater than annual inputs. Considerable fluctuation of annual discharge totals may result from changes in glacier mass, independent of annual precipitation variations.

Useful conclusions about the nature of glacier drainage can probably be derived from discharge records. This chapter describes and examines annual and seasonal variations of discharge in the context of catchment water balance, and glacier mass balance. The study of a glacier's interaction with its basin hydrological cycle allows determination of annual and seasonal variations of the amounts and proportions of runoff derived from changes in glacier mass, and of the impact of glacierisation on precipitation-discharge relationships. In particular, the aim is to provide information concerning the range of annual and seasonal throughputs of water transferred through the internal drainage system.

3.2 Components of the water balance of a glacierised catchment

The annual water balance of a glacierised catchment is given by:

$$Q_t = P_g - E_g + C_g - S_g + A_g \pm \Delta W_g + P_r - E_r \qquad (3.1)$$

where Q_t is discharge, P precipitation, E evaporation, C condensation, S the amount of snowfall remaining at the end of the summer melt season, A ablation and ice melting, and ΔW_g the net change in volume of liquid water stored within the glacier between the beginning and end of the hydrological year. Subscript g refers to the glacierised part of the catchment, and r to the non-glacierised areas. Equation (3.1) is appropriate only in definable, water-tight drainage basins, where very limited, if any, groundwater flow occurs within thin detrital mantles on steep slopes of impermeable rocks. P_g and P_r include wind drifting of snow and avalanche redistribution.

The net mass balance of the glacier is the difference in water equivalent between the volume of snow remaining at the end of the budget year and the amount of ice and firn ablation during the year: $(S_g - A_g)$, assuming $\Delta W_g = 0$, although not all water from the internal hydrological system drains by the end of the ablation season (Tangborn and others, 1975; Hodge, 1976). In calculations of mass balance from water balance data, ΔW_g is assumed to be relatively constant from year to year, since recession curves at the end of each hydrological year show approximately the same flow characteristics (Tangborn, 1966). While some depletion occurs, the volume of which may be obtained from integration beneath the curve of the end of season recession curve, the volume of water remaining from one year to the next cannot be estimated. The actual quantity of water stored may be large, particularly if it is to account for anomalous drainage events (Mathews, 1964a), some of the winter recession flow (Stenborg, 1965), and high residual water pressures in glaciers in winter (Vivian and Zumstein, 1973; Hodge, 1976). It is suggested that to consider a glacier storage function (F_g) as a surrogate measure of glacier mass balance is more realistic where:

$$F_g = S_g - A_g \pm \Delta W_g \tag{3.2}$$

In hydrological studies of mass balance, C_g and E_g have been ignored, since they tend to be compensating (Tangborn, 1966) and are also very small in relation to other quantities (La Chapelle, 1959). Equation (3.1) can be simplified:

$$Q_t = P_g + P_r - E_r - F_g \tag{3.3}$$

In steady state conditions, used loosely to indicate that the total mass of ice and stored water in the glacier is the same at the beginning of the hydrological year as at the end:

$$Q_t = P_g + P_r - E_r \tag{3.4}$$

and $F_g = 0$.

If $F_g > 0$, because $S_g > A_g$, the mass balance of the glacier will be positive, and total annual catchment runoff will be less than total precipitation input. Conversely, should A_g exceed S_g, F_g becomes negative, and runoff will exceed precipitation input. The availability and source areas of meltwater inputs to the internal drainage system depend on relative influences on mass balance changes and summer ablation of winter precipitation and summer energy supply. Calculation of the water balance, and estimation of F_g require accurate measurement of the parameters Q_t, P_g, P_r and E_r. Most of the components of the water balance show temporal, spatial and altitudinal variations. Precipitation ($P_g + P_r$) varies in type and amount seasonally and annually, and in mountainous catchments is distributed unevenly in space and with altitude (Loijens, 1972). Unhappily, the evaporation term cannot be measured easily.

3.3 Measurements

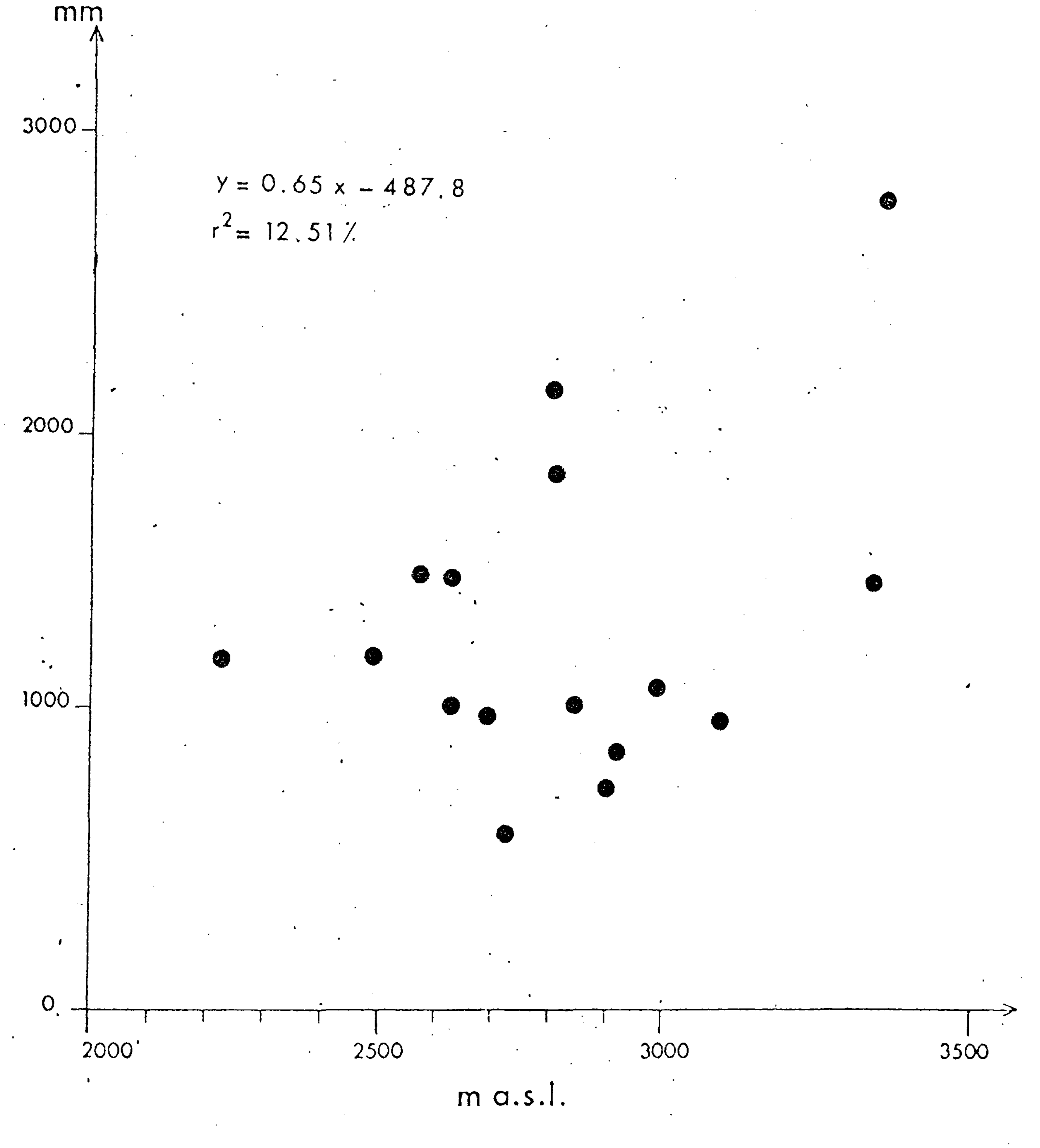
3.3.1 Feegletscher catchment

Continuous records of the discharge of the Feevispa, obtained from the gauges at Saas-Fee, were examined for the period between October 1966 and September 1976. The error of measurement of discharge is about 5 per cent, surprisingly low for a glacier meltwater stream, in which turbulence, standing waves and shifting beds make gauging problematical (Rudolph, 1961), on account of the well-designed flume and weir structure.

Daily precipitation measurements are available from a gauge at Saas-Fee (at 1785m a.s.l.) for 1962-1968, and from a station at Saas-Almagell (1630m), located about 4 km south-east of the catchment boundary, for 1967-1971 (Schweizerische Meteorologischen Zentralanstalt, 1964-1972; 1974). Mean annual precipitation at Saas-Fee was 781mm and at Saas-Almagell 729mm.

Precipitation data at these points are not representative of those expected over the altitudinal range of the catchment area, but provide an indication of seasonal and annual variations, which are probably reflected throughout the basin. A network of totalising raingauges at various altitudes throughout the massif of Monte Rosa and the Mischabel chain provides measurements of total mountain precipitation about every six months (Schweizerische Meteorologischen Zentralanstalt, 1964-1972; 1974). The accuracy of these gauges, surrounded by windshields and standing 3m above the ground surface, is difficult to assess. Aerodynamic conditions created around gauges only 0.3m from the ground surface induce errors in the catch of rain such that precipitation is underestimated by an average of 6.6 per cent (Robinson and Rodda, 1969). Each of the gauges in this network probably experiences a different degree of exposure to wind. In the Aletschgletscher catchment, Kasser (1954) considered that totalising raingauges gave poor measures of pricipitation, but suggested no alternative method. Rudolph (1961) emptied totalising raingauges every month, rather than bi-annually, in order to minimise losses of catch by evaporation. Totalising raingauges probably underestimate both winter snowfall and summer rainfall by up to 15 per cent in mountainous terrain.

Precipitation measurements were corrected to provide values for complete hydrological years to remove effects of varying dates of emptying of gauges in April and October (Schweizerische Meteorologischen Zentralanstalt, 1964). A plot of mean annual precipitation measurements against gauge site altitudes for 16 totalising raingauges in the Monte Rosa and Mischabel mountains shows little consistent variation of precipitation with altitude (Fig. 3.1). The importance of local aerodynamic conditions and topographic situation probably governs catch,



<u>Figure 3.1</u> Relationship of mean annual precipitation catch to altitude for 16 totalising raingauges in the massif of Monte Rosa and Mischabel chain.

and also actual ground surface precipitation. In order to represent spatial and altitudinal variation of precipitation over the Feevispa catchment, the annual precipitation averaged over the entire catchment has been assumed to be equal to the mean of the annual precipitation measurements at all 16 gauges. Although most of these gauges are outside the watershed, it is probable that the range of local precipitation environments inside the catchment boundary forms a sample of those in surrounding mountains and glaciers with similar topography. This appears preferable to estimation of basin precipitation from one index gauge, as used by Tangborn (1966) for winter input in the accumulation area of South Cascade Glacier, where error results from the precipitation at a point being unrepresentative of the catchment as a whole. Summer rainfall was measured at various altitudes in the South Cascade basin in gauges "equipped with windshields to increase the accuracy of the catch".

No measurements of evaporation were possible, but this parameter was estimated from the relationship between evaporation and altitude in catchments in the Swiss Alps found by Lütschg (1945). A linear decrease of evaporation with altitude is given by:

$$E_r = 426.3 - 0.0707\ h \qquad (3.5)$$

where E_r is evaporation (mm yr^{-1}) and h mean catchment altitude (m a.s.l.), for watersheds with sparse vegetation, and low temperatures dominating much of the year. However, Haefelin (1946) calculated that 440mm yr^{-1} was a reasonable evaporation rate for Jungfraujoch (3500m a.s.l.), Berner Oberland, rather than 179mm predicted from equation (3.5). Since Jungfraujoch is a limited rock site surrounded by firn, Haefelin's estimate is atypical of conditions in the lower non-glacierised areas of Feegletscher catchment. Total annual evaporation for the Feegletscher was estimated as 192mm. Evaporation and condensation are probably trivial components of the water balance of a glacierised catchment. Errors in precipitation measurement may already include an element for evaporative loss from catchments, particularly when catch volume is determined infrequently from exposed totalising gauges.

3.3.2 Gornergletscher

Continuous limnigraph records are available for the prise d'eau gauging station on the Gornera for periods of up to 25 weeks during the summer ablation seasons of 1970-1975. Deposition of coarse sediment in the prise d'eau, and excessive turbulence prevents the calibration of a reliable rating curve for the station, and errors of about 15 per cent are inevitable in the discharge measurements. After passing through the prise d'eau, the intake to a hydro-electric adduction gallery, both the extracted water and that remaining in the river bed are subsequently gauged again in flumes and the sum of these measurements provides a useful check on the performance of the limnigraph station. Measurements from summation are more accurate and have been used in this study.

No attempt has been made to measure the parameters of the water balance at Gornergletscher on account of the incomplete discharge record. Some of the totalising raingauges described in section 3.3.1 are located in the Gornergletscher catchment. The 1977 gauging record for the Findelenbach was insufficiently long for meaningful investigation of seasonal variations.

3.4 Results and discussion

3.4.1 Annual precipitation in the massif of Monte Rosa and Mischabel chain

Annual precipitation totals for the 16 raingauges are given in Table 3.1, together with mean annual precipitation for each gauge for the 10 hydrological years 1962-63 to 1970-71 and 1972-73. Results from 1971-72 are not available. The range of mean annual precipitation measured at individual gauges during the above period was 617-2827mm. Percentage deviations of each year's precipitation from the period mean for each gauge are also given in Table 3.1. Each year, the mean of the percentage deviations from the period mean precipitations at each gauge provide a measure of variations in total annual precipitation. 1963-64 and 1972-73 were particularly dry (84 per cent and 87 per cent of the period mean), and in 1962-63 and 1968-69 particularly wet (121 per cent and 114 per cent of the period mean). The mean annual precipitation, averaged for all gauges, all years, was 1339mm.

Kasser (1954) estimated mean annual precipitation averaged over the catchment of Gornergletscher for the hydrological years 1920-21 to 1933-34 as 1112mm yr^{-1}. In the same period, mean precipitation at Aletschgletscher was 2079mm yr^{-1}. In general, glaciers in the Pennine Alps receive relatively low annual precipitation inputs, although Rudolph (1961) found a mean of only 1320mm yr^{-1} at Hintereisferner. A

TABLE 3.1 ANNUAL PRECIPITATION CATCH IN TOTALISING RAINGAUGES IN THE MASSIF OF MONTE ROSA AND MISCHABEL CHAIN

Station	Catchment	Site	Altitude m a.s.l.		1962-63	1963-64	1964-65	1965-66	1966-67	1967-68	1968-69	1969-70	1970-71	1972-73	Period mean $\bar{x}$
1		Trift		mm	1200	810	1200	1030	1150	1010	1210	1140	970	930	1065.0
			2620	$(x/\bar{x})$%	112.7	70.6	112.7	96.7	108.0	94.8	113.6	107.0	91.1	87.3	100.0
2	Gorner-	Gandegg		mm	840	710	920	760	770	740	850	920	790	610	791.0
	gletscher		2900	$(x/\bar{x})$%	106.2	89.8	116.3	96.1	97.3	93.6	107.5	116.3	99.9	77.1	100.0
3	Gorner-	Monte-Rosa		mm	1060	730	910	970	990	900	1020	930	810	770	909.0
	gletscher	Plattje	2920	$(x/\bar{x})$%	116.6	80.3	100.1	106.7	108.9	99.0	112.2	102.3	89.1	84.7	100.0
4		Findelen		mm	770	520	670	620	590	580	790	550	560	520	617.0
			2720	$(x/\bar{x})$%	124.8	84.3	108.6	100.5	95.6	94.0	128.0	89.1	90.8	84.3	100.0
5		Mondelli-		mm	2670	1840	2130	1450	2730	2480	2270	1770	2330	1730	2149.0
		pass	2800	$(x/\bar{x})$%	128.4	85.6	99.1	67.5	127.0	115.4	105.6	82.4	108.4	80.5	100.0
6		Tälliboden		mm	1400	1000	1180	990	1440	1240	1420	1080	1270	1211	1223.1
			2485	$(x/\bar{x})$%	114.5	81.8	96.5	80.9	117.7	101.4	116.1	88.3	103.8	99.0	100.0
7		Ofentalpass		mm	2350	1560	1810	1450	1980	1930	2130	1530	2040	1830	1861.0
			2800	$(x/\bar{x})$%	126.3	83.8	97.3	77.9	106.4	103.7	114.5	82.2	109.6	98.3	100.0
8		Galmen		mm	1190	650	1040	750	1280	1220	1060	960	1000	1113	1026.3
			2690	$(x/\bar{x})$%	116.0	63.3	101.3	73.1	124.7	118.9	103.3	93.5	97.4	108.4	100.0
9		Stelli-		mm	1870	1380	1350	1220	1660	1570	1670	1310	1690	1300	1502.0
		weisstal	2620	$(x/\bar{x})$%	124.5	91.9	89.9	81.2	110.5	104.5	111.2	87.2	112.5	86.6	100.0
10		Schwarzberg-		mm	1290	880	1220	960	1230	1210	1400	990	1070	1020	1127.0
		gletscher	2986	$(x/\bar{x})$%	114.5	78.1	108.3	85.2	109.1	107.4	124.2	87.8	94.9	90.5	100.0
11		Schwarzberg-		mm	2020	1570	1270	1200	1500	1420	2000	1180	1760	1250	1517.0
		kopf	2565	$(x/\bar{x})$%	133.2	103.5	83.7	79.1	98.9	93.6	131.8	77.8	116.0	82.4	100.0

/Continued

TABLE 3.1 (Continued)

12		Allalin-gletscher		mm	1460	1200	1540	1460	1750	1670	1790	1390	1400	1360	1502.0
			3369	$(x/\bar{x})\%$	97.2	79.9	102.5	97.2	116.5	111.2	119.2	92.5	93.2	90.5	100.0
13	Fee-gletscher	Kessjen		mm	1300	960	1050	860	1160	1140	1190	960	1050	970	1064.0
			2840	$(x/\bar{x})\%$	122.2	90.2	98.7	80.8	109.0	107.1	111.8	90.2	98.7	91.2	100.0
14	Fee-gletscher	Plattje		mm	1660	1130	960	1050	1290	1170	1620	1040	1280	930	1213.0
			2228	$(x/\bar{x})\%$	136.9	93.2	79.1	86.6	106.3	96.5	133.6	85.7	105.5	76.7	100.0
15		Furgghorn		mm	2550	2160	3070	2870	3500	3370	2760	3220	2380	2390	2827.0
			2390	$(x/\bar{x})\%$	90.2	76.4	108.6	101.5	123.8	119.2	97.6	113.9	84.2	84.5	100.0
16	Gorner-gletscher	Gornergrat		mm	1700	930	1160	1340	960	780	1020	850	800	690	1023.0
			3100	$(x/\bar{x})\%$	166.2	90.9	113.4	131.0	93.8	76.2	99.7	83.1	78.2	67.4	100.0
				mean %	120.7	84.0	101.0	90.1	109.7	102.3	114.4	97.3	103.2	86.9	100.0

totalising raingauge of a different pattern at Riedmatten, 2800m a.s.l., about 15 km from Gornergletscher, operated by Grande Dixence S.A. since 1961, has collected a mean annual fall of 1240mm. 1963-64, 1970-71, 1971-72, 1972-73 and 1975-76 were exceptionally dry, each about 85 per cent of the usual mean annual precipitation. 1962-63 and 1976-77 were the wettest years (160 per cent of period mean in 1976-77) (Bezinge, 1978). 1974-75 was almost exactly an average year for precipitation.

3.4.2 Seasonal variations of precipitation

Seasonal variations of precipitation were calculated for periods of calendar months for Saas-Fee and Saas-Almagell (Table 3.2). Between 28 and 73 per cent, with a mean of 50 per cent of the total annual precipitation, occurred during the summer months (May-September). The months with maximum summer precipitation were May and August. In summer, the internal drainage system thus has to transmit much of the annual input from precipitation, at the same time as the ablation component. Although a considerable proportion of the total winter snowfall may occur in the space of one month, that actual month varies from year to year. In 1965-66, 66 per cent of the total annual precipitation occurred as winter snowfall, but in 1967-68 only 30 per cent was snow.

3.4.3 Annual and seasonal variations of discharge of Feevispa

Total annual runoff varied considerably from year to year between the limits of 37.3 to 54.0 x $10^6 m^3$, from 75-111 per cent of the period mean ($\bar{x}$ = 48.9 x $10^6 m^3$) (Table 3.3). The proportion of annual total runoff contributed to flow in the summer months (May-September) was about the same each year, despite the variable total discharge and variations in the length of the ablation season. The average proportion of total annual flow discharged during summer was 88.7 per cent, with a range from 85.1-92.1 per cent. Over 50 per cent of total annual runoff always occurred in the months of July and August, suggesting that the internal drainage system develops rapidly each summer. Maximum monthly runoff was either that of July or August. Recession flow resulting from partial drainage of water stored within the glaciers commences in late September and reaches a minimum in late November or early December. Between 6 and 9 per cent of the total annual flow (about 5-9 x $10^6 m^3$) may occur in this period of depletion. Since all

TABLE 3.2 SEASONAL VARIATIONS OF PRECIPITATION AT SAAS-FEE AND SAAS-ALMAGELL

		O	N	D	J	F	M	A	M	J	J	A	S	Annual total	Mean monthly $\bar{x}$
SAAS-FEE															
1963-64	mm	69	136	5	3	5	62	132	73	72	30	44	37	668	55.67
	%	10	20	1	0.5	1	9	20	11	11	4	7	6		
1964-65	mm	42	51	18	32	0	61	23	83	55	124	132	243	864	72.00
	%	5	6	2	4	0	7	3	10	6	14	15	28		
1965-66	mm	9	78	146	39	185	28	68	55	23	65	61	18	775	64.58
	%	1	10	19	5	24	4	9	7	3	8	8	2		
1966-67	mm	247	50	72	22	63	52	13	131	36	42	64	85	877	73.08
	%	28	6	8	3	7	6	1	15	4	5	7	10		
1967-68	mm	19	33	37	87	29	15	35	154	70	55	111	78	723	60.25
	%	3	5	5	12	4	2	5	21	10	8	15	11		
	$\bar{x}$	77.2	69.6	55.6	36.6	56.4	43.6	54.2	99.2	51.2	63.2	82.4	97.8	781.4	65.2
	%	9.81	8.84	7.06	4.65	7.17	5.54	6.87	12.6	6.51	8.03	10.47	12.43		
SAAS-ALMAGELL															
1967-68	mm	14	34	32	64	20	19	42	172	66	46	185	74	688	57.33
	%	2	5	5	9	3	3	6	25	10	7	15	11		
1968-69	mm	22	267	61	35	31	21	48	178	117	37	53	49	919	76.58
	%	2	29	7	4	3	2	5	19	13	4	6	5		
1969-70	mm	6	62	25	34	99	34	103	76	94	27	81	16	657	54.75
	%	1	9	4	5	15	5	16	12	14	4	12	2		
1970-71	mm	98	32	30	28	13	128	42	84	83	21	83	9	651	54.25
	%	15	5	5	4	2	20	6	13	13	3	13	1		
	$\bar{x}$	35.0	98.8	37.0	40.3	40.8	50.5	58.8	127.5	90.0	32.8	100.5	37.00	728.8	60.48
	%	4.67	13.19	4.94	5.38	5.45	6.74	7.85	17.02	12.02	4.38	13.42	4.94		

TABLE 3.3 ANNUAL RUNOFF FROM FEEGLETSCHER CATCHMENT, 1966-67 TO 1975-76

Hydrological year	Annual total runoff		Summer runoff (May-September)	
	$\times 10^6 m^3$	mm	$\times 10^6 m^3$	Percentage of annual total runoff %
1966-67	51.13	1448	45.56	89.1
1967-68	37.25	1055	32.26	86.6
1968-69	46.00	1303	39.74	86.4
1969-70	50.88	1441	46.86	92.1
1970-71	51.73	1465	46.28	89.5
1971-72	45.93	1301	41.23	89.8
1972-73	53.97	1529	49.20	91.2
1973-74	49.82	1411	43.13	86.6
1974-75	51.00	1444	45.71	89.6
1975-76	51.06	1446	43.47	85.1
Period mean 1966-67 to 1975-76	48.88	1385	43.34	88.7

the water may not drain, this suggests that a significant proportion of the total annual discharge may be stored as liquid within Feegletscher in summer, and that much persists to the onset of winter. The volume stored is at least about 6 per cent of the total annual runoff.

Other glaciers show similar behaviour. Ninety-five per cent of the total annual discharge from Glacier de Ferpècle, Pennine Alps, Switzerland (64 per cent glacierised, 36 km^2) occurs between May and September (Bezinge, 1978), and 93 per cent of that of Aletschgletscher (Kasser, 1954; see Table 3.4). Fifty-seven per cent of the annual discharge from Aletschgletscher occurs in July and August. In comparison with other Alpine glacierised catchments, the percentage of total annual flow occurring in winter is high, the proportion in April especially noticeable. This may result from the hydrological behaviour of the large low altitude ice-free area of the catchment during spring snowmelt (Table 3.4).

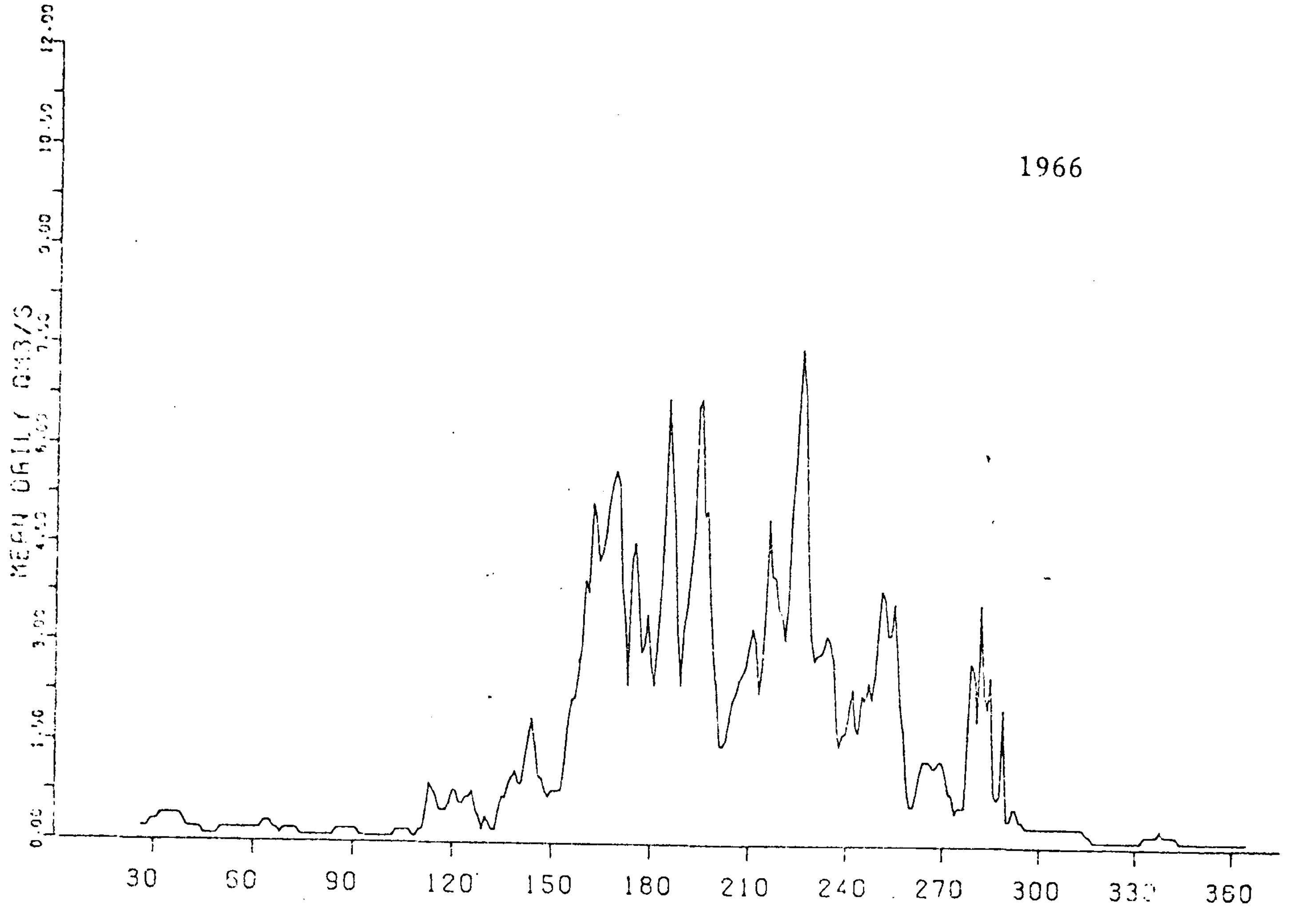
A more detailed impression of the seasonal pattern of discharge from Feegletscher can be obtained from curves of mean daily discharges (Fig. 3.2), which have been constructed for the calendar years 1966 to 1976. From January to late April, the flow of the Feevispa is a mere trickle (about a daily mean of 0.25 $m^3 s^{-1}$), made up of flow from basal icemelt, deformational icemelt and possibly from springs, in addition to any water continuing to drain from internal reservoir storage. The flow is too great to be generated simply by geothermal melting. In 1970 and 1974, snowmelt commenced early, producing increased flow during March ($0.52 \times 10^6 m^3$ and $0.75 \times 10^6 m^3$ respectively, about 1 per cent of the total annual flow each year).

It is not until May that snowmelt over the lower areas of the catchment starts the stream on a slow rise, but distinctive early snowmelt peaks are surprisingly absent from the records, except in 1969, 1971, 1975 and 1976. May runoff totals ranged from $0.67 \times 10^6 m^3$ (1973), representing 1.25 per cent of total annual flow, to $3.51 \times 10^6 m^3$ in 1971 (6.73 per cent of total annual flow), with a period mean of $2.16 \times 10^6 m^3$ (4.42 per cent of period mean annual flow). Some snowmelt will have been retarded in runoff within the snowpack.

Melting snow accounts for a large proportion of the flow in June, during which month, in most years, discharge increased five-fold from May, with the onset of ablation of ice bared by the rise of the transient snowline. Some of the increase probably results from the release of

TABLE 3.4 MEAN MONTHLY DISCHARGES FROM ALPINE GLACIERS AS PERCENTAGES OF MEAN TOTAL ANNUAL FLOWS

Glacier		Feegletscher	Aletschgletscher	Hintereisferner
Source			Kasser (1954)	Rudolph (1961)
Catchment area	km^2	35.3	205.0	26.4
Percentage glacierisation	%	53.7	66.8	60.0
Observation period		1966-67 to 1975-76	1922-23 to 1927-28 and 1931-32 to 1951-52	1953-54
O		4.6	4.2	3.3
N		1.7	0.9	2.1
D		1.0	0.3	1.0
J		1.1	0.2	0.7
F		0.8	0.2	0.5
M		0.9	0.3	0.5
A		1.6	0.9	0.8
M		4.4	4.4	2.8
J		14.5	15.8	19.4
J		28.8	28.7	22.5
A		27.4	28.2	29.0
S		13.3	15.9	17.4



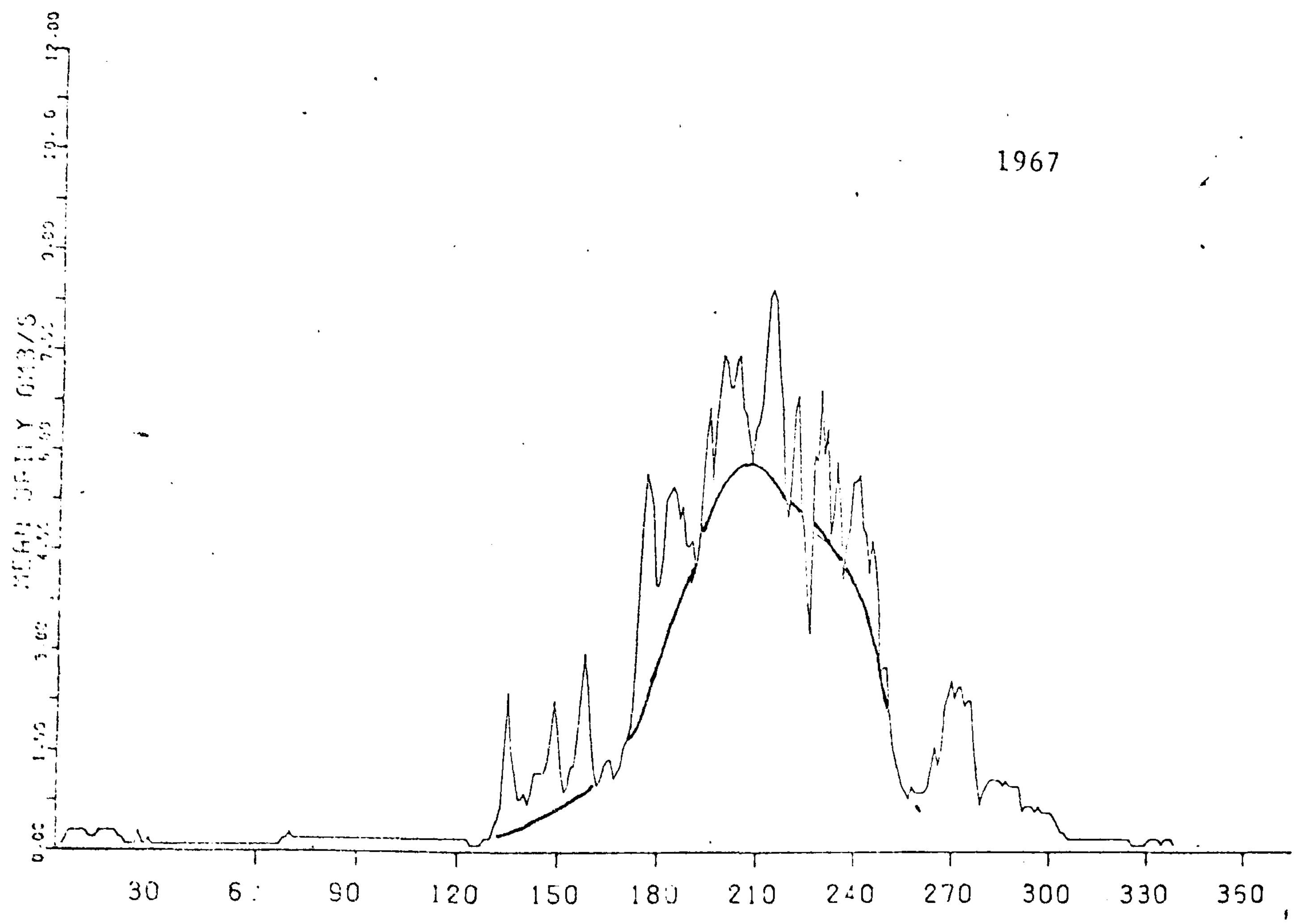
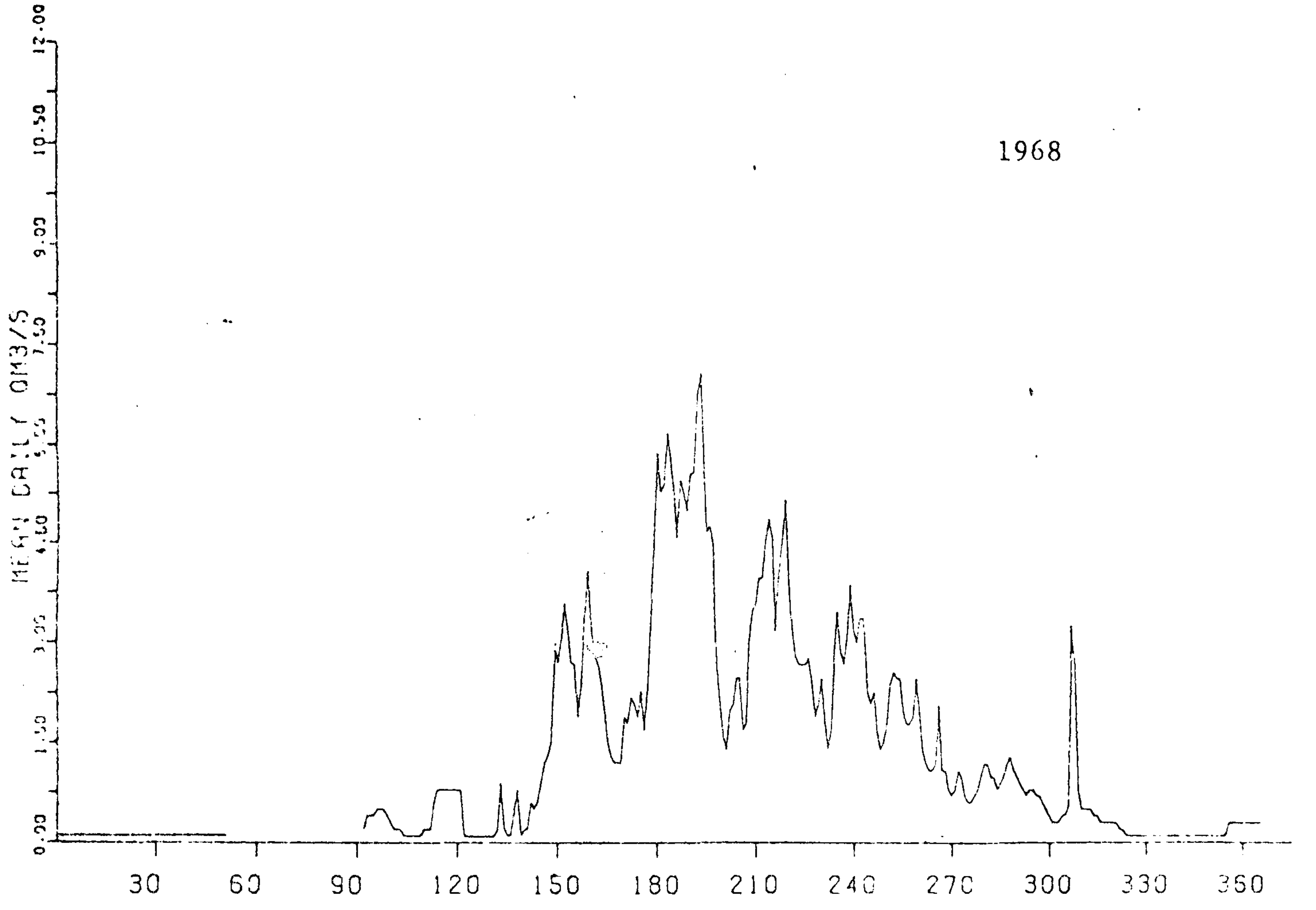
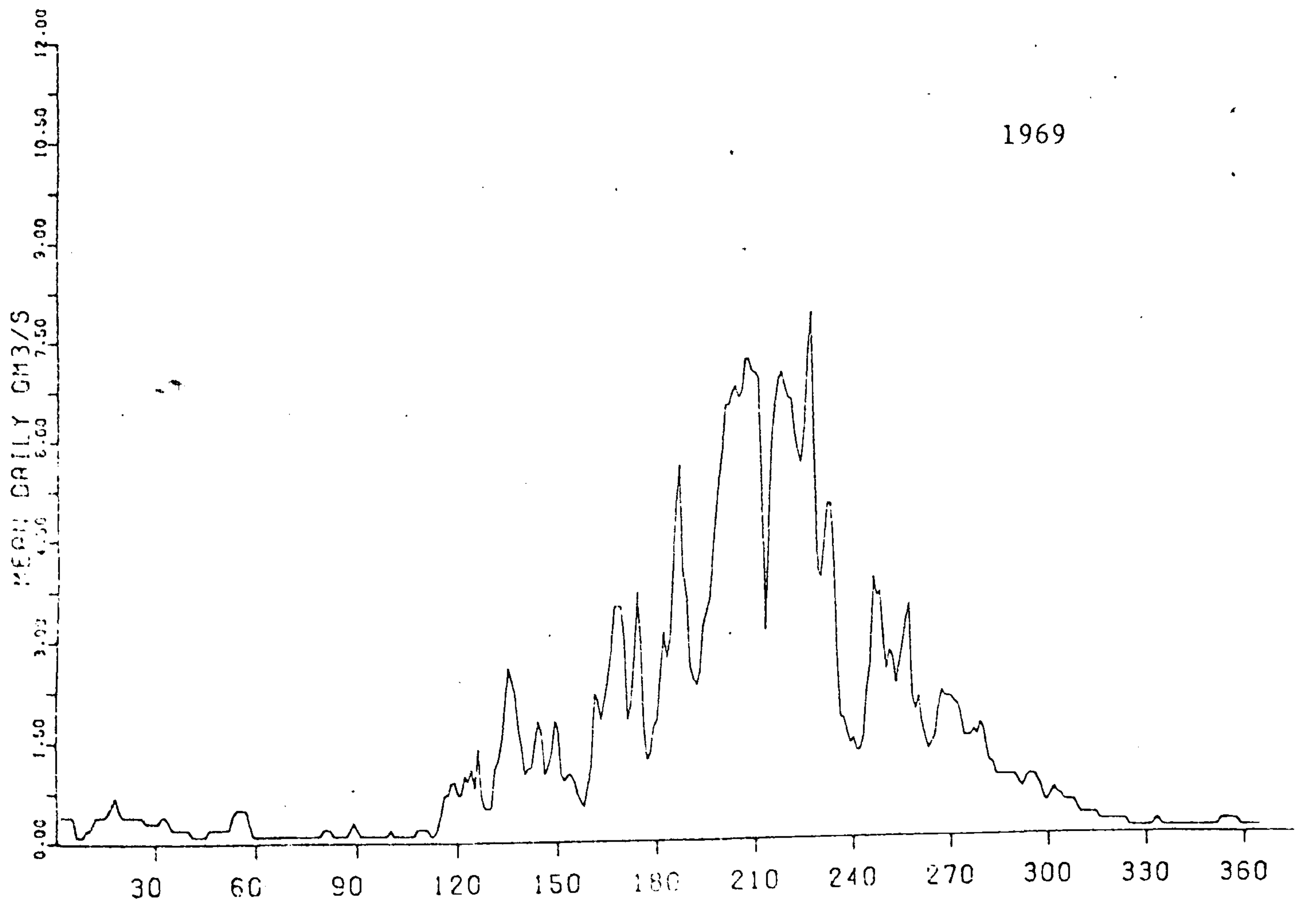


Figure 3.2 Mean daily discharge of the Feevispa, 1966 - 1976. Days are numbered from 1 (1 = 1 January).





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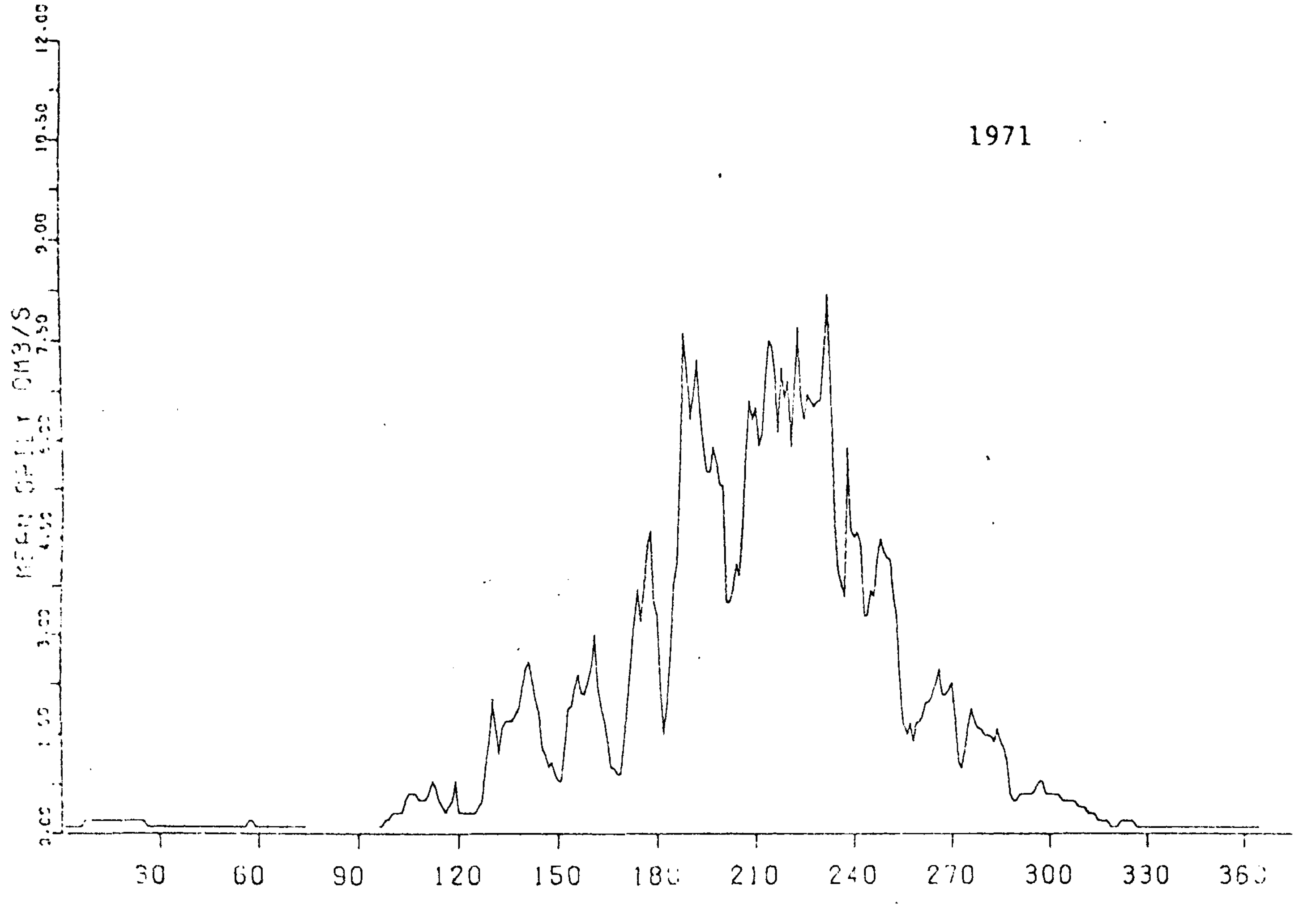

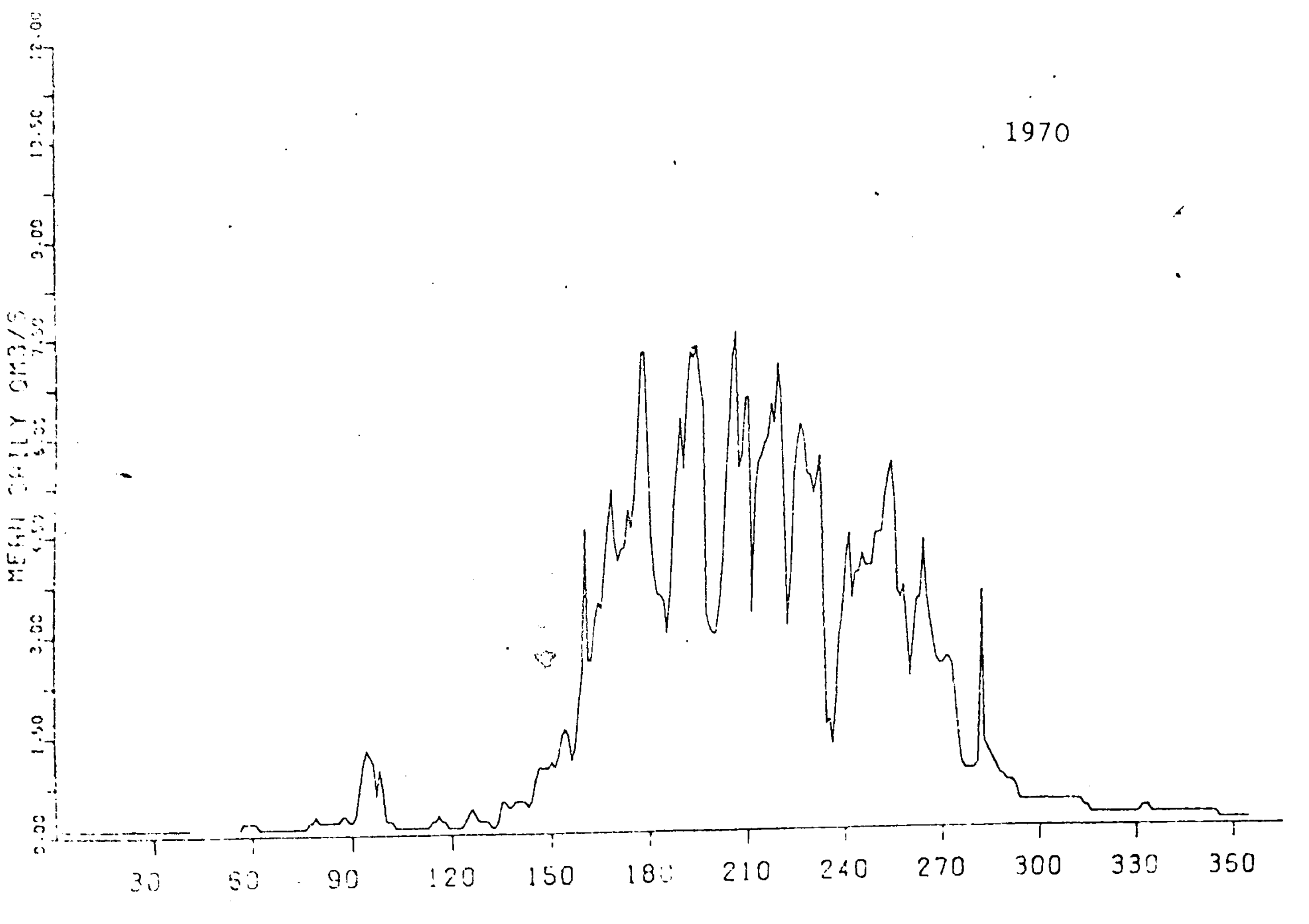

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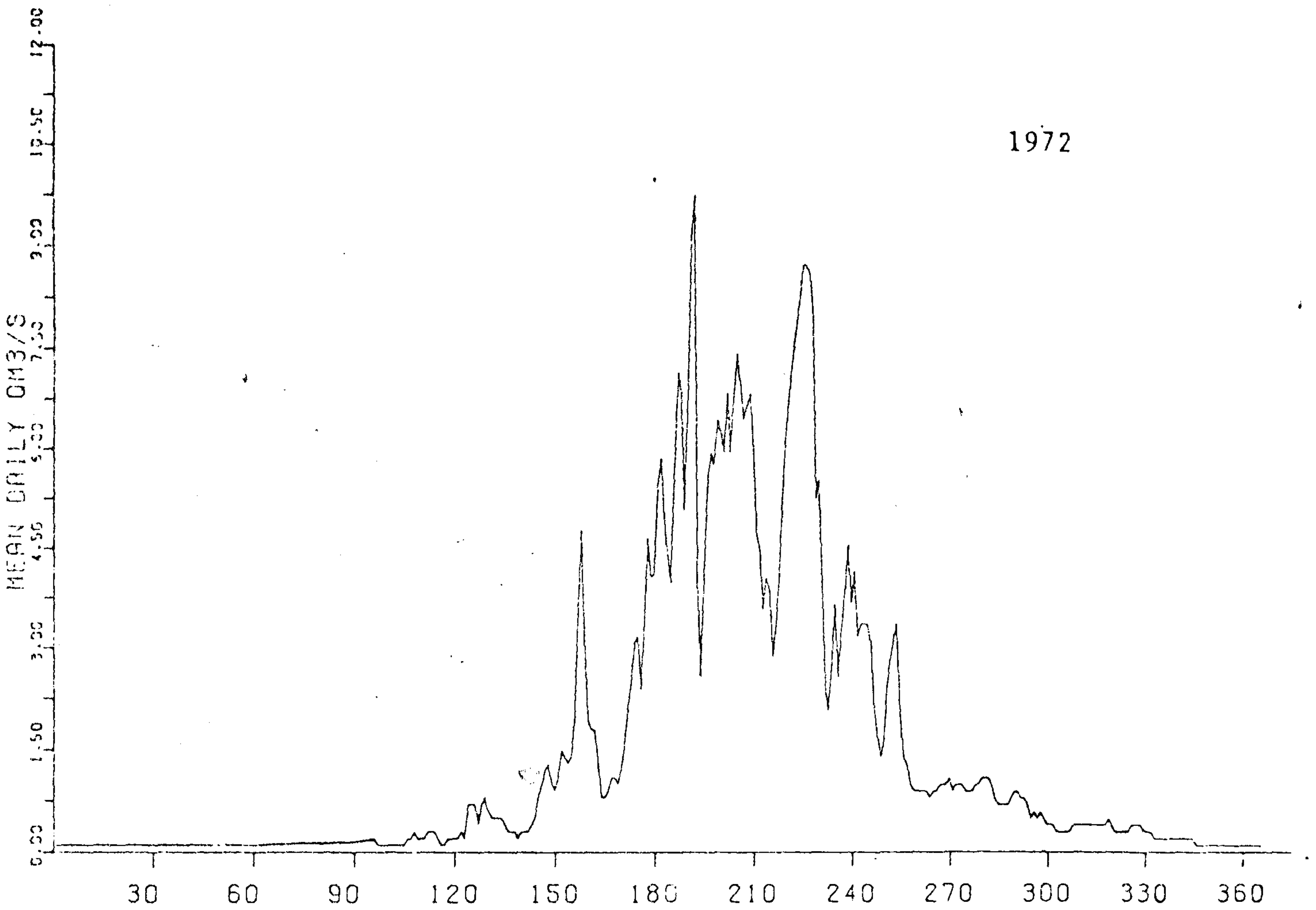
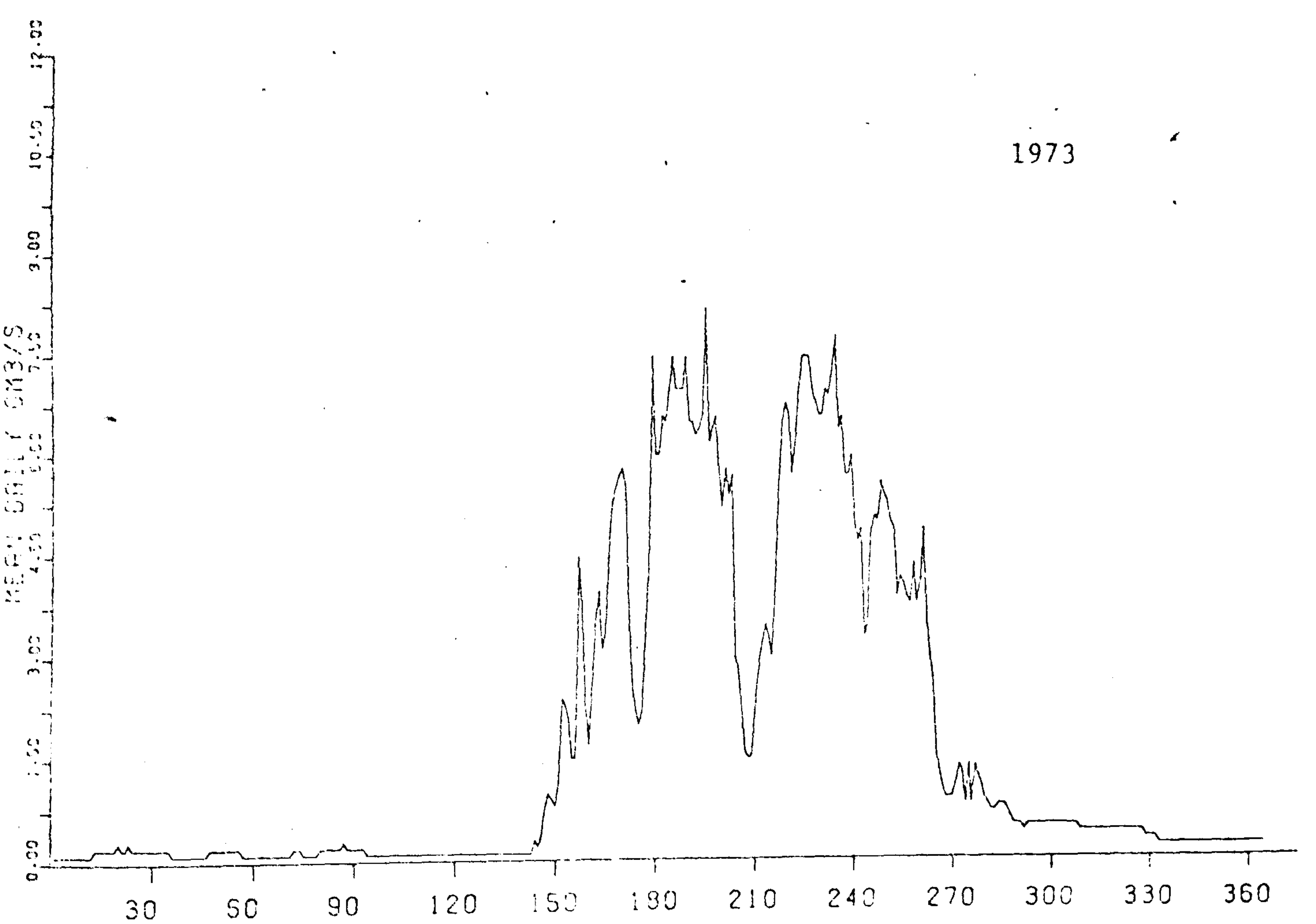
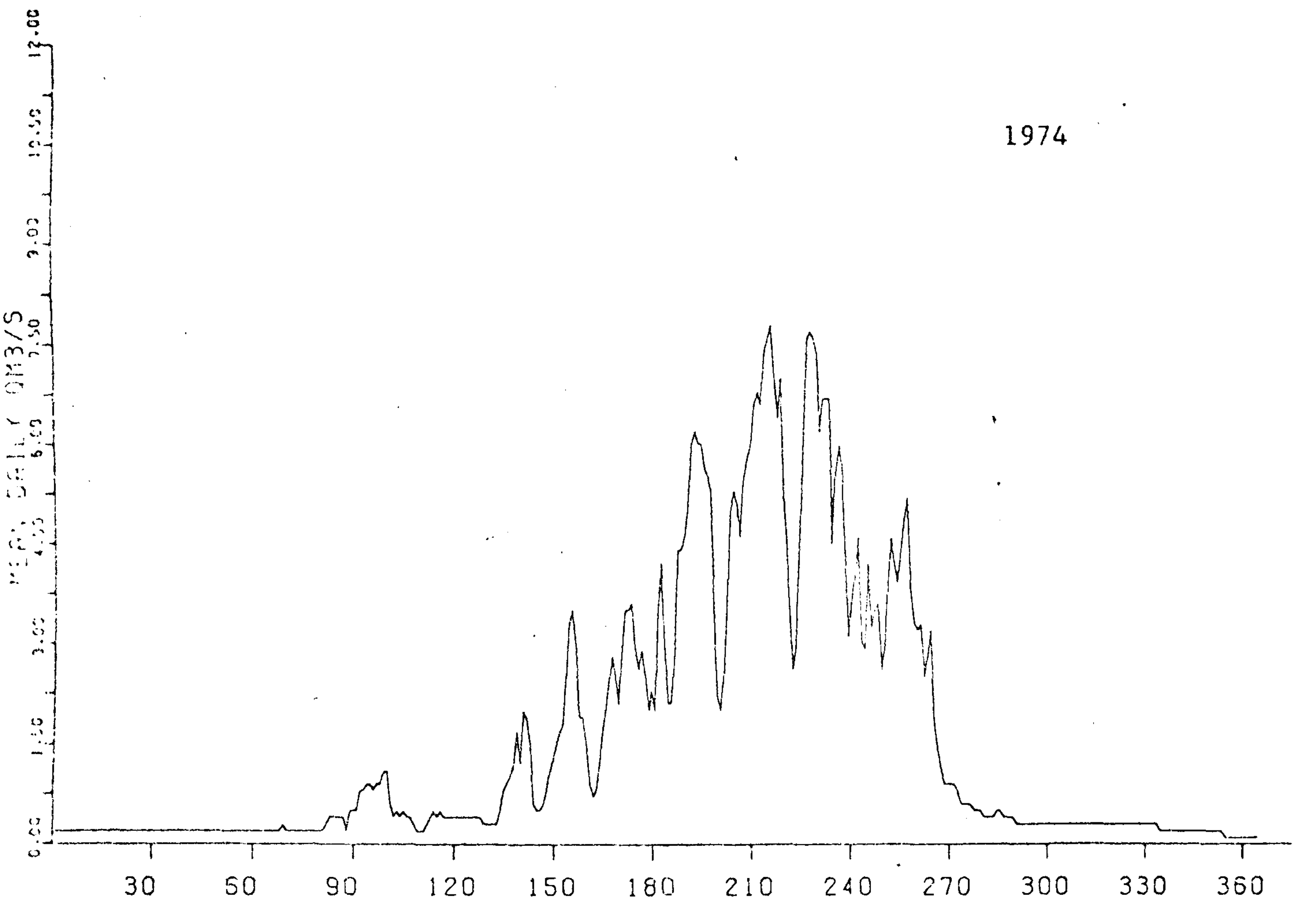
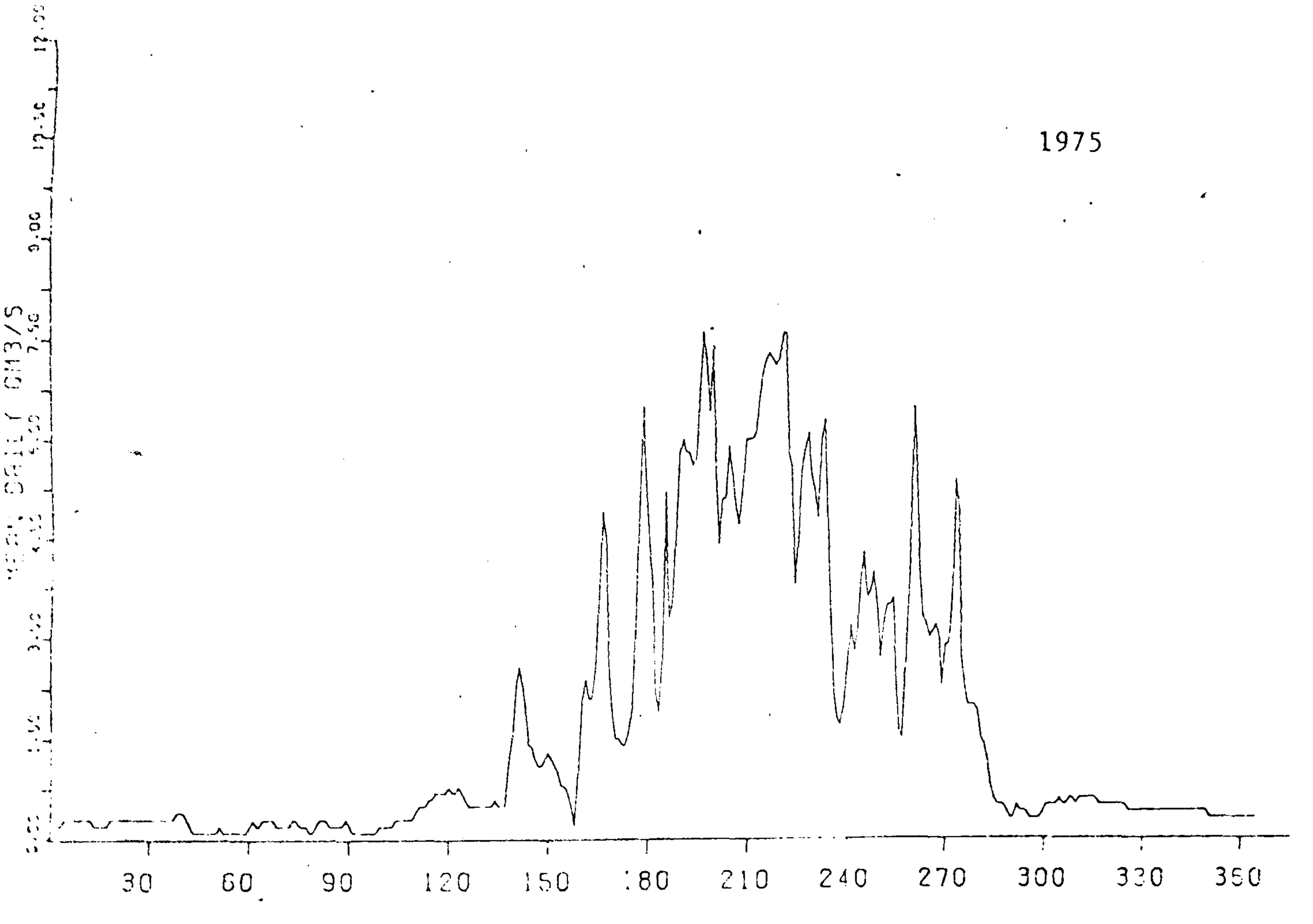




<u>Figure 3.2</u> continued.





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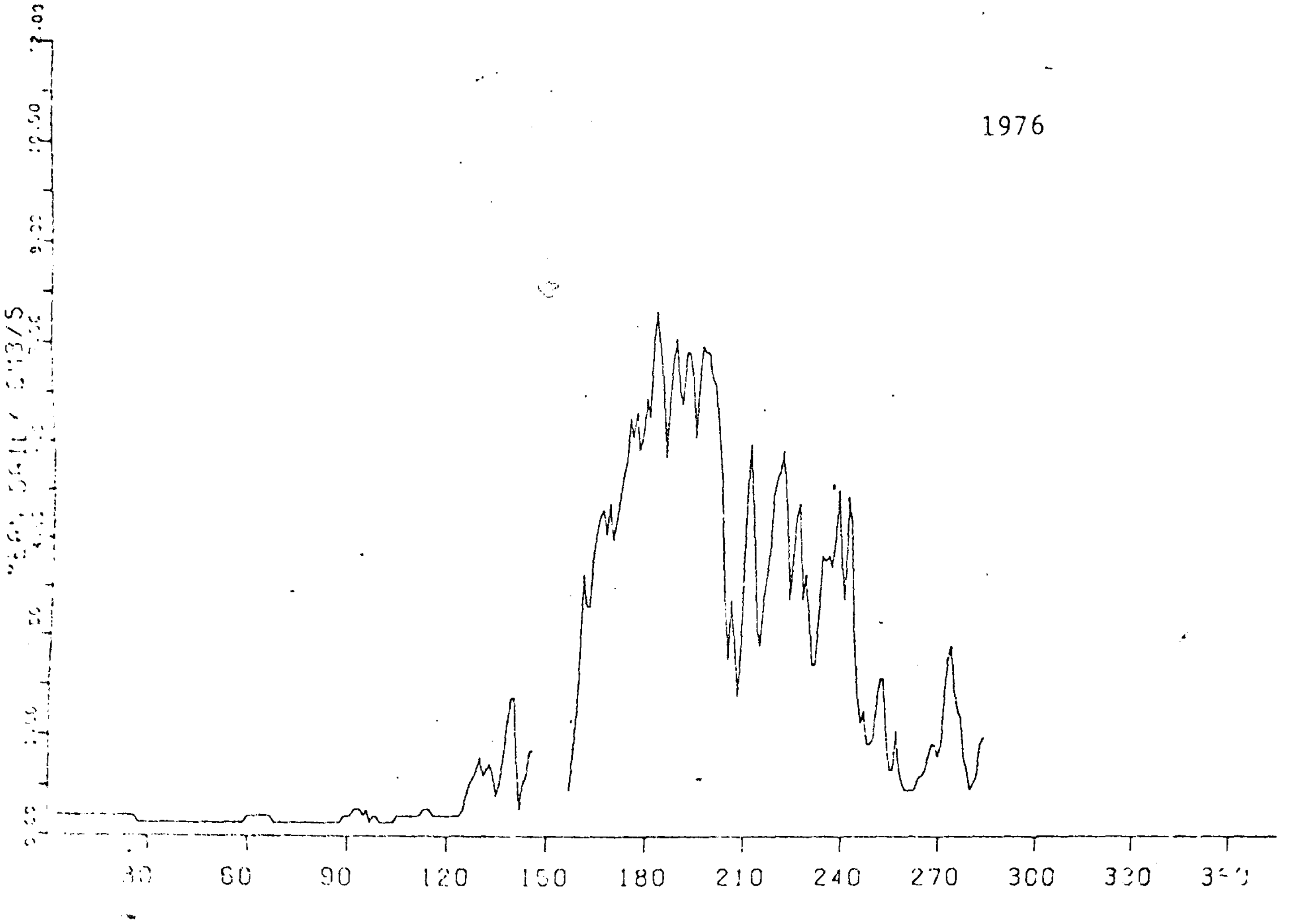


Figure 3.2 continued.

meltwaters stored in snowpack, and release through the re-opening and widening of glacier internal drainage system conduits. Discharge usually increased rapidly during a period of several days. While useful energy inputs may increase rapidly because of the decreased albedo of ice in comparison with snow and increasing solar radiation at this season, this sudden increase in a few days suggests that the internal drainage system can readjust remarkably quickly to changing potential flows once the potential has built up. Flow probably increases because the pressure of water built-up in storage is able to overcome the winter closure of the conduit network, and force a route to the portal, or because sub-snow surface drainage becomes integrated over the glacier surface. However, the latter would lead to steady rather than sudden increases of flow.

Actual discharge in June was variable from year to year, ranging from $4.99 \times 10^6 m^3$ (1969, 10.85 per cent of total annual flow), to $10.02 \times 10^6 m^3$ (1976, 19.64 per cent), period mean $7.08 \times 10^6 m^3$ (14.51 per cent). June flows probably relate to winter snow cover in that a high residual snowcover limits melting by delaying ice exposure for melting. Hence, following very low snowfall in the winter 1975-76, flow in June 1976 was the maximum recorded in the 10 year period.

Maximum mean daily discharges in all years occur in July and August, when energy inputs are strongest and the area of exposed ice greatly increased. Throughout June, July and August of all years mean daily discharges remain high, but considerable irregularity between days, according to meteorological conditions, produces the distinctive variable serrated hydrograph. Not only is the total area under the hydrograph from June to August variable from year to year, but the number, period and amplitude of serrations is extremely irregular both within and between years. A background minimum mean daily discharge defines the shape of the summer flow hydrograph, reflecting the length of the ablation season, the curve of ice-area-exposure through time and seasonal variation in the rate of melting. Superimposed on this background shape (see Fig. 3.2 for 1967), irregular mean daily flows result from changing energy supply/ablation conditions, and from the effect of rainfall, which when the contributing areas of bare ice and debris-free rock surfaces are approaching their seasonal maxima, may contribute rapidly to the formation of runoff.

Some autocorrelated interrelationship between flows on adjacent days result from the superimposition of a daily melt component on a background flow determined by antecedent conditions. The existence of the background flow, changing slowly, alongside widely fluctuating individual daily flows, suggests that runoff from glaciers is subject to some limitation from the drainage system which, while allowing rapid change to accommodate increased flows, prevents all flow leaving immediately on its production. During several sequential days when meteorological conditions provided large energy inputs, mean daily runoff was very high. Lower daily mean discharges were associated with cool wet periods. Annual maximum daily runoff may occur therefore at any time in July or August, and maximum monthly flow may occur in either month, according to meteorological episodes.

By September, flow declines sharply, and recession continues in October and November at decreasing rates. About 5 per cent of the total annual flow is discharged in October. For Alpine glaciers, investigations based on hydrological years might better use the period between 1 November and 31 October, as adopted by Rudolph (1961), though the use of totalising raingauges prevented such a change for this catchment.

During recession, occasionally ablation conditions restored higher flows in the space of two or three days, for example 1968, 1970 and 1976. Such sudden increases in discharge through Feegletscher, in 1976 resulting from increased melting occasioned by higher temperatures during the influence of a foehn wind, suggest that the factors which limited runoff in early summer no longer restrict discharge in the fall. One plausible explanation relates to the larger contributing area of exposed ice, and the lack of snow cover in the recession permitting rapid runoff of meltwater into open channels within the glacier. Another possibility is that during recession, ice conduits have had insufficient time to become closed, and that the extra volume of water can readily runoff, and if necessary, increase the size of channel by melting. Conversely, in spring, channels have suffered closure to such an extent that the rate of flow of water is insufficient to permit rapid conduit widening, even under the pressure of stored meltwater. A conduit size threshold is implied beneath which closure dominates and above which flow can widen the conduits easily and quickly.

3.4.4 Seasonal variations of discharge of the Gornera, Gornergletscher

Monthly mean discharges for the Gornera for 1970-75 were calculated only for those months for which complete data were available (Fig. 3.3). As for the Feevispa, the month with maximum flow was either July or

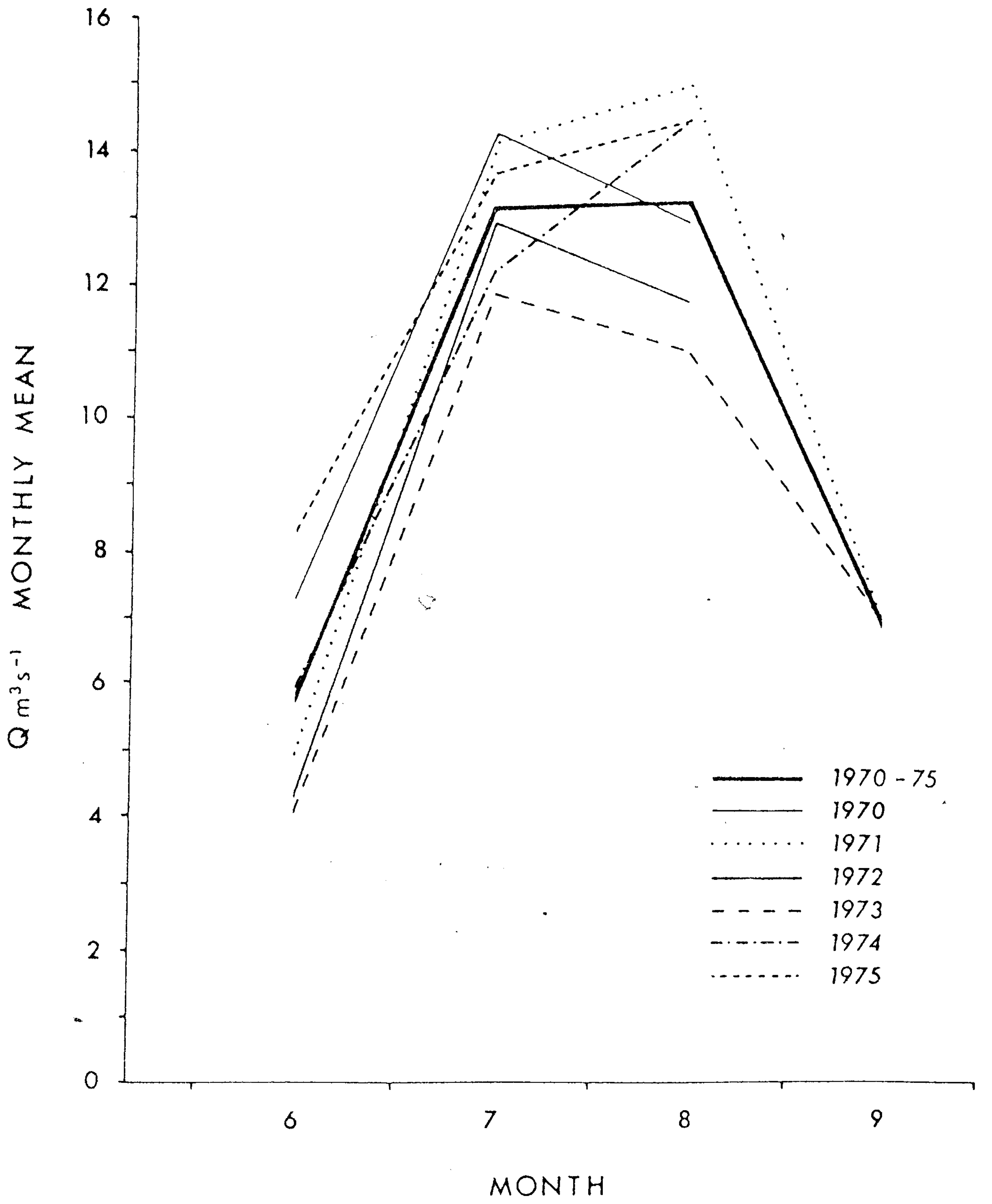


Figure 3.3 Mean monthly discharge of the Gornera, 1970 - 1975.

August. Unlike the Feevispa, September flow was higher than that of June, suggesting a greater delay of runoff within Gornergletscher. Considerable variation between years characterises the summer flows of the Gornera throughout the six-year period, especially in June, under the influence of the extent of remaining winter snow cover. Total flow in the three months June, July and August differed significantly between years (Table 3.5).

The highest annual total summer discharge, in 1973, followed a relatively snow-free winter (Bezinge, 1978), yielding 96.93 x $10^6 m^3$ (112 per cent of the period mean). Lowest summer runoff was 71.82 x $10^6 m^3$, in 1975 (83 per cent of the period mean). Mean total annual runoff is estimated at 142 x $10^6 m^3$ (1731mm).

To provide further indication of the seasonal pattern of runoff, weekly mean discharges were calculated for all weeks for which complete data are available in all years (Fig. 3.4). Marked variability between weeks results from variation in meteorological conditions affecting ablation rates. A different week in each year saw a weekly mean flow much higher than all the others in that summer, because of the discharge arising from the catastrophic drainage of the ice-dammed Gornersee. The volume of the lake, and timing of draining, differ annually. About 2.0 - 3.0 x $10^6 m^3$ of water have accumulated in the lake 6 km from the portal by the time of drainage in most recent years (Bezinge and others, 1973) accounting for approximately 5 per cent of the total monthly flow of the Gornera in July and August, the months in which drainage events are most likely.

During summer months, mean daily discharge fluctuations follow a similar pattern to those described for the Feevispa. From the end of May, flow increases steadily to produce the background flow maintained until September, on which are superimposed periodic large amplitude fluctuations produced by variations in meteorological conditions (Fig. 3.5). The shape of the background hydrograph differs widely from year to year in length and amplitude. The range of amplitude of short-term variation over 4-8d intervals was much greater for the Gornera than for the Feevispa, dependent on the absolute discharges of the two streams. In 1975, sudden peak flows resumed for a few days in late September at Gornergletscher interrupting the usual very steep end of ablation season recession. This further suggests that the internal drainage system remained sufficiently open to take these enhanced discharges.

TABLE 3.5 TOTAL MONTHLY FLOWS FROM GORNERGLETSCHER DURING SUMMERS OF 1970-1975

Year	Monthly flow $\times 10^6 m^3$				Seasonal total flow (June-August) $\times 10^6 m^3$
	J	J	A	S	
1970	18.87	38.37	34.92	-	92.16
1971	12.72	37.83	40.46	18.18	91.01
1972	11.05	34.69	31.56	-	77.30
1973	21.28	36.65	39.00	-	96.93
1974	15.29	32.76	39.17	-	87.22
1975	10.41	31.89	29.52	18.23	71.82
1970-75 mean	14.94	35.37	35.77		86.07

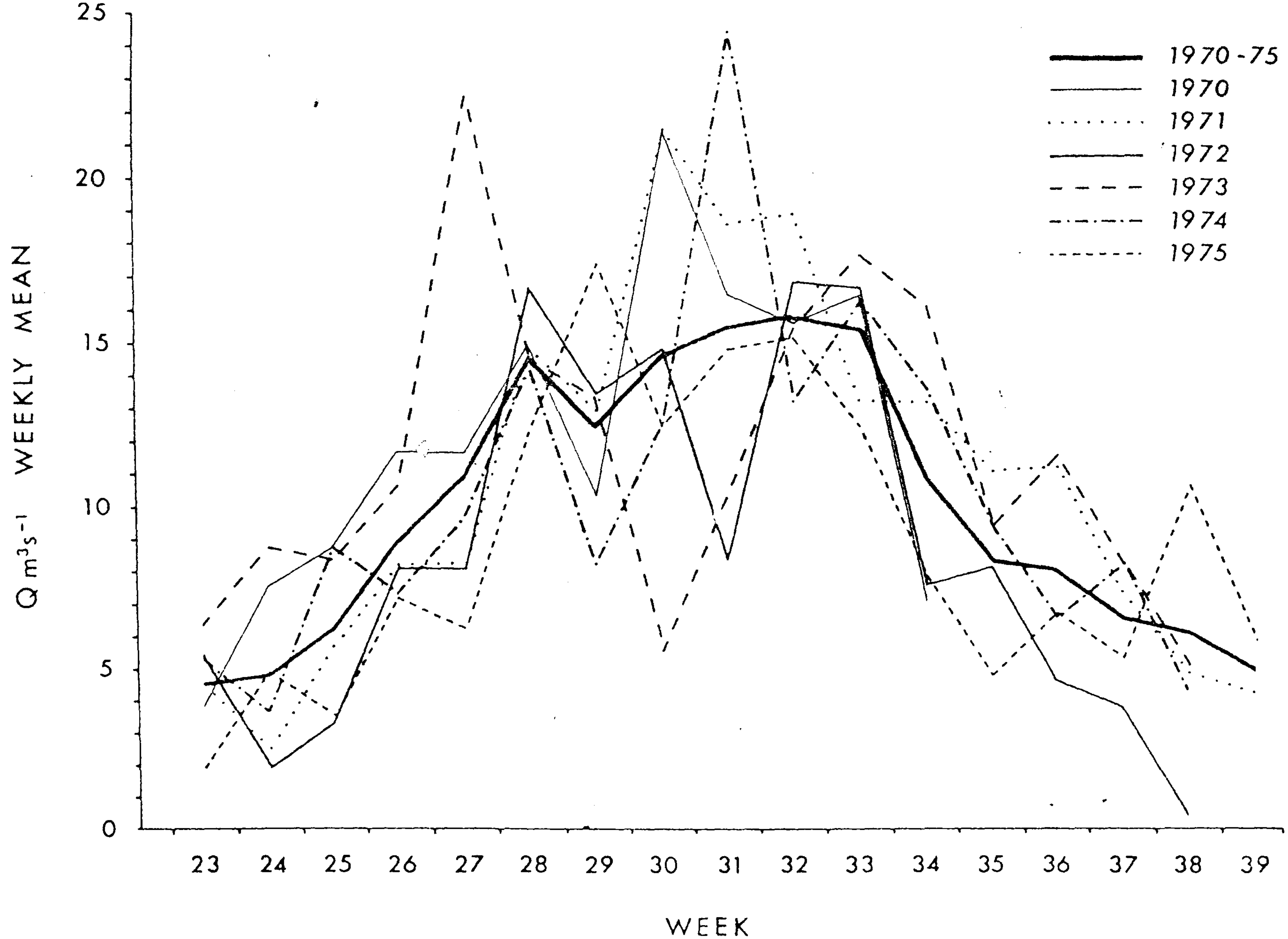
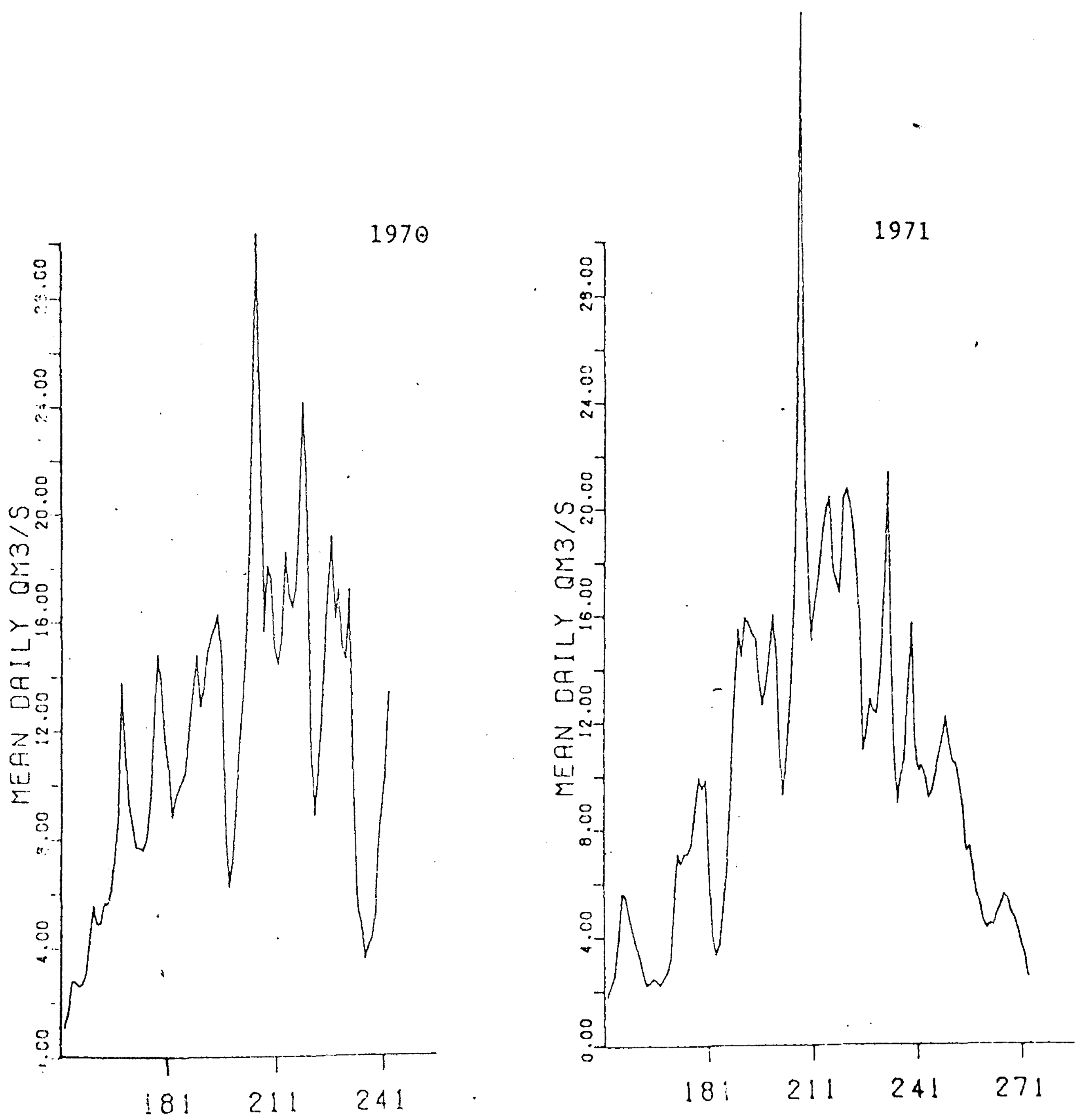


Figure 3.4 Mean weekly discharge of the Gornera, 1970 - 1975. Weeks are numbered from 23 (4 - 10 June, except in 1972, 5 - 11 June).



<u>Figure 3.5</u> Mean daily discharge of the Gornera, 1970 - 1975. Days are numbered from 1 (1 = 1 January)

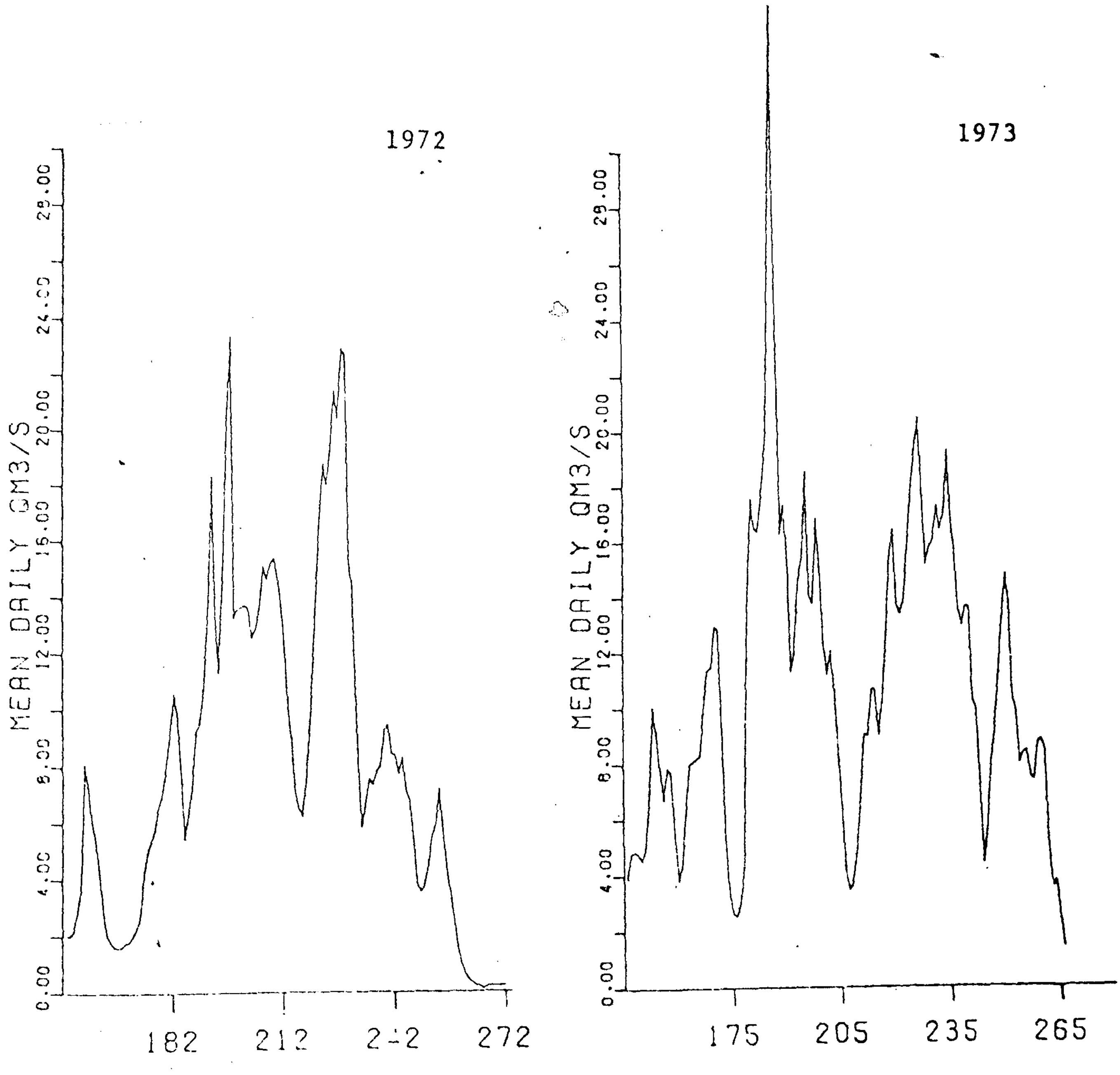
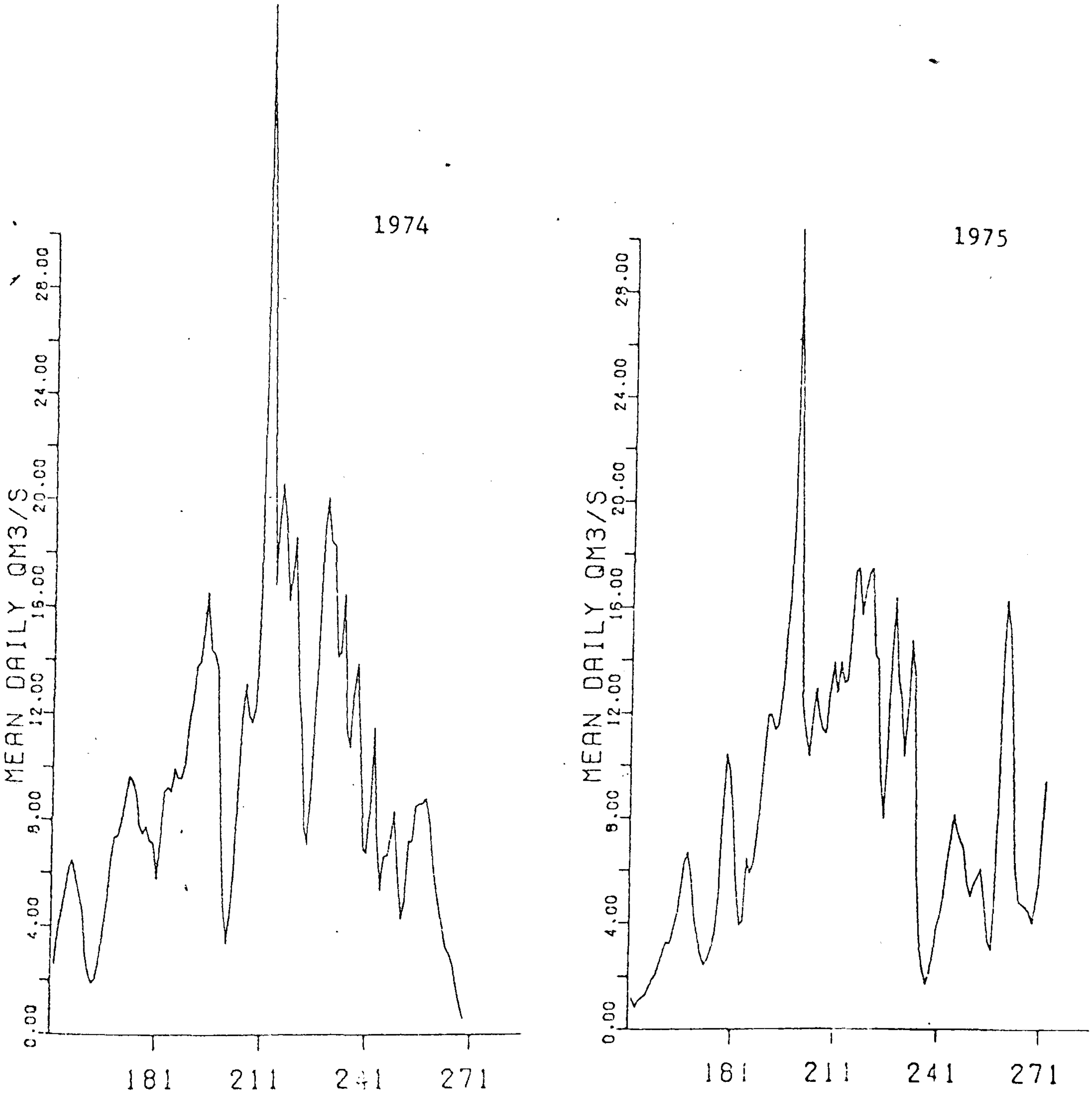


Figure 3.5 continued.



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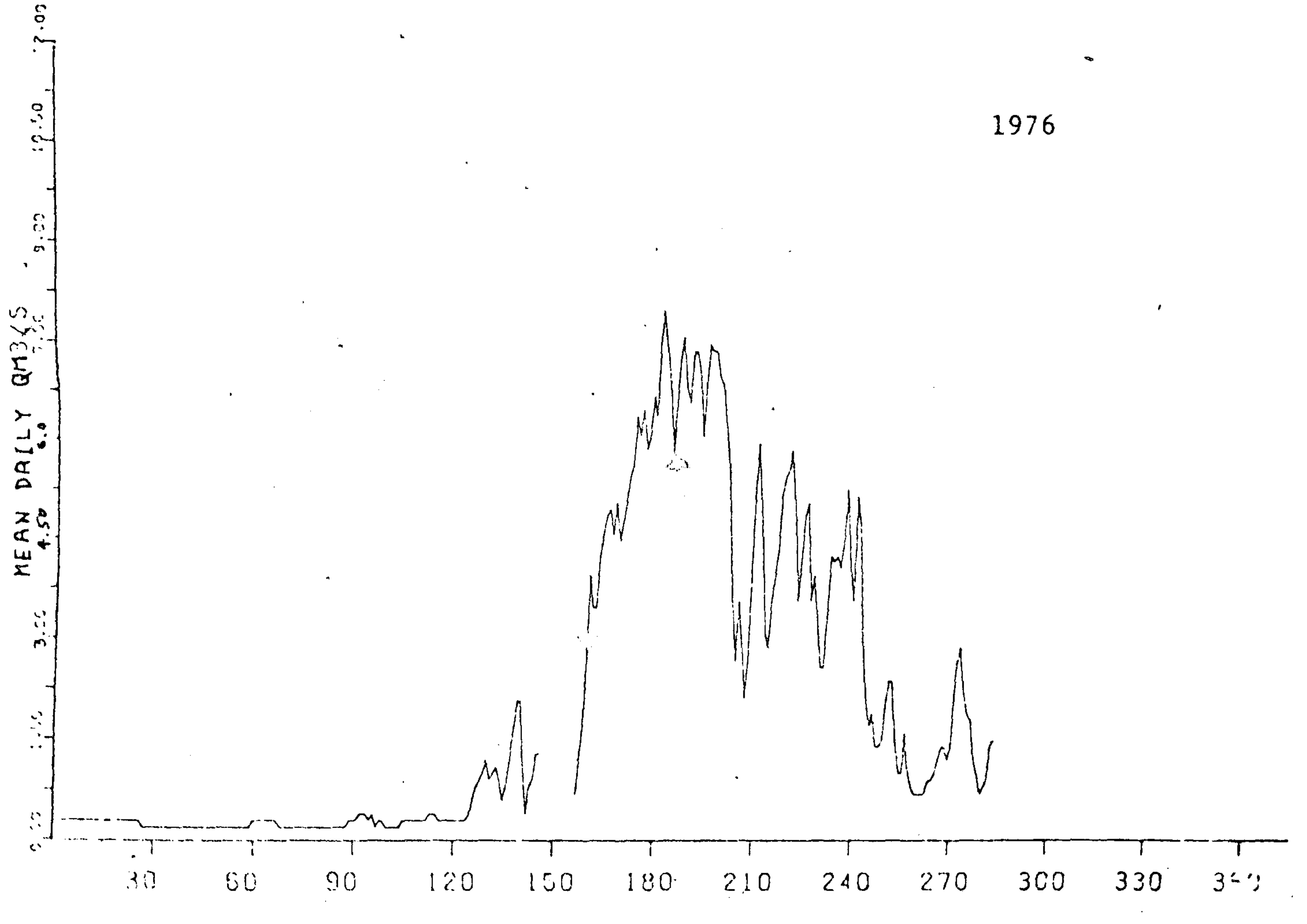


Figure 3.2 continued.

3.4.5 Water balance of the Feegletscher catchment

Annual water balance was calculated for those hydrological years for which both precipitation measurements and discharge hydrographs are available. Precipitation measurements were not corrected for the unknown aerodynamic characteristics of the raingauges. Net water balance assuming an annual evaporation of 192mm was calculated from equation (3.3) for the years 1966-67 to 1970-71 and 1972-73 (Table 3.6). With the exception of 1967-68 and 1968-69, annual discharge exceeded total precipitation less evaporation, which would be expected at a time of secular glacier decline. In four of the six years, therefore, Feegletscher contributed extra icemelt over the amount of snow accumulated, F_g being negative. Unfortunately, calculation of F_g by the method of differences has included errors in measurement or estimation of other parameters in the resulting value of F_g. Where F_g has a high magnitude, in 1969-70, 1970-71 and 1972-73, it seems probable that a substantial amount of total discharge was actually derived from excess icemelt over that necessary to balance snow accumulation. Small values of F_g however probably reflect errors to so large an extent that the sign may be positive when it should be negative. F_g is not a measure of overall icemelt contribution to runoff, since the total icemelt waters also include that amount of melt which, at steady state, would exactly balance accumulation in the firn area.

A study of catchment water balance thus provides a measure of glacier mass balance, but, in comparison with glaciological methods of mass balance determination, has the advantage that it can also provide a means of understanding the runoff from glaciers because continuous observations of precipitation and runoff are undertaken. Water balance data therefore permit investigation of the seasonal and annual interactions of precipitation and runoff in glacierised watersheds, and hence of the interaction of glaciers with their basin hydrological cycles.

Seasonal distribution of precipitation over Feegletscher catchment was obtained by allocating proportions of the mean annual catch of the 16 totalising raingauges on a monthly basis according to the percentage of total annual precipitation at Saas-Fee and Saas-Almagell following in each month. Ideally, more frequent measurements of precipitation at high altitude would have checked the accuracy of this distribution. Seasonal variation of estimated evaporation could not be distributed, and evaporation was not considered in the construction of curves of

TABLE 3.6 ANNUAL WATER BALANCE OF FEEGLETSCHER CATCHMENT CALCULATED FROM EQUATION (3.3)

Hydrological year	Discharge (Q_t) mm yr^{-1}	Precipitation mm yr^{-1}	Evaporation mm yr^{-1}	F_g mm	(F_g/Q_t) %
1966-67	1448	1468	192	-172	-11.9
1967-68	1055	1369	192	122	11.6
1968-69	1303	1531	192	36	2.8
1969-70	1441	1303	192	-330	-22.9
1970-71	1465	1382	192	-275	-18.8
1972-73	1529	1163	192	-558	-36.5
Period mean	1374	1369	192	-196.2	-12.6

$(P_g + P_r) - Q_t$ for the period October 1966 to September 1971 (Fig. 3.6). Because of the errors of measurement and the assumption $E_r = 0$, the absolute values of $(P_g + P_r) - Q_t$ are probably incorrect, but it is the relative shapes of the curves for different years which are of interest here.

Heavy snowfall in October 1966, which persisted into winter at high altitude, coincided with the end of the ablation season. Progressive accumulation of snow continued to May, when discharge increased quickly with the onset of favourable ablation conditions. June-September 1967 received lower precipitation than usual. Winter snow accumulation was low, but spring rainfall was held in the snowpack before subsequent ablation. A short, cool and wet summer in 1968 melted little ice, despite a mild, dry October. Late in 1968, exceptionally heavy snowfall provided 35 per cent of the high total annual precipitation in two months. Snowfall continued into late spring when direct runoff from precipitation was impeded by the snowpack, and a cool ablation season followed. In 1969-70, winter precipitation was low, and a warm ablation season, together with heavy rainfall in August, resulted in high summer runoff from icemelt. Ablation contributed more meltwater to streamflow than the water equivalent of winter snow remaining in the accumulation area at the end of the balance year, and the glacier suffered a net loss of mass. In winter 1970-71, snow build-up remained limited until March, when 20 per cent of the low annual precipitation accumulated as snow in the catchment. The summer was hot and dry and the accumulated snow, and glacier ice, were melted early in the season to reduce the stored component rapidly.

The water balance of Feegletscher varies widely from year to year because of variations of both precipitation inputs and net change in mass of glacier storage. Consequently, total annual runoff is also highly variable, and annual development of the internal drainage system must also be variable. Similar variability was noticed for Aletschgletscher (Kasser, 1954), and for South Cascade Glacier, and Wolverine Glacier, Alaska (Meier and others, 1971; Tangborn and others, 1977).

3.5 Conclusion

The analysis of measurements of discharge has shown the pronounced seasonal variation of runoff from Alpine glaciers, from very low winter outflows, to high fluctuating summer flows. Total annual runoff differs

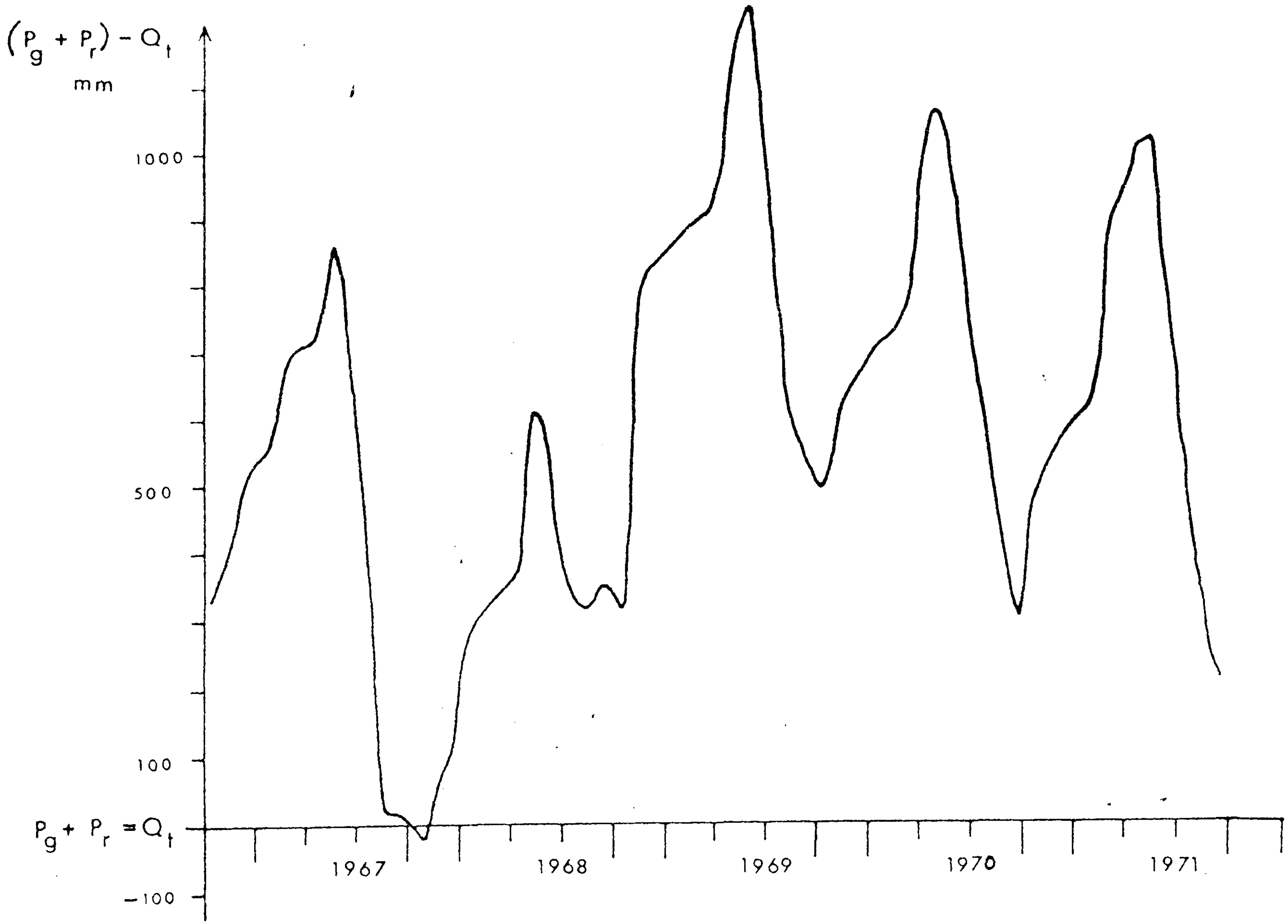


Figure 3.6 Curves of $(P_g + P_r) - Q_t$, a measure of water balance, for the Feegletscher catchment for the period October 1966 - September 1971.

greatly between years because of differing annual precipitation inputs and summer ablation conditions. The temporal changes of discharge mean that the internal hydrological system of an alpine glacier is required to transmit rapidly fluctuating total discharges, which must be of critical importance to any adjustment of the system to flow.

Although measurement errors in the data render the water balance calculations of little absolute value, the results suggest the following conclusions: study of the hydrological balance of a glacierised catchment can provide useful information concerning the interrelationships between the glacier and its basin hydrological cycle, especially precipitation-runoff, and allows rough calculation of the additions to summer runoff from melt of ice and snow stored in the catchment. Further, the proportion of waters from different sources in runoff can be identified.

Summer water yield from alpine glacierised catchments is made up of a component from the ice-free area equal to the annual input over that area, flow equal to the annual precipitation input over the ablation area of the glacier, a sizeable component from melting of the ice in the ablation area made up of an amount about equal to precipitation addition to the accumulation area storage, and often, at present, an amount resulting from additional melting out of storage, and some snowmelt from the lower accumulation area. To determine the exact origins of these components quantitatively would require simultaneous measurements of water balance components and isotopic composition of meltwaters. The importance of evaporation losses in alpine watersheds also needs further investigation. The actual quantities of water added to and released from glacier storage are much greater proportions of total input and output respectively than suggested by the net mass balance of the glacier (F_g).

The shape of the annual hydrograph is related to several interacting variables, as determined by calculations of temporal variations of catchment water balance. Heavy winter snowfall favours accumulation and increased storage at high altitude, and also limits the length of the icemelt season, since the transient lower limit of a thick snowpack rises slowly up the catchment in spring. Low summer rainfall, although not a controlling factor, is associated with those warm clear conditions which enhance ablation rates. Summer heat energy input is important, since it affects the rise of the snowline and can produce melting of the reservoir of ice throughout the season to September. The regulatory effect of a glacier on runoff results from a balance between the withholding of winter precipitation and the release of summer icemelt waters. Only over a long period of many hydrological years will basin inputs balance outputs. A knowledge of the interaction of glaciers with their catchment hydrological cycles is essential to an understanding of the variations in proportions of runoff derived from changes in glacier mass and of the impact of glacierisation on temporal changes of discharge.

Most important, the internal hydrological systems of Alpine glaciers have been shown to have the following characteristics:

1. In spring, sudden development of the network produces a rapid increase in mean daily discharge.

2. In summer, while some runoff is delayed, the system appears to show immediate response to increased flows.

3. Sudden large flows in the fall point to capacity of the system remaining large.

4. Each year the internal hydrological system might be expected to develop differing characteristics to accommodate the varying seasonal distributionsand amounts of discharge.

4. HYDROGRAPH ANALYSIS

4.1 Introduction

Not only is runoff from a highly-glacierised catchment distinctive in that most of the total annual discharge occurs in the summer months, but also during this ablation season, marked diurnal fluctuations of flow characterise hydrographs of meltstreams draining from portals of alpine glaciers (Meier and Tangborn, 1961). While this rhythmic diurnal regime apparently reflects diurnal variations in the supply of energy for melting ice at the glacier surface, the peak component of the hydrograph accounts for only a fraction of total daily discharge (Elliston, 1973). The diurnal rhythm consists of repeating asymmetrical peaks superimposed on a background flow component, the volume of which varies more slowly during the ablation season. In the morning, as ablation sets in, flow rises rapidly to give a hydrograph with a steep, sharp rising limb (Fig. 4.1), AC, reaching a maximum in late afternoon or early evening, at time t_{max}, followed by a gently-sloping recession curve (CD) to a minimum discharge between 06.00 and 09.00h. Changes of the shape of the curve ACD occur through an ablation season, and the time of maximum discharge arises progressively earlier in the day, which also affects the daily range of discharge ($Q_{max} - Q_{min}$) (Lang, 1973; Elliston, 1973).

Changes of the shape of the curve ACD during summer suggested to both Lang and Elliston that the internal hydrological system progressively enlarged its capacity, to allow meltwaters to pass more easily through the glacier, although changing melt conditions, and increasing areas of snow-free exposed ice also affect the concentration of runoff.

Studies of meltstream hydrographs have predominantly investigated relationships between meteorological parameters and discharge. Mathews (1964a) attempted to predict runoff from Athabasca Glacier from air temperature measurements using regression analysis, and Lang (1968, 1973) added radiation, sunshine duration and precipitation in a multivariate approach. Hydrometeorological measurements provide a useful surrogate for actual surface melt inputs (Derikx, 1973) in lumped runoff modelling for forecasting purposes (for example: Campbell and Rasmussen, 1973;

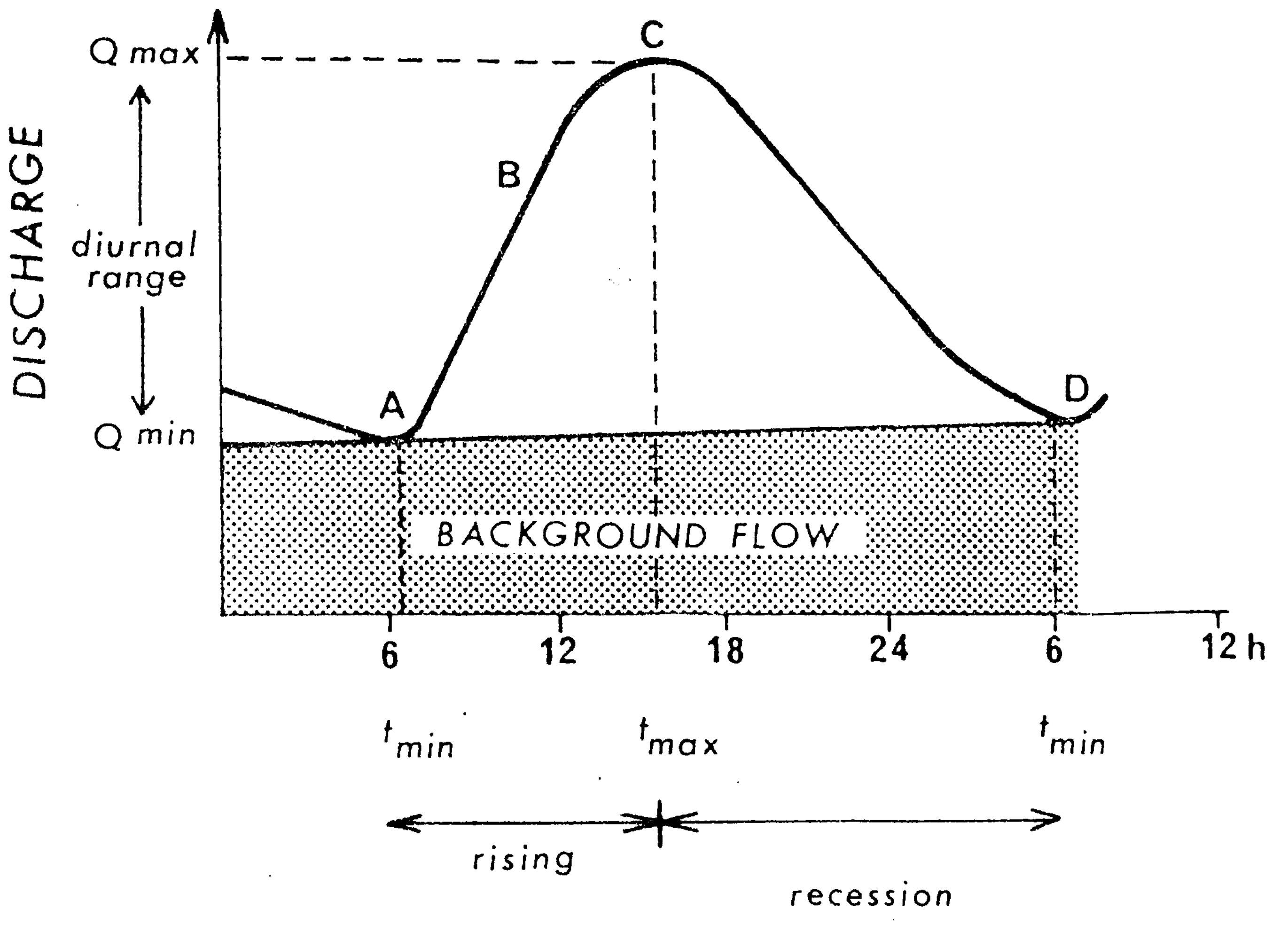


Figure 4.1 Components of the diurnal hydrograph of an alpine glacier meltstream. For explanation see text.

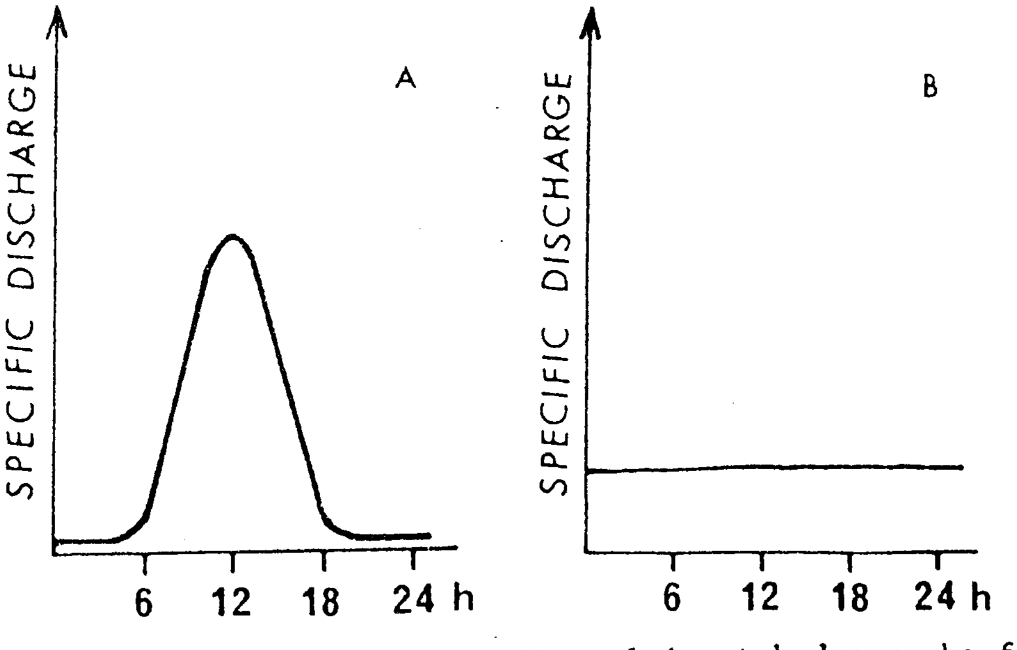


Figure 4.2 Diagrammatic diurnal input hydrographs for small areas of the surface of (a) ablation area and (b) accumulation area of an alpine glacier.

Derikx, 1973; Gudmundsson and Sigbjarnasson, 1972; Jensen and Lang, 1973). Most models operate for daily total runoff prediction rather than for diurnal variations, and consequently provide little information about the physical processes of runoff. What they do show is that water emerging from the snout may have been subject to internal storage (see 2.6.1 and 2.6.2).

However, short-term variations of discharge can provide some information about the nature and behaviour of the internal plumbing, in that the pattern of surface inputs is translated by its flow through the ice into the outflow hydrograph. This chapter aims to assess the use of discharge hydrographs of meltstreams as a method of determining the behaviour and functioning, and hence changes in capacity and evolving structure, of the internal drainage network of two of the Alpine glaciers investigated, Feegletscher and Gornergletscher. Runoff hydrographs from the two glaciers when compared should provide an indication of any effects of glacier size and altitude-area distribution , on the shape of the hydrograph (rather than simply dimensions resulting from different discharges). Seasonal changes of diurnal hydrographs of the meltstreams from the two glaciers are described and analysed in an attempt to evaluate the nature of interior water flows.

4.2 Factors affecting the shape of the daily hydrograph

The shape of the daily hydrograph of a meltstream is determined by the nature of the glacier surface input hydrograph, the structure of the internal drainage system, and hydraulic conditions in the conduits. Runoff from precipitation, over the ablation area of the glacier and the non-glacierised parts of the catchment, also contributes to the hydrograph shape.

The characteristic input hydrograph for a small area (c. $100m^2$) in the ablation zone consists of a symmetrical peak, centred about the time of radiation maximum (12.00h) and following the energy supply available for melting (Fig. 4.2a). This curve may be asymmetrical, depending on surface aspect and topography, and shading of the area by surrounding mountains (Meier and Tangborn, 1961). At night, melting almost compmletely ceases. The actual quantities of surface icemelt vary with temporal energy supply fluctuations changing the amplitude of the hydrograph. Estimates of input hydrographs can be obtained from representative sites by gauging of supraglacial streams, or from computation using meteorological observations. With increasing distance, and consequently altitude, upglacier, the quantities of meltwater produced per unit area decrease, reducing also the input hydrograph amplitude (Campbell and Rasmussen, 1973).

The input hydrograph for the accumulation area is probably about constant throughout 24h (Hughes and Seligman, 1939; Sharp, 1952) (Fig. 4.2b), though the quantity of melt produced and available for runoff per unit area decreases to zero with increasing altitude. Again, the actual quantity of the constant input depends on the useful surface energy received. Specific meltwater yield from a firn plot is much lower than from an ice plot. Since energy supply for melting first increases and then decreases in an ablation season, temporal variation of firn and icemelt input quantities would occur even without changes in source contributing areas.

Arrival of water from surface input at the glacier portal is delayed by the travel time from the source area. In the ablation area, no surface delay occurs and, assuming there is no internal restriction on runoff (i.e. open channel flow), and that no wavefront is propagated down conduit as flow increases, travel time is probably linearly related to distance from source input to portal. From the firn area, a further slower transit time linear with distance from the end of the conduit network to source should be added for runoff from the accumulation area.

The portal meltstream hydrograph is composed of surface specific input hydrographs weighted by the area for which they are representative and lagged by travel time to the portal. Hydrograph shape at the portal is determined therefore by the altitude-area frequency curve for the glacier and consists of a time-area concentration curve multiplied by time variable specific inputs (Fig. 4.3). Whether flow is in open channels, or in closed pipes, the discharge-velocity routing behaviour will result in an accentuation of the steepness of rise of the daily peak, as velocity increases with discharge, and a wave may propagate down conduit (Elliston, 1963) as the increased flow of the flood catches up with the slower moving water of the background flow. Certainly, dye-tracing tests suggest that water transit times beneath ablation areas decrease significantly when flows are increased (Behrens and others, 1975). This explains the shape of the diurnal peak component. Runoff

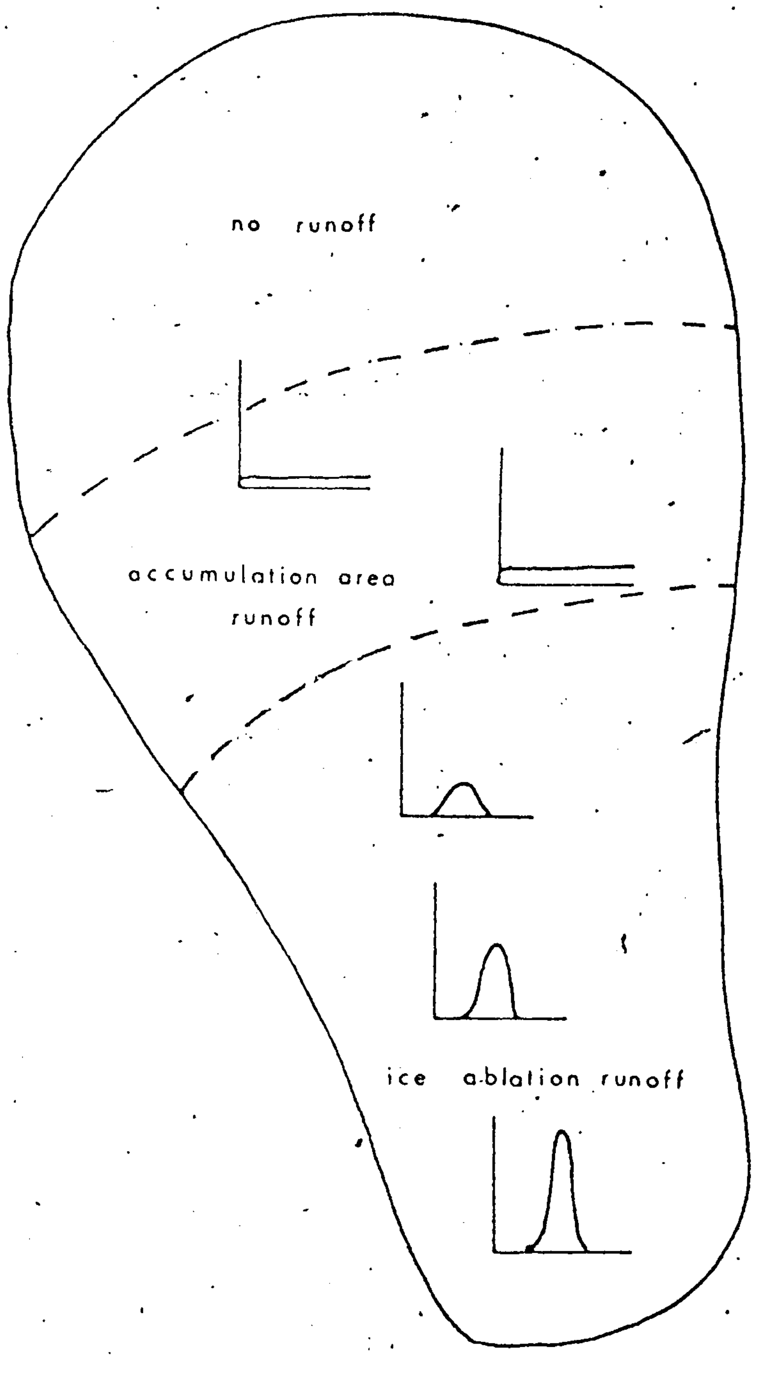


Figure 4.3 Distribution of diurnal input hydrographs over the surface of an alpine glacier.

from the ablation area reaches the portal rapidly to produce the late afternoon peak, although there appears to be some unexplained delay (12.00h to 18.00h).

Firnmelt runoff is steadily produced and maintains flow at night (Golubev, 1973). Using the simple division that the diurnal peak (c. 40 per cent of total daily flow) was made up solely of icemelt, Golubev attempted to determine basin lags for the entire glacier, and ablation and accumulation areas separately for Lednik Dzhankuat, Caucasus Mountains (area about 4 km^2). By graphical analysis of meltstream recession hydrographs, the mean basin lag was found to be 2.5d, but the ablation area lag 3h. It is unlikely that 60 per cent of flow arises from the firn area, and isotopic determinations suggest (for one day only, in late summer) that no more than 40 per cent of the total daily flow was derived from firnmelt at Hintereisferner (Behrens and others, 1971).

Elliston's (1973) explanation of the shape of the hydrograph of the Matter-vispa suggests that runoff is considerably delayed, not only in a firn aquifer, but in many englacial reservoirs and in crevasses and cracks, discharging through restricted exits, dependent on hydrostatic pressure varying with diurnal ablation input. The shape of the hydrograph is determined by the capacity of the internal hydrological system to transmit supplied water. Both the lag of peak discharge several hours after the time of the daily ablation peak and background flow relatively high at night, when ablation rates fall very low, suggest that the amount of water supplied to conduits is usually greater than their flow capacity. When flow capacity is exceeded, water is ponded back, upstream of the limiting restrictions, effectively raising the water pressure within the hydrological network. Flow of water through an orifice under pressure is given by:

$$Q = a\ P^{0.5} \qquad (4.1)$$

where Q is discharge, P water pressure and a is a coefficient dependent on size and shape of the orifice (Golubev, 1973). Similar-shaped repeating hydrographs suggest that while P may vary considerably, a is relatively constant.

Taking retention into consideration, and treating the glacier as a whole, the daily hydrograph is made up of two components defined by day of origin as melt:

$$Q_n = M_n (1 - k) + k M_{n-1} \qquad (4.2)$$

where Q_n is discharge on day n, in mm, M_n melting on day n in mm and

$$k = \frac{Q_n}{Q_{n-1}} \qquad (4.3)$$

where k is a recession coefficient. Only part of the meltwater appears in the hydrograph on the first day of melting, and further daily contributions are superimposed on the recession curve of the previous day. Although an equal amount of melting may occur each day, flow would rise because of this superimposition (Martinec, 1970). k has been shown to change as the season progresses (Elliston, 1973), ostensibly because of evolution of the internal drainage system.

While glacier size, altitude-area distribution, and seasonally-changing ablation-accumulation area ratio affect the shape of the diurnal hydrograph of a portal meltstream, in addition to diurnal and seasonal variations of energy availability for melting, the internal hydraulic conditions appear to be of importance. The nature of the two end members of a series of many possible combinations of internal flow conditions is suggested. Following Golubev (1973), unrestricted flow occurs in open channel networks under the ablation area, and the rate of supply of meltwater over the accumulation source area determines background flow. Alternatively, all flow is restricted and flow from the glacier depends on internal water pressure, as postulated by Elliston (1973). The restrictions are maintained by a balance between melting of ice by water flow and deformational closure (Röthlisberger, 1972).

4.3 Seasonal evolution of internal drainage systems

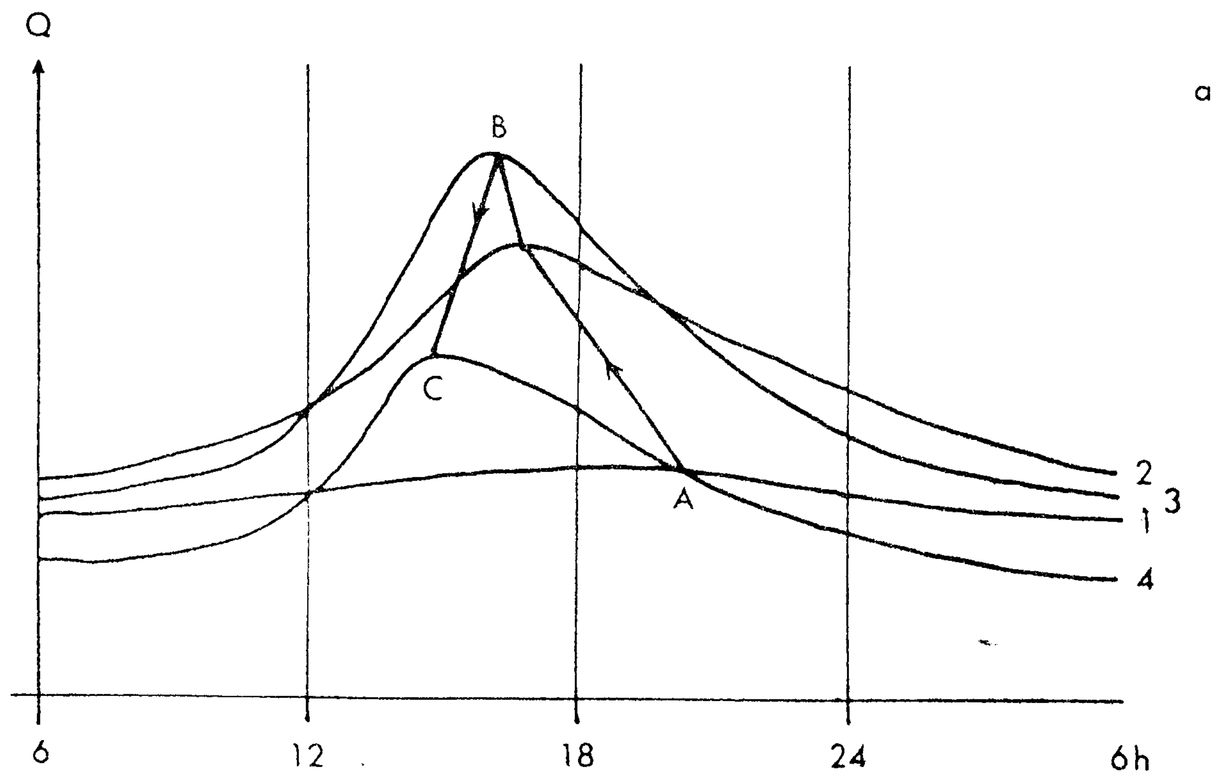
4.3.1 Seasonal evolution with open channel flow

The diurnal hydrograph of an internal hydrological system with no restrictions on flow is composed of a background flow component arising from steady continuous flow from the accumulation area, with a peak quickflow from the ablation area. The shape of the peak depends on the ice-free zone area-altitude distribution and the diurnal curve of the input hydrographs, as modified by velocity-discharge effects and down-conduit wave propagation.

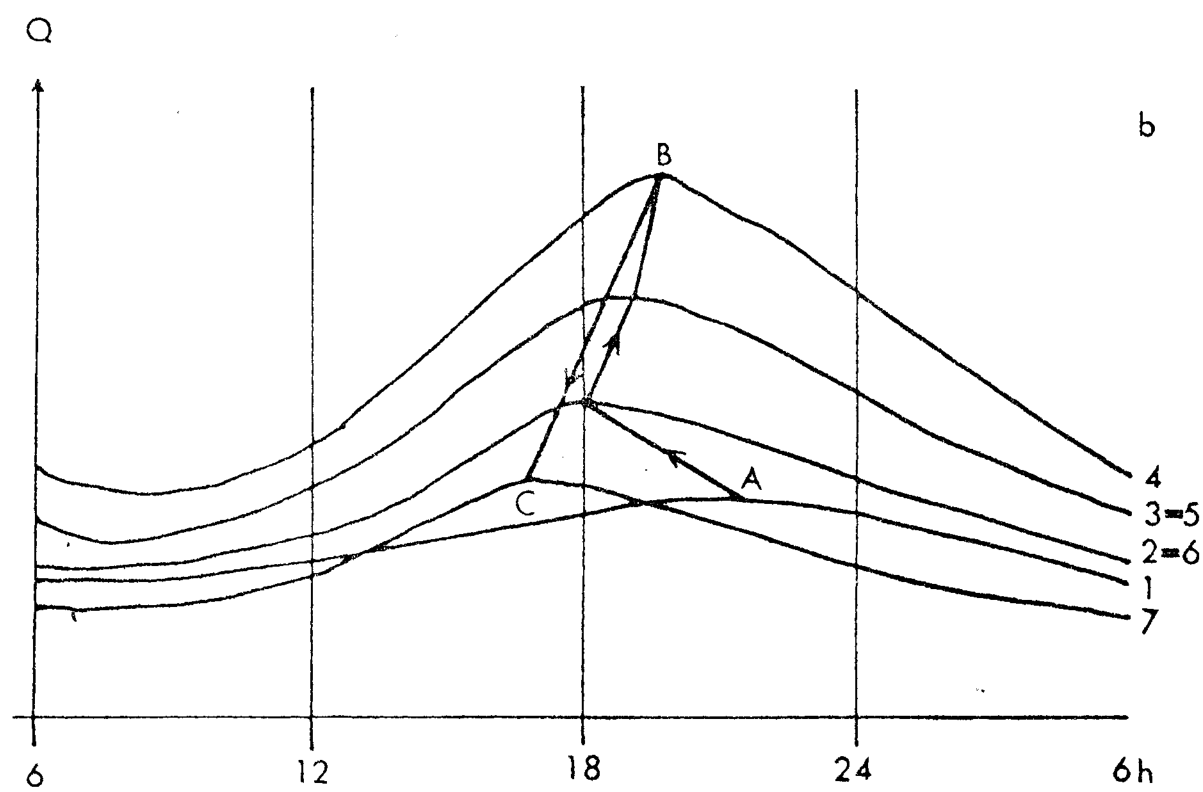
The following thought-experiment describes expected changes in diurnal hydrograph shape during an ablation season. In June, a large snowmelt component provides a substantial steady background flow in relation to that from icemelt, derived over a limited exposed area, where the peak is delayed by supraglacial slush and remaining snow (Fig. 4.4a). By late June, increasing exposure of ice and increased energy supply produces strong icemelt, while removal of snow cover reduces ablation area retention. The increased distance of melt source areas from the portal is offset by the velocity-discharge routing effect, and daily peaks are increased in size, the rising limb becomes steeper and t_{max} occurs earlier each day, according to energy supply conditions. Background flow also increases with increased energy supply. By August, daily energy supplies become reduced, inputs decrease in volume, but the area of ice exposed to melting remains constant or increases until the first snow of winter. Consequently, background flow is reduced since its source area has been reduced by the expansion of the area of ice exposed, and also firn and snowmelt is more sensitive to energy reduction. Diurnal peak amplitude is enlarged on a lower background flow. Timing of diurnal maximum t_{max} may advance since the maximum contribution to the peak progressively arises from lower parts of the ablation zone nearer to the portal. Eventually, as surface temperatures fall beneath $0^{o}C$ at high altitudes, flow is maintained less by snowmelt runoff, but increasingly from the lower ablation area, and although the flow-routing effect is decreased, t_{max} continues to advance as icemelt is derived from closer to the portal.

4.3.2 Seasonal evolution with time-independent restrictions on flow

Coefficient a in equation (4.1) was assumed to be constant, and conduits are adjusted in size to a mean discharge, not to individually variable flows (Röthlisberger, 1972). In spring, runoff is delayed each day by the seasonal snow cover. As flows increase in volume in June and July, water pressure builds up in conduits, because of restrictions to flow. Increasing flow velocity with increasing pressure is analogous to the flow-routing effect in open channel flow. The seasonal variations of diurnal pressure changes are probably a function of the changing area-altitude distribution of meltwater inputs and the changing energy supplies for melting. The shape of the peak of the diurnal hydrograph is determined by the pressure-discharge function (equation 4.1) and would be expected to be relatively rounded, reflecting pressure build-up, and the slowly increased discharge each day (BC in Fig. 4.1). The timing of peak discharge will occur later in the day, because of the pressure-discharge



<u>Figure 4.4a</u> Thought experiment to show the seasonal evolution of the diurnal hydrograph of an alpine meltstream under open channel flow conditions. 1 represents June, 2 early-mid July, 3 late July-August and 4 September. The line ABC joins maximum daily discharges. For explanation see text.



<u>Figure 4.4b</u> Thought experiment to show the seasonal evolution of the diurnal hydrograph of an alpine meltstream under water pressure in conduits. 1 represents June, 2-4 early July to mid-August, 5-7 mid-August to September. The line ABC joins sequential maximum daily discharges. For explanation see text.

effect as pressure increases, and background flows would also be expected to increase as daily input totals increase (Fig. 4.4b). As inputs decrease, the shapes of daily hydrographs remain similar to earlier in the season, although the area-altitude distribution of inputs differs. t_{max} appears progressively earlier as flows recede, since diurnal internal pressures remain lower, hence flows are less delayed.

4.4 Hydrograph analysis procedures

4.4.1 Strategy

Since no information was available concerning inputs to the internal drainage systems, the method of comparative hydrograph analysis was used. Continuous hydrograph records from Feevispa and Gornera gauging stations were filtered to produce hourly mean discharges, necessary to remove minor background fluctuations especially at high flows. Since previous studies used monthly average conditions to determine seasonal changes (Elliston, 1973; Lang, 1973), average hydrographs were calculated for monthly and weekly periods during summer ablation seasons. The probable importance of individual meteorological events on the hydrograph suggested more detailed analysis of hydrographs from groups of days experiencing similar surface input hydrographs. Deviations from such short-period average hydrographs were investigated to determine the character of apparent anomalous hydrograph shapes. At Gornergletscher, drainage of the Gornersee provides the largest annual flows, and the impact of such flows on the development of the internal drainage network was investigated. Discharge records of the ablation seasons of 1971 for the Feevispa and 1974 and 1975 for the Gornera were examined in detail, these periods being those for which precipitation records are also available.

4.4.2 Descriptive parameters

Daily maximum and minimum mean hourly flows, and mean daily discharge and the times of occurrence of daily maximum and minimum flows were used as descriptive parameters. Diurnal peak hydrograph shape was characterised by the following measures: height, a shape index, and the proportion of the total daily flow represented by the peak.

Height (h) is the difference between daily maximum and minimum flows:

$$h = Q_{max} - Q_{min} \qquad (4.4)$$

Background flow (Q_{st}) was defined as the flow making up the area of the hydrograph beneath a straight line connecting the minimum flows of adjacent days (line AD, Fig. 4.1). The proportion of total of daily flow (Q_{tot}) represented by the peak (Q_k) is:

$$Q_k = \frac{Q_{tot} - Q_{st}}{Q_{tot}} \cdot 100 \qquad (4.5)$$

and the shape index S (effectively a measure of average hydrograph width):

$$S = \frac{Q_k}{h} \qquad (4.6)$$

In order to evaluate evolution of the internal drainage network, average parameters of the diurnal hydrograph were calculated for four-weekly and weekly periods. Such average hydrographs smooth out irregularities resulting from variations on individual days. Mean diurnal hydrographs were constructed by calculating for each of the 24h of the day the mean discharges occurring at that hour throughout the selected week or four-week period. Similar average conditions for the Gornera were determined for periods before and after the drainage of the Gornersee.

4.4.3 Depletion curves

Summer snowfall prevents ablation by increasing surface albedo, and retains meltwater in the body of the snow, so interrupting supply of meltwater to the internal hydrological system. Flow from the glacier portal declines exponentially as the diurnal peak hydrograph is suppressed.

This recession curve is usually given by:

$$Q_t = Q_0 e^{-kt} \qquad (4.7)$$

where Q is discharge, t elapsed time from start of depletion (t = 0), and k a recession constant (Webber, 1961). The value of the recession constant depends on the initial discharge Q_0, and on the length of elapsed time t available for its calculation, since discharge is inevitably prevented from ceasing altogether or from even approaching an asymptote because of restoration of favourable ablation conditions. Elliston (1973) used seasonal changes of k as evidence for evolution of the internal drainage system. Since network evolution is only one factor determining the calculated value of k, in this study, recession curves have been used only to estimate the volume of water accumulated in storage within the glacier. The volume of water (V_0) stored at the start of depletion in englacial pockets, subglacial cavities, the firn aquifer, and in transit in conduits and available for runoff is given by integration beneath the curve of equation (4.7):

$$V_0 = \int_{t_0}^{t_1} Q\,dt \qquad (4.8)$$

where $Q_{t_1} \rightarrow 0$. V_0 is a minimum estimate of the total volume of water storage, since some stored water may remain within the glacier. V_o also includes the amount of water contributed by recession of the diurnal peak component on the first day of depletion. No break of slope separates the true depletion curve from the falling limb of the peak on the first day of the depletion.

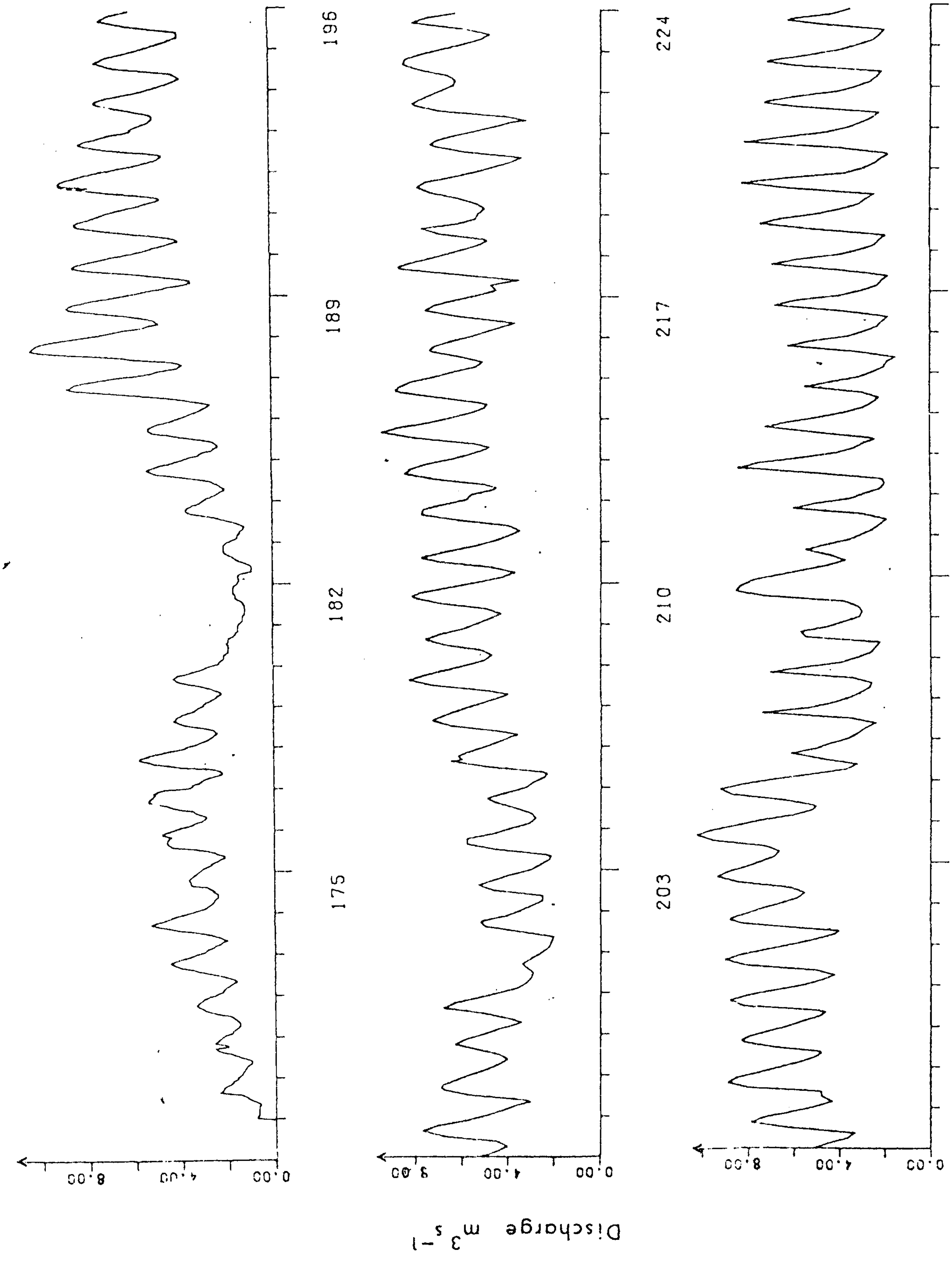
4.4.4 Anomalous diurnal hydrographs

Anomalous discharge events were identified where individual portions of the rhythmic diurnal hydrographs of the summer ablation season divided from the average shape of the hydrograph. Flow was either suddenly increased or diminished, for a short interval. Precipitation records were examined in order to determine causes of short-lived temporary increases of flow.

4.5 Results and interpretation

4.5.1 Description and explanation of hydrographs of Feevispa

Hydrograph curves of mean hourly discharges of the Feevispa for the period 19 June - 9 September 1971 are shown in Figure 4.5, and daily precipitation totals recorded at a gauge near the snout of Nordzunge, Feegletscher, in Figure 4.6. At the beginning of the ablation season, discharge was low, but the diurnal rhythm was well established. Between 19 June and 30 June, both daily minima and daily maxima increased, until a period of cooler weather, associated with rainfall, caused recession flow. High energy inputs from 1 July reintroduced marked diurnal fluctuations, which increased in amplitude slowly as background flow built-up to around 4 $m^3 s^{-1}$. High amplitude and high background flows continued until 17 July, when decreased temperatures and lowered radiation during precipitation produced recession from 20 July. Improving meteorological conditions restored the characteristic diurnal pattern, which continued to the end of the analysis period. Both peaks and background showed fluctuations throughout this remaining period. The hydrographs were surprisingly regular in shape, showing few perturbations at a time period less than 24h and greater than the 1h filter limit applied.



<u>Figure 4.5</u> Discharge hydrograph from Saas-Fee limnigraph station on the Feevispa for the period 19 June (=170) to 9 September (=253) 1971. (Days are numbered from 1 = 1 January). For description of hydrograph see text.

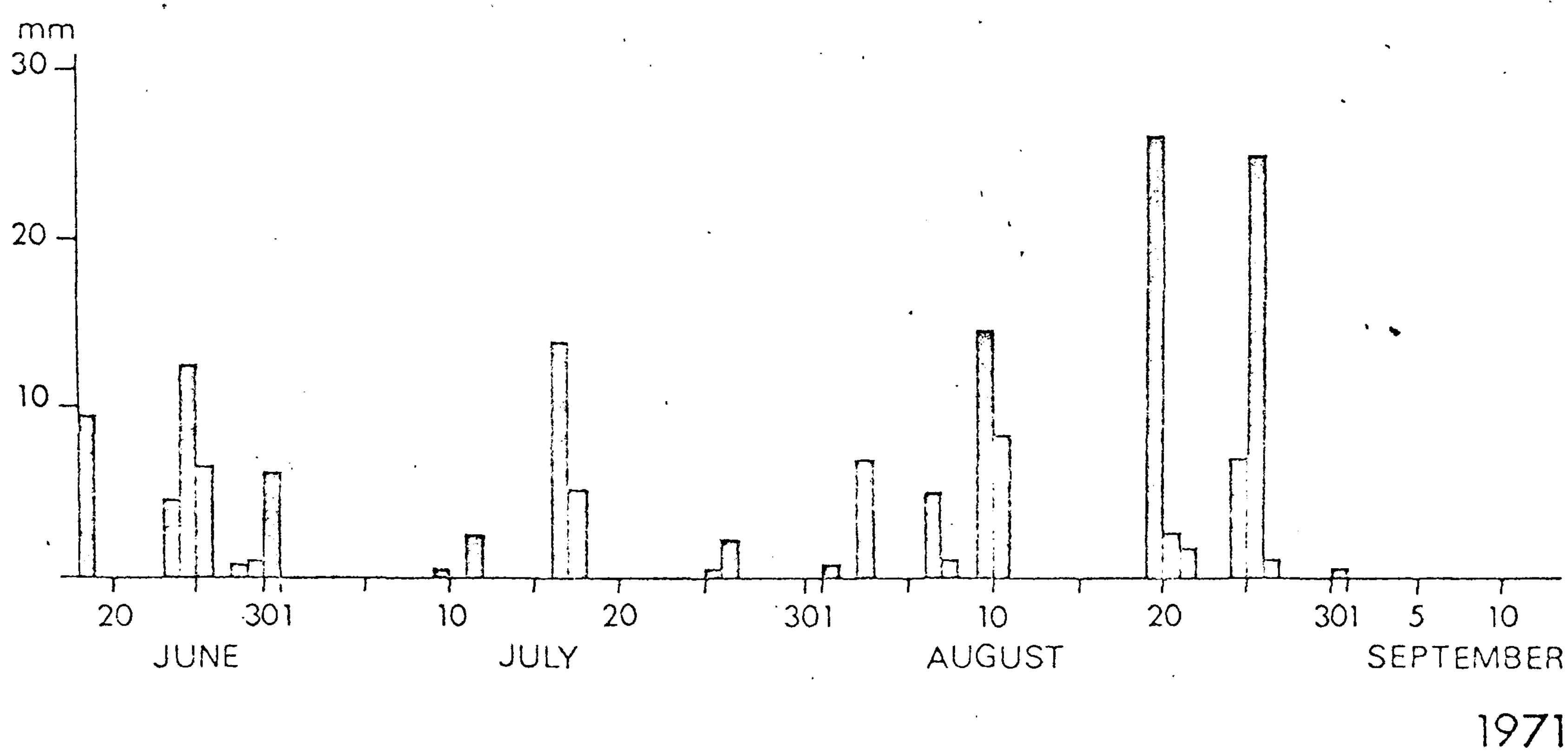


Figure 4.6 Precipitation recorded at a gauge near the snout of Nordzunge, Feegletscher, summer 1971.

During the analysis period, large precipitation events occasionally modified the flow of the Feevispa. On 10-11 August, 23mm of rain fell over the catchment, beginning during the evening of 10 August. The minimum discharge on 11 August was considerably higher than previous daily morning minima, 6.3 $m^3 s^{-1}$, in comparison with the usual 3.2 - 3.4 $m^3 s^{-1}$. High precipitation on 19-20 August again raised the morning low flow to give the largest minimum flow recorded, 6.6 $m^3 s^{-1}$, and greatest maximum discharge 10.2 $m^3 s^{-1}$.

From 22 August, the peakedness of the hydrograph appears to change, and during relatively low flows, sharp-pointed narrow hydrographs replaced the previously more rounded peaks (curve BC). Over 33mm of rain on 25-26 August occurred when both background flow and peak flow were decreasing. The peak discharge maximum was increased to 8.5 $m^3 s^{-1}$ on 26 August, when the wider round-peaked hydrograph shape was restored. Subsequent maximum flows failed to reach 8.5 $m^3 s^{-1}$, and narrow sharp-pointed hydrographs ensued, until the declining energy inputs reduced both peak and background flows in September. This change of peak shape was also associated with a change in symmetry of the diurnal peak (ABCD) of the hydrograph, from asymmetric to more symmetrical. This is suggestive of the hypothesis that as flow increased in July until mid-August, the conduit capacity, although probably increasing slowly, was usually exceeded at high flows, producing a curved peak (as ABC in Fig. 4.1). Excess delayed flow was released in the evening, contributing to the flow of the falling limb. After the maximum flow of 20 August, subsequent flows were less than the flow-capacity of the conduits, so hydrograph shape was probably controlled only by altitude-area relationship and the input hydrograph shape. By 26 August, conduit flow-capacity was reduced by deformation closure, and the high flow from intense precipitation was held up by this constriction within the conduit network. Subsequent lower flows were therefore below this maximum conduit flow-capacity, and narrow peaked diurnal hydrographs ensued. However, sharp-peaked high flows on 29 August, and 5-6 September, suggest that the rate of conduit closure was slow, and that the shape of the rounded diurnal peak on 26 August resulted not so much from conduit closure by deformation in the few days following the previous highest flow on 20 August, but from the temporal distribution of the rainfall concentrating runoff to overload the capacity, creating backing-up of flow. This further suggests that conduits do not expand rapidly to take all available flows.

Overall, in the 1971 ablation season, discharge ranged from a minimum of 0.6 m^3s^{-1} at the start of the summer to the maximum of 10.2 m^3s^{-1}. Afternoon peak discharge was usually in the range 7.0 - 9.5 m^3s^{-1}, and minimum flow between 2.0 and 5.0 m^3s^{-1}. Peak discharge characteristically appeared between 15.00 - 16.00h in July and 14.00 - 16.00h in August, with minima occurring between 07.00 - 09.00h throughout the season. No systematic changes in timing of maximum or minimum hourly flows were detected.

4.5.2 Description and explanation of hydrographs of Gornera

Figure 4.7 shows variations in the discharge of the Gornera for the duration of gauging during the ablation season, from 30 May to 26 September 1974. Extremely detailed records of precipitation were also obtained using an autographic raingauge located close to the snout of Findelengletscher, installed by Grande Dixence, S.A. Hourly precipitation totals for this gauge are probably representative only of the approximate timing of precipitation, not of precipitation quantities over the mountainous area (Fig. 4.7).

In contrast with the hydrographs of the Feevispa, hourly smoothed flows at the Gornera limnigraph were rather irregular. Hydrographs are asymmetrical, and show a steep rise, followed by rounding of the peak of the daily ablation flow. At the start of the season, flow was characterised by low amplitude diurnal variation based on a slowly changing background flow from 30 May to 11 June. Subsequently, background flow rose steadily until 23 June with the amplitude of daily variation (Q_{max} - Q_{min}) also increasing. Precipitation during the afternoon of 23 June may relate to the irregularity of the peak flow on that day, although irregularity on the previous day was not related to input characteristics. During cooler overcast weather, both background and peak flows declined slowly. A wide peak discharge hydrograph on 26 June resulted from a recorded 12mm rainfall between 12.00 - 24.00h. A small peak ahead of the discharge maximum on 29 June resulted from heavy rainfall in the morning.

Clear skies and high energy inputs increased both peak and background components of diurnal hydrographs until 16 July. An extremely high minimum flow on 14 July was not induced by precipitation. Snowfall on 19 and 20 July over much of the Gornergletscher was followed by steep recession of flow in the Gornera to a minimum of 3.0 m^3s^{-1}, only four days after the previous season maximum of 17.8 m^3s^{-1}.

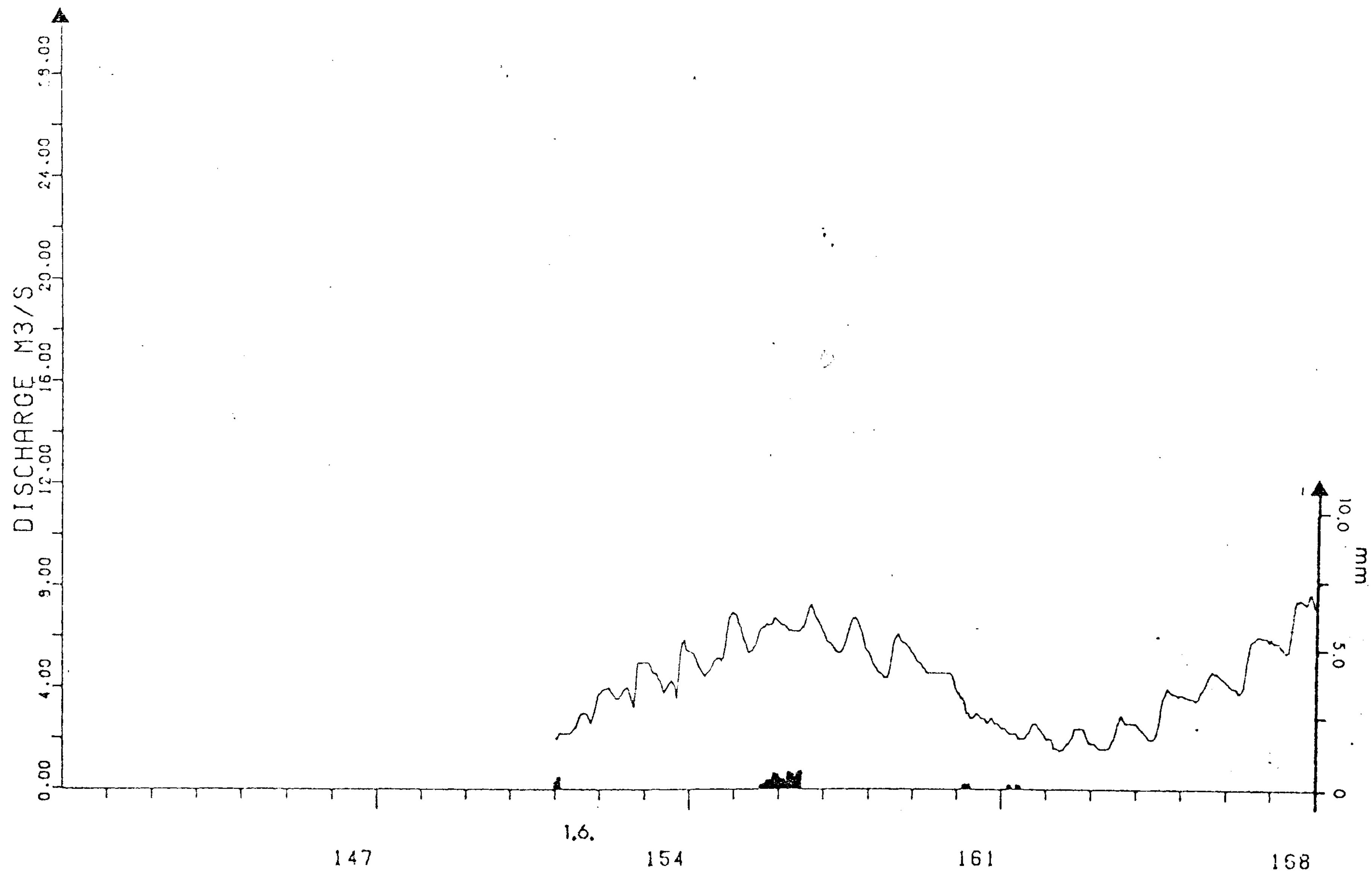
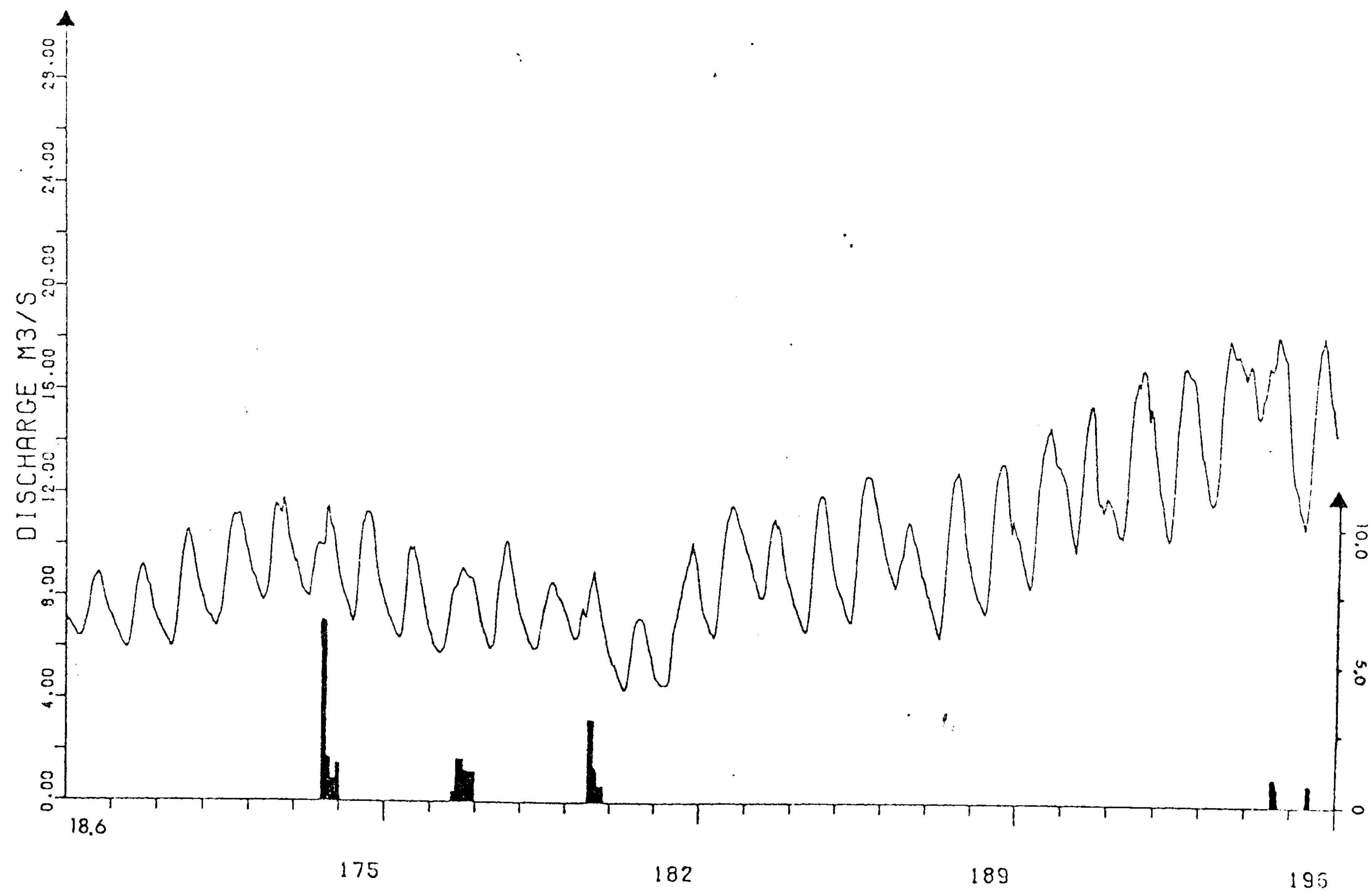


Figure 4.7 Discharge hydrograph for the Gornera 1 June-26 September 1974 recorded at the prise d'eau gauging station.



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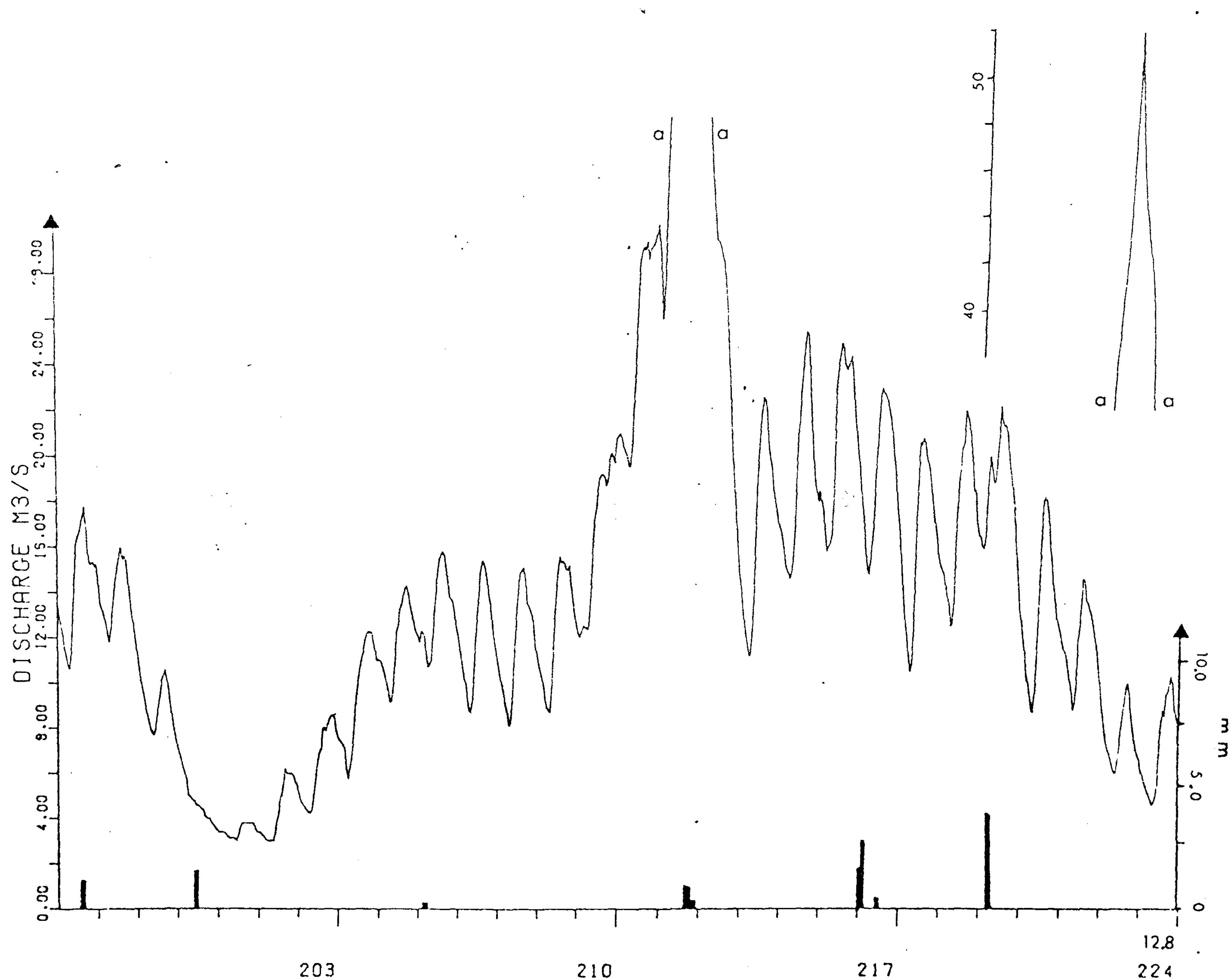
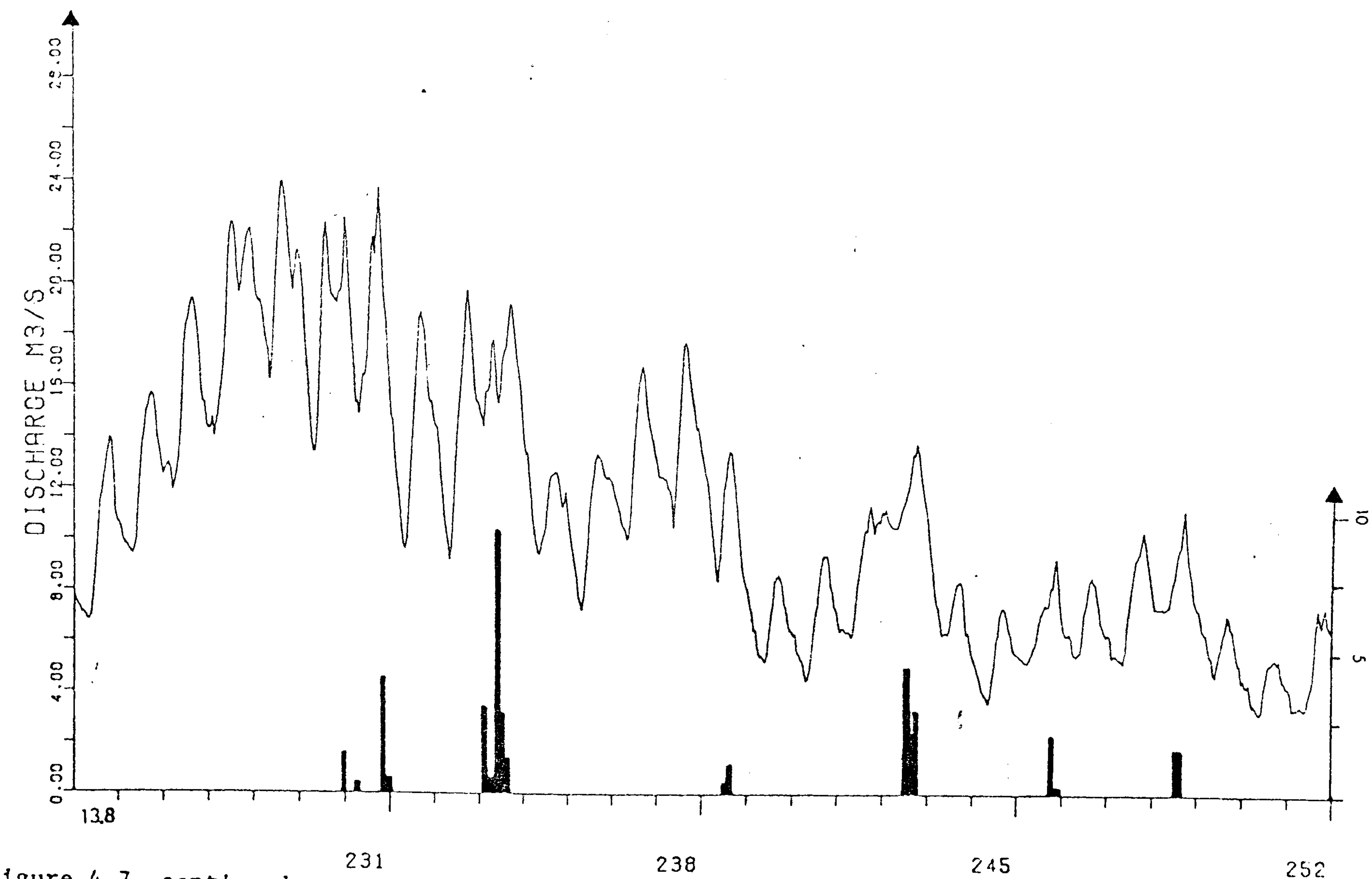


<u>Figure 4.7</u> continued



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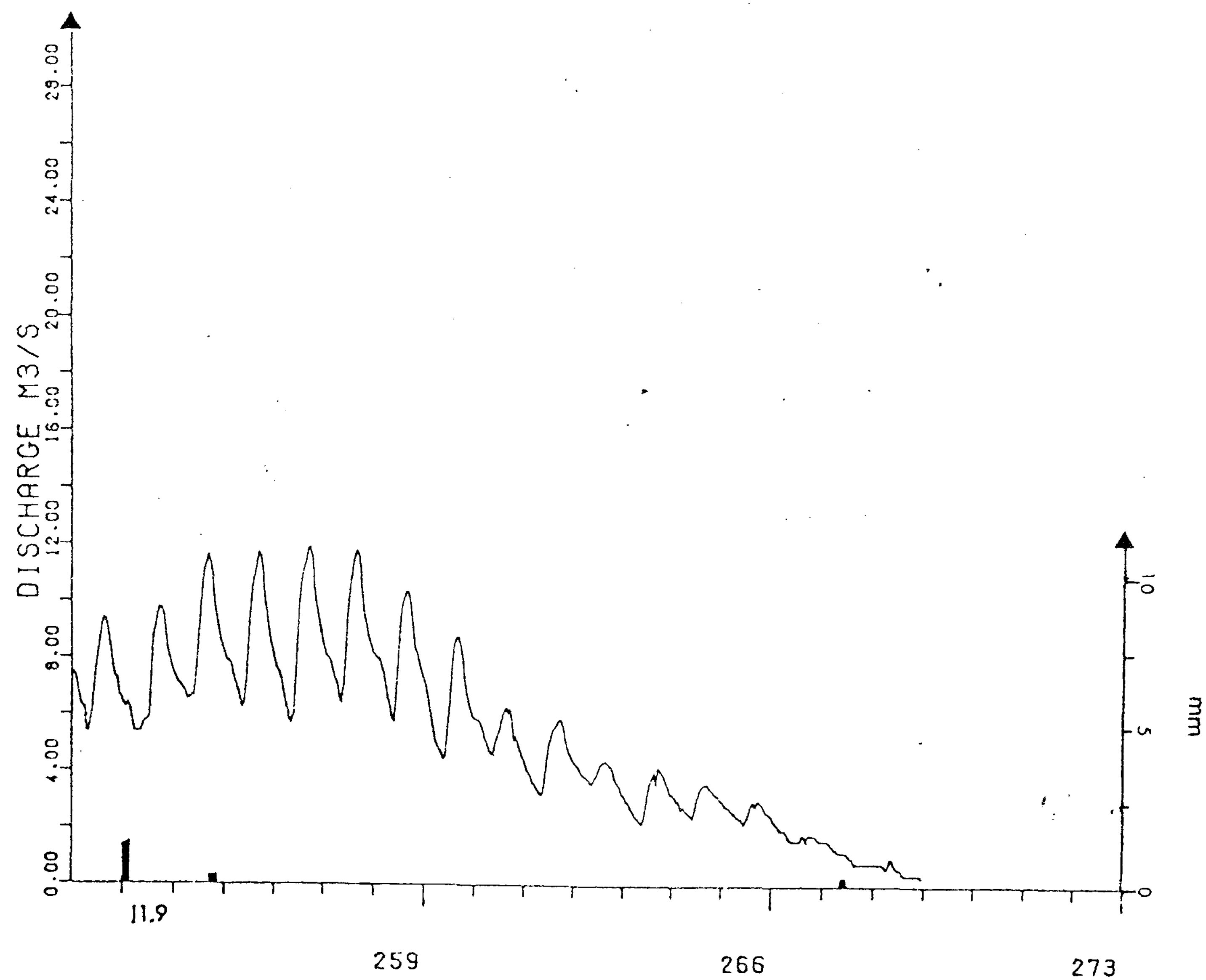


<u>**Figure 4.7**</u> continued

From 21 July, diurnal peaks were restored, with rapidly increasing background flow until 26 July, when background flow declined, but the diurnal peaks remained large. The major hydrological event of the ablation season was the draining of the Gornersee between 29 July and 1 August, which produced the maximum annual discharge of 51.5 m^3s^{-1}. Subsidiary peaks on the rising limb of the lakeburst hydrograph are indicative of the simultaneous existence of the usual diurnal rhythm. Following the lakeburst, diurnal fluctuations showed increasing amplitude, increased daily peak and minimum flows, and more short-term irregularity of flow, with no significant precipitation until 8 August. The hydrograph of the draining of the Gornersee suggests that flow rapidly widened conduits to allow drainage to take place in 3.5d, but at the same time diurnal flows were superimposed and apparently delayed in runoff. This suggests that the constrictions delaying runoff may be located in various parts of the internal hydrological network, or it is probable that the main arterial canals are not the flow-restricting elements of the system. The subsequent irregular variation of the diurnal hydrograph suggests some settling down period of readjustment to lower flows after the catastrophic impact of the lakeburst.

An intense rainstorm in the early morning of 8 August resulted in a peak in the hydrograph in advance of the daily discharge maximum. Peaks and background flow were both reduced on subsequent days as cooler conditions prevailed to 15 August.

Between 16-19 August, a time of clear skies and high sustained ablation, diurnal fluctuation was characterised by twin peaks surmounting the daily hydrograph peak. From 19 August to mid-September, diurnal hydrographs were extremely irregular. On only two occasions, however, did precipitation directly influence runoff in the Gornera. A storm in the early hours of 22 August produced 25mm of rainfall in 6h at the Findelen raingauge. Overnight reduction of flow in the Gornera was prevented and a rapid rise in discharge ensued at 10.00h. On 31 August, an eight-hour storm yielded 23mm of rain, resulting in a later than usual peak flow at 22.00h of 13.0 m^3s^{-1}. Reduced discharges in September were associated with smooth, regularly repeating hydrographs, superimposed on a declining background flow. From 10-16 September, a noticeable break of curvature characterised the falling limb of daily hydrographs.

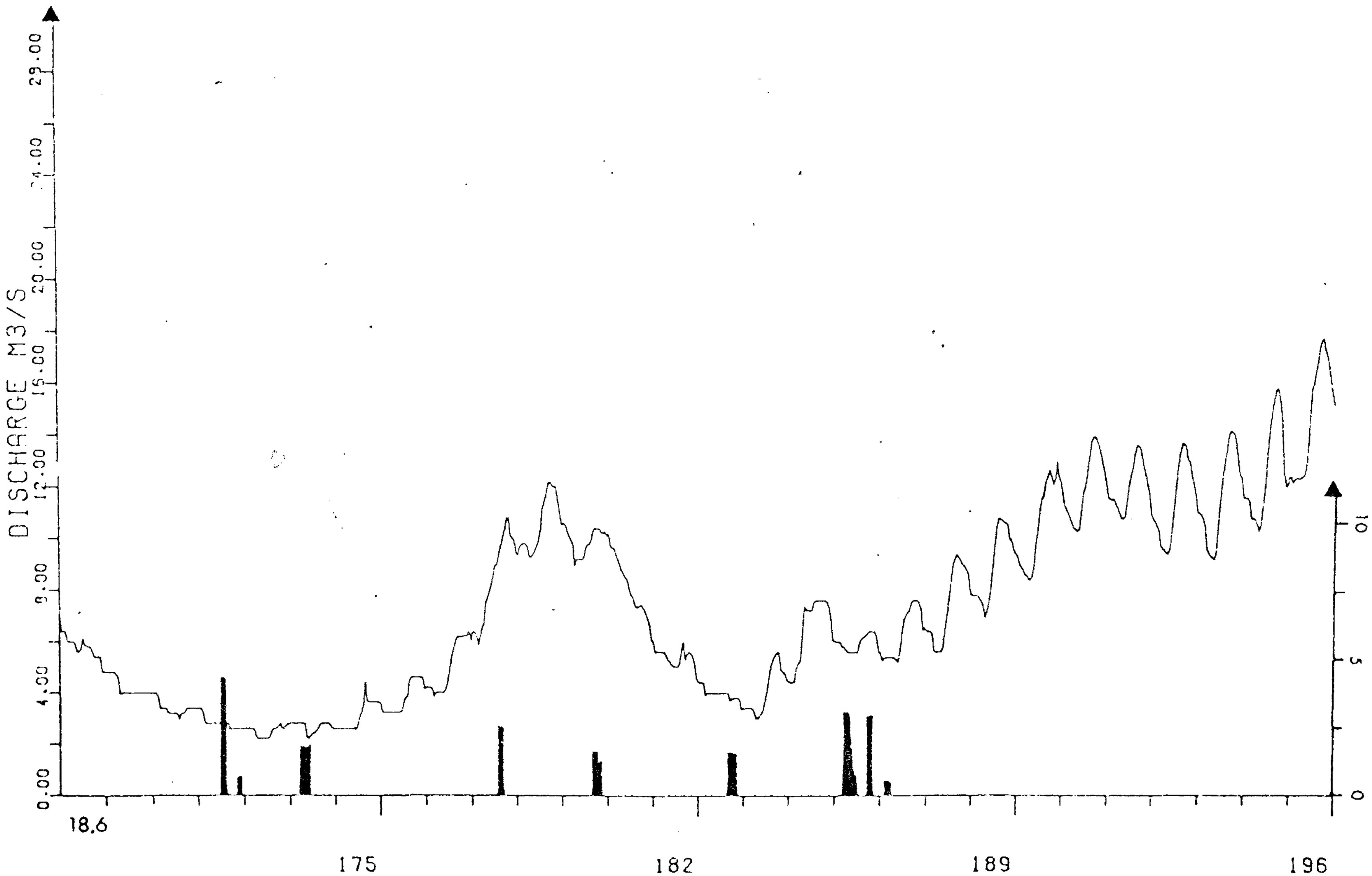
The maintenance of rounded peaks and a high proportion of total flow each day as background flow suggests that conduit capacity continued to restrict runoff into late August. However, runoff from precipitation appears to concentrate subsidiary peaks rapidly. The probability that precipitation peaks from rainfall over the ablation area arise from rapid flow, suggests that either there is little restriction on flow beneath the ablation area, or that different networks of conduit may exist, some of which preferentially transmit surface inputs without delays. Röthlisberger's (1972) proposal of englacial conduits in addition to basal conduits may provide such a network. At depth, ice deformation reduces conduit capacity after high flows, but in the top 50m of the glacier, such closure would not occur, and the network once opened by melting would remain open.

In the 1974 measurement period, discharge of the Gornera varied from a minimum of 0.8 m^3s^{-1} to a maximum of 25.5 m^3s^{-1}, excluding the flood of the Gornersee lakeburst. Daily peak flows occurred between 17-18.00h at the start of the season, 15-16.00h towards the end, and minimum daily flows between 08-10.00h throughout.

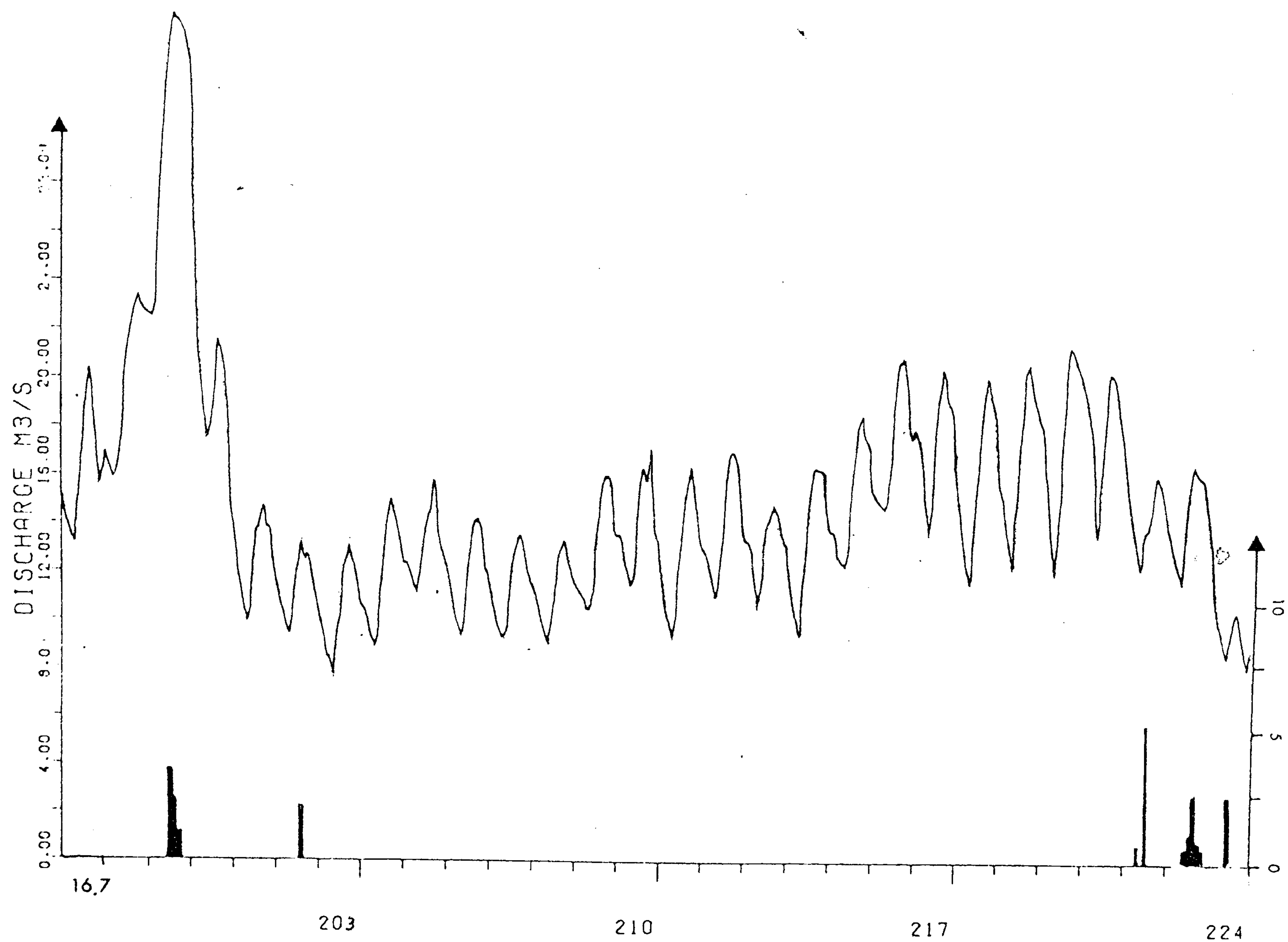
In 1975, the Gornera was gauged from 23 June to 30 September (Fig. 4.8). A sudden build-up and decline of background flow between 24 June and 3 July was not related to precipitation. Only 5mm of rainfall was recorded in the nine day period, and temperatures remained low, so that meteorological effects could not have produced such a rapid rise of flow. It is probable that either an ice marginal, supraglacial, or englacial water body drained through the glacier at this period. Several temporary marginal ice-dammed lakes have been observed in the catchment in May and early June, formed by snowmelt on the non-glacierised parts of the catchment exceeding the capacity of subglacial conduits. Surface entonnoirs (Renaud, 1936) are often full in spring, and are known to drain catastrophically.

However, inspection of the surface and margins downglacier from the full Gornersee provided no evidence of another lakebed elsewhere. It must be concluded that an englacial water pocket drained on this occasion.

Heavy precipitation on 4 July melted large amounts of snow and produced an oddly-shaped peak component. Clearing skies increased background flows but maintained the volumes of flow represented by the diurnal peak hydrographs constant until 16 July. Drainage of the Gornersee caused a lower maximum flow (32.7 m^3s^{-1}) than in 1974, since the lake had not filled sufficiently to reach its former level. Outburst waters were recorded at the limnigraph station from 17 until 20 July. Following the lake drainage, the regular diurnal rhythm returned, though



<u>Figure 4.8</u> Discharge hydrograph of the Gornera 18 June-30 September 1975 recorded at the prise d'eau gauging station.



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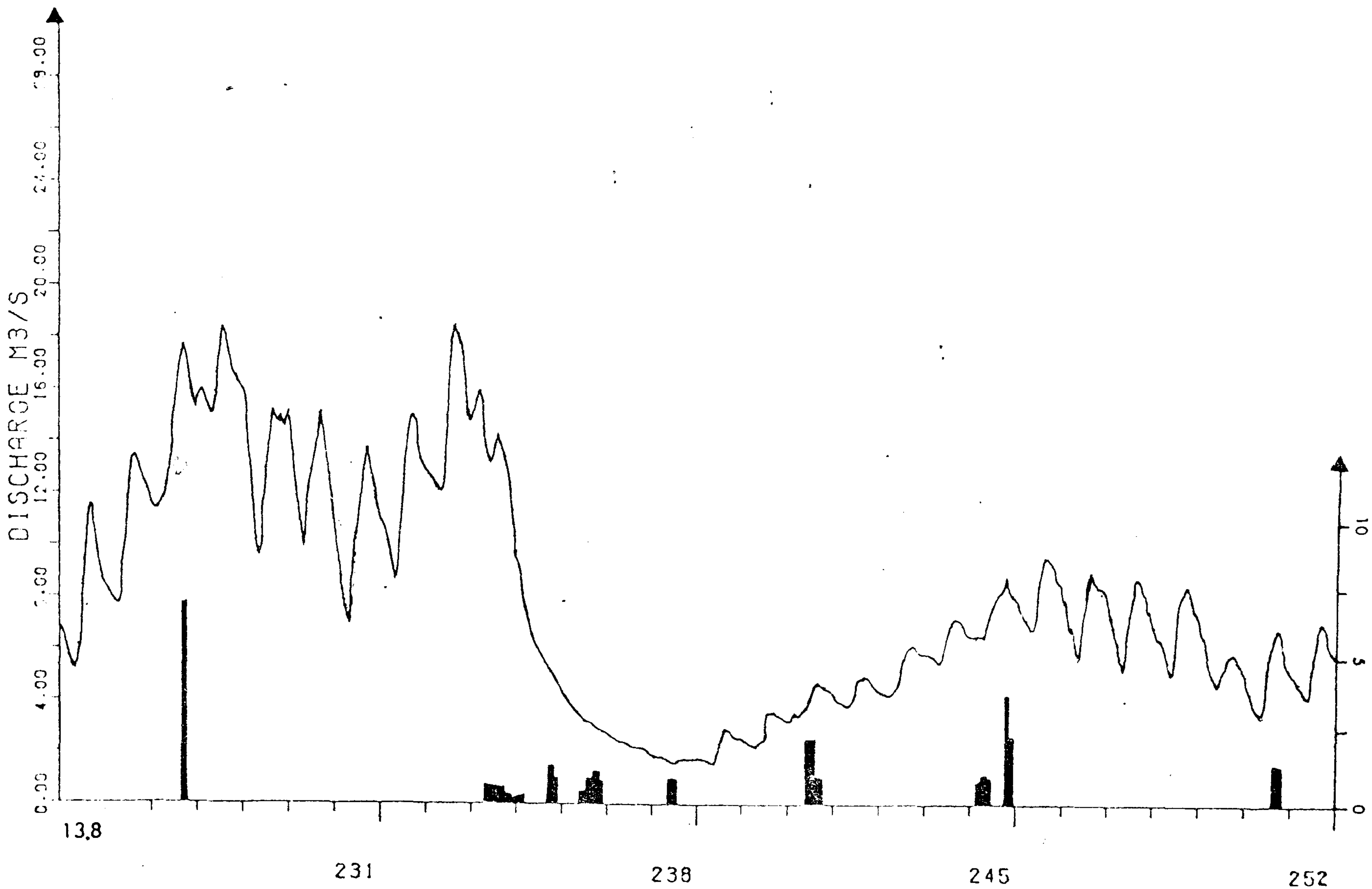

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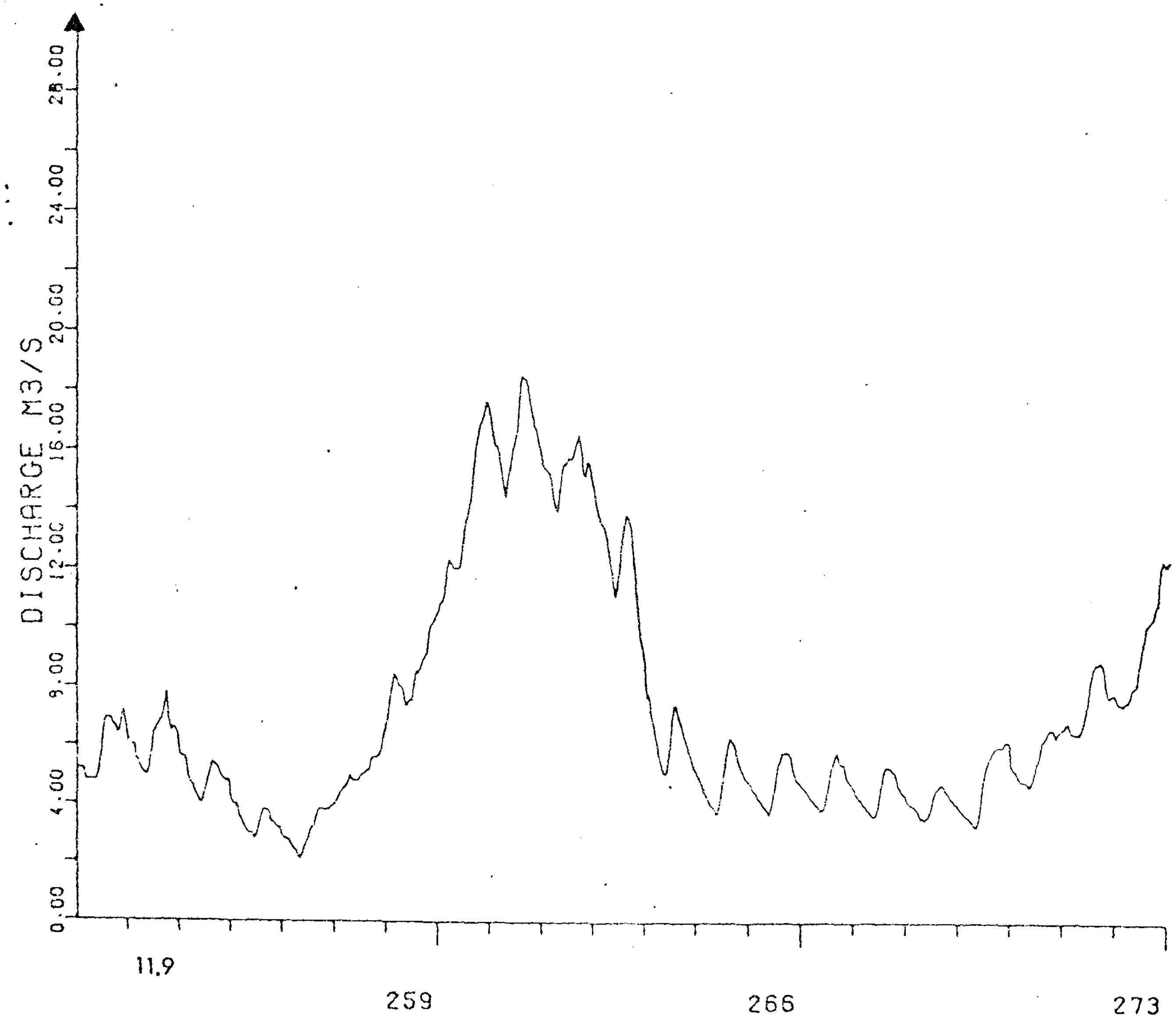


<u>Figure 4.8</u> continued

with maximum discharges and background flows much lower than immediately before. This contrasts with the great increases in diurnal ranges and maximum values recorded after the 1974 lakeburst.

Regular repeating asymmetrical diurnal hydrographs continued until 12 August, when recession for a limited period was followed by the return of the diurnal peak component, albeit of irregular shape. This followed heavy precipitation on 15 August, when a storm of 3h duration commencing at 18.00h maintained a flow of 16.0 $m^3 s^{-1}$ at the time of the usual daily minimum. After 22 August, snowfall induced recession, and flow reached a minimum on 27 August. An explanation of hydrology of the Gornergletscher during this period is described in detail in Chapter 8.

From 27 August, background flow increased, and peak flow components gradually enlarged. Generally cloudy weather subsequently checked flow, but from 14-19 September, high rainfall affected the catchment and direct runoff from snow-free slopes and the ablation area of the glacier resulted in a precipitation-controlled flood, rising rapidly to high background flow on the depletion limb of which were superimposed small rhythmic peaks. A further storm on 30 September produced a similar flood peak. This suggests that conduit restriction was overcome rapidly.

4.5.3 Temporal variation of diurnal hydrograph shapes of Feevispa

Average diurnal hydrographs for weekly periods are shown in Figures 4.9 (1971) and 4.10 (1972) for the Feevispa. The mean hydrographs show the changing shapes of the diurnal hydrograph and variations of flow magnitudes during the summer ablation seasons, removing some of the irregularity introduced by meteorologically-controlled fluctuations. A line connecting sequential mean maximum discharge is also shown. The average time of maximum flow occurrence (t_{max}) varies irregularly. During snowmelt in 1971, the time of peak advanced 1h from 17.00-16.00h in a week, but then receded 1h despite a doubling of average flow the next week. The following week, t_{max} occurred 3h earlier, at 14.00h, despite maximum flow, steeper rising limb and a higher background flow. The proposition that decreased flows under the peak were below the conduit capacity would account for the steeper rising limb, and earlier t_{max}. Higher background flow probably resulted from increasing snowmelt higher up the catchment or from constricted flow from parts of the glacier. To the end of July, mean t_{max} varied between 14.00 and 16.00h. In August, as background flow decreased, the amplitude of peak components also decreased, while the falling limbs of the peaks steepened and t_{max}

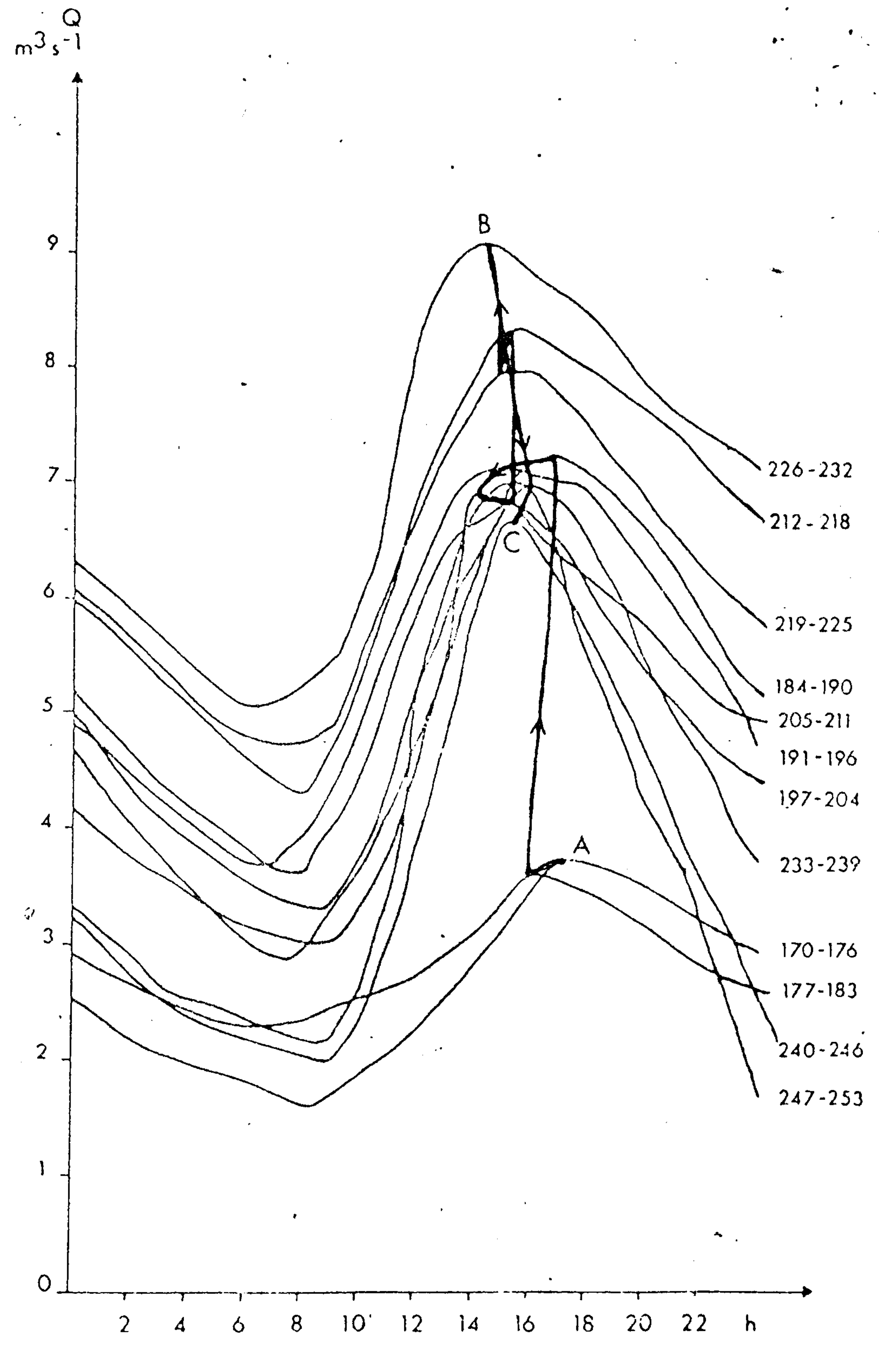


Figure 4.9 Weekly mean diurnal hydrographs of the Feevispa in the ablation season of 1971. The line ABC connects points of sequential weekly mean maximum discharge. For explanation see text.

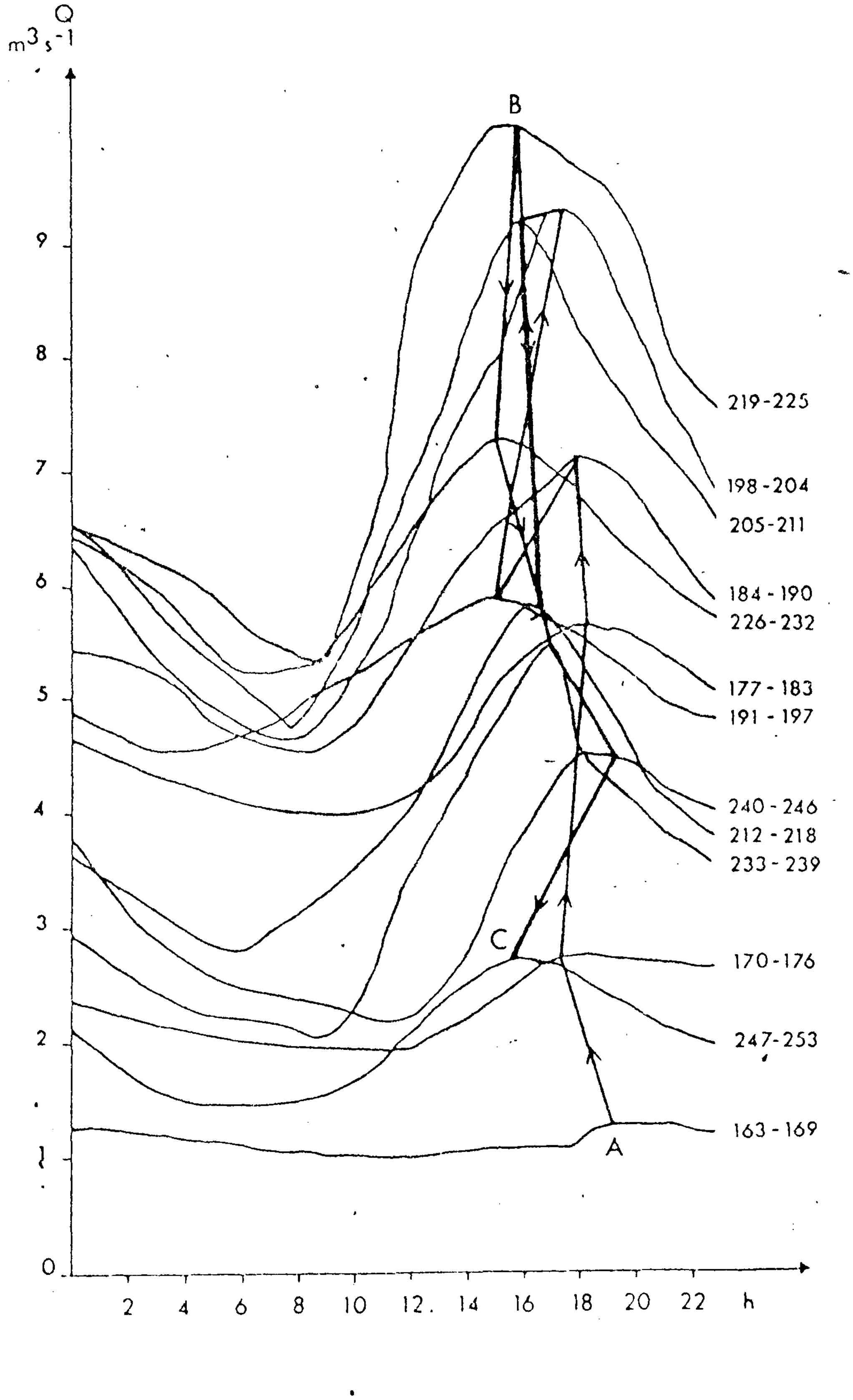


Figure 4. 10 Weekly mean diurnal hydrographs of the Feevispa in the ablation season of 1972. The line ABC connects points of sequential weekly mean maximum discharge. For expalnation see text.

was usually 16.00h.

In 1972, although peak flow amplitude and range increased, t_{max} remained after 18.00h until mid-July. Then increased background flow, but decreased peak components coincided with 3h advance of Q_{max} to occur at t_{max} of 15.00h. Following weeks with increased absolute discharges showed steeper rising limbs, based on higher background flows, with t_{max} maintained at 15.00h. In late August, low maximum flows (under 5.0 $m^3 s^{-1}$) were associated with the original asymmetrically-shaped hydrographs, in contrast to late summer 1971. Weekly means of the proportion of daily flow accounted for by the peak (Q_k) were in the range 29-34 per cent until the week ending 21 August, when Q_k reached 39 and finally 46 per cent, as background flow decreased.

Four-weekly averaged diurnal hydrographs provide a more regular pattern of shape changes in both 1971 and 1972 (Fig. 4.11). For 12 July - 7 August 1971 a strongly asymmetrical rising limb led to a peak at 14.00h, with a steady decline to a minimum flow at 07.00h, with Q_k = 30 per cent. In the four weeks 8 August - 3 September, the rising limb had steepened, a higher peak flow occurred also at 14.00h, recession was more rapid and 40 per cent of the total daily discharge occurred under the peak. In 1972, the four-weekly averages showed a similar pattern.

Average hydrographs conceal much of the variance of the individual diurnal hydrographs occurring in the period of time over which the average was determined. If individual days vary markedly, it is hardly surprising that weekly means fluctuate widely, and that monthly averages are thus unrealistic determinants of temporal changes of hydrograph shape. Clearly, the parameters of diurnal hydrograph shape change from day to day in response to varying meteorological conditions. The probability that sequences of hydrographs occur in response to similar combinationsof weather characteristics led to analysis of distinctive but uniform periods of flow. Descriptive parameters of the diurnal hydrographs of the Feevispa were calculated for several such periods, an example of which is the 13 days of sustained ablation 4-16 August 1972. Neither uniformity nor a progressive variation of parameters could be discerned (Table 4.1). In other periods also, extreme variability characterised the parameters calculated for successive days.

4.5.4 Temporal variations of diurnal hydrograph shapes for Gornera

Weekly mean diurnal hydrographs for the Gornera were calculated for the period 3 June to 22 September 1971 (Fig. 4.12). As for the Feevispa,

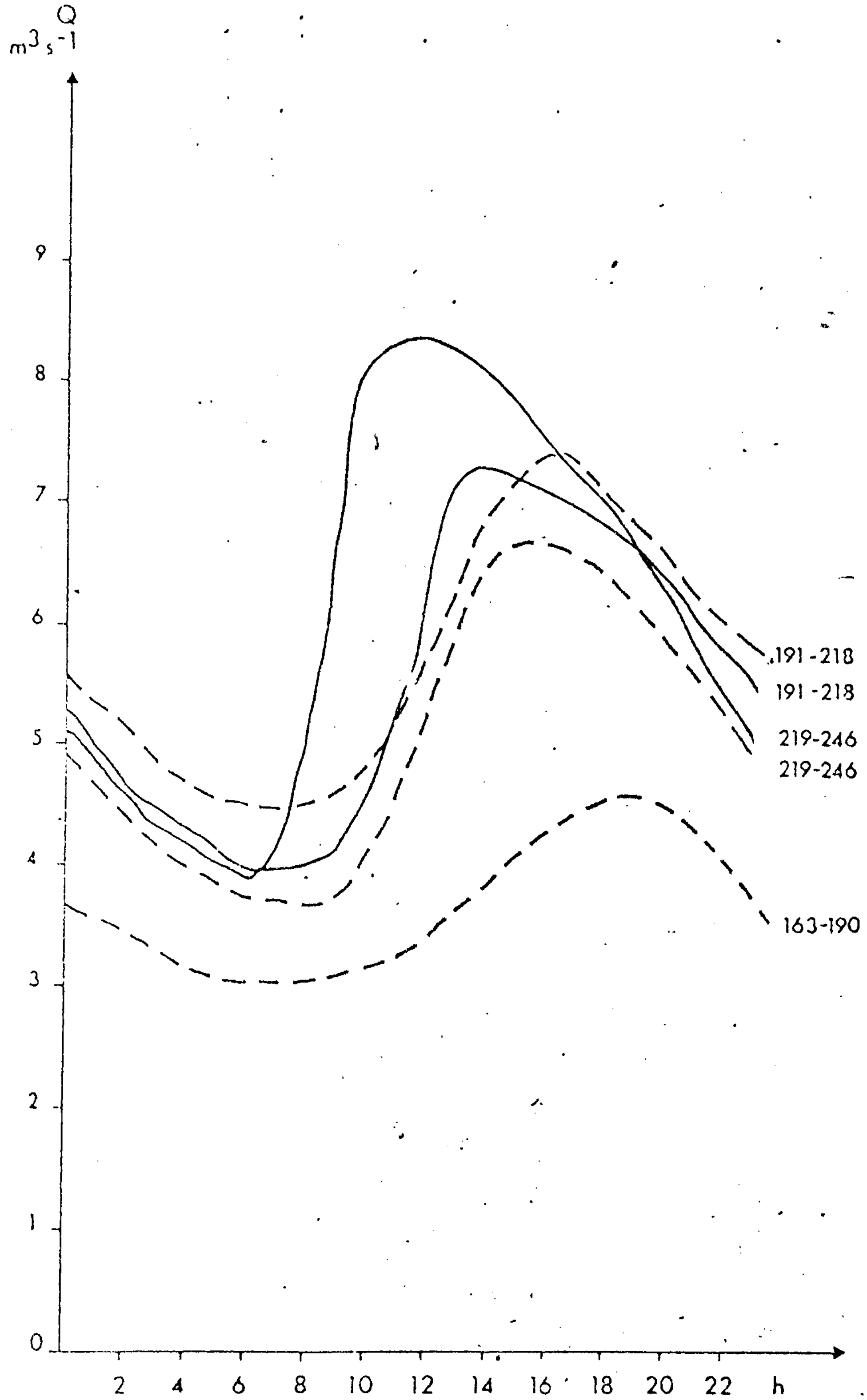


Figure 4.11 Four-weekly mean diurnal hydrographs of the Feevispa during the ablation season of 1971 and 1972.
(——— 1971; ----- 1972)

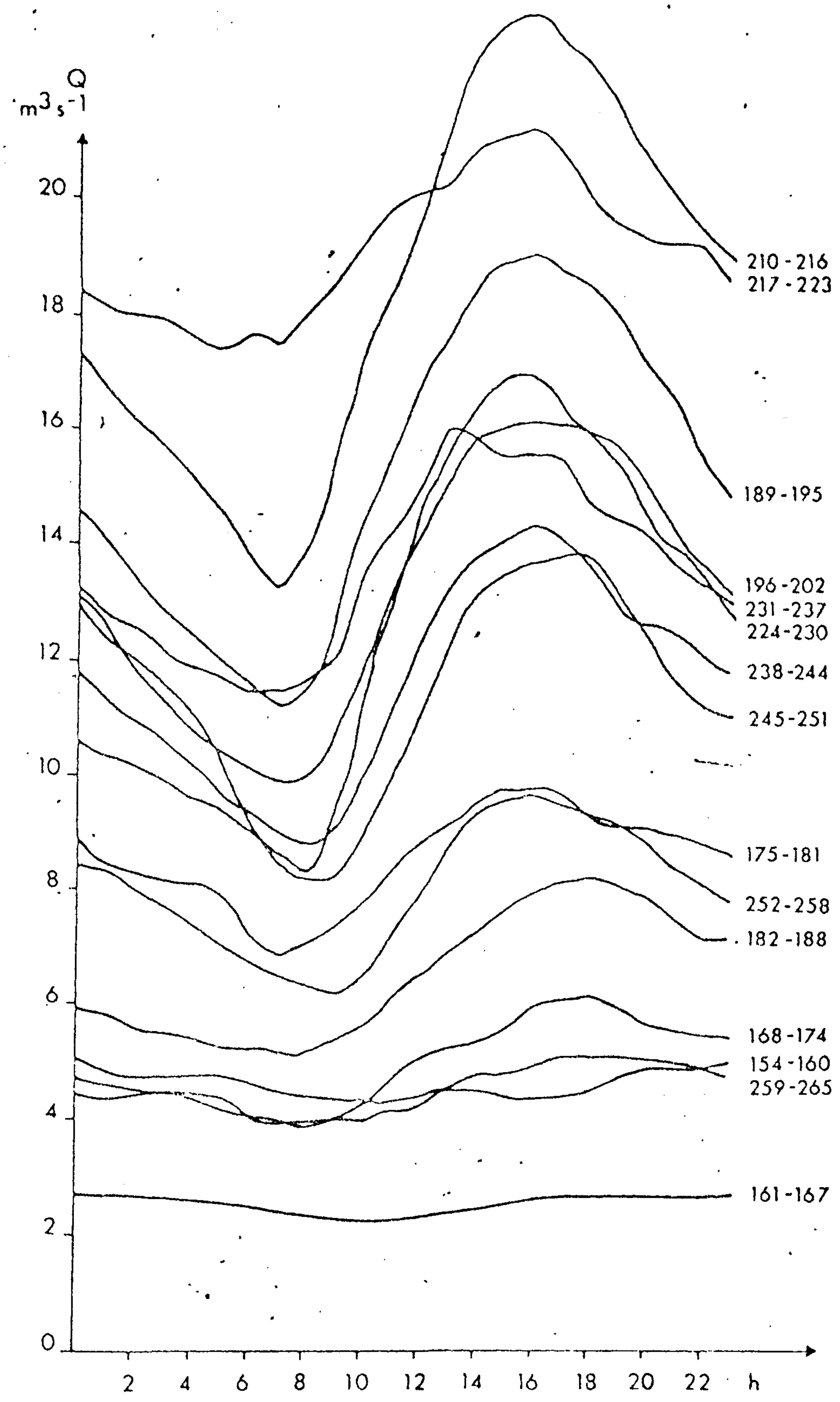


Figure 4.12 Weekly mean diurnal hydrographs of the Gornera during the ablation season of 1971. Days are numbered from 1 (1 = 1 January).

TABLE 4.1 PARAMETERS OF DAILY DISCHARGES OF THE FEEVISPA DURING A PERIOD OF SUSTAINED ABLATION FROM 4-16 AUGUST 1972

Date August	Minimum discharge $m^3 s^{-1}$	Minimum discharge time h	Maximum discharge $m^3 s^{-1}$	Maximum discharge time h	Maximum-minimum discharge $m^3 s^{-1}$	Total daily discharge $x\ 10^5 m^3$	Discharge contributing daily peak $x\ 10^5 m^3$	Discharge contributing daily peak Proportion of daily total %	Shape index
4	1.9	8-9	5.0	18-19	3.1	2.65	0.88	33.2	0.28
5	2.2	9-10	6.8	17-18	4.6	3.85	1.60	41.7	0.35
6	3.0	9-10	8.8	16-17	5.8	5.08	2.27	44.7	0.39
7	3.5	8-9	9.3	15-16	5.8	5.27	1.77	33.6	0.31
8	4.6	8-9	9.5	15-16	4.9	5.70	1.77	31.1	0.36
9	4.5	8-9	10.2	15-16	5.7	6.06	1.74	28.7	0.31
10	5.5	6-7	10.3	15-16	4.8	6.89	2.13	31.0	0.44
11	5.5	7-8	10.7	15-16	5.2	6.90	2.02	29.3	0.39
12	5.8	8-9	11.6	15-16	5.8	7.27	1.98	27.5	0.34
13	6.4	6-7	11.2	15-16	4.8	7.54	1.75	23.2	0.36
14	7.0	8-9	10.3	16-17	3.3	7.50	1.67	22.2	0.51
15	7.2	7-8	9.3	14-15	2.1	6.98	2.14	30.7	1.02
16	4.7	9-10	5.9	16-17	1.2	4.59	0.79	17.2	0.66

in the first four weeks the removal of snow cover and the opening of internal conduits permitted increased amplitudes of daily flows, and the timing of maximum daily flow advanced 2h. By the fifth week (1-7 July) flow decreased, daily range was reduced, and the time of peak flow t_{max} returned to 18.00h. Large amplitude diurnal flow variations during July were associated with asymmetrical hydrographs, with steep rising limbs. About 25 per cent of total flow made up the daily peak. Following the draining of the Gornersee, both high peak and minimum discharges characterised the hydrographs of early August. Subsequently, at the end of August flows dropped, but hydrograph shape remained relatively constant. In September decreasing discharges maintained a similar shaped hydrograph to earlier in the summer. The regular repeating hydrograph shape suggests that restrictions on conduit flows were maintained throughout the ablation season, and that the changing time t_{max} depends on absolute discharge rather than on the evolution of the conduit network. However, individual daily behaviour differed considerably from the mean.

At the four-weekly period, the similarity of the asymmetrical hydrograph shapes is apparent throughout the season (Fig. 4.13). The proportion (20 per cent) of total daily flow on average contributing to the peak hydrograph was almost uniform throughout the 16 week investigation period. Flows arising from the bursting and drainage of the Gornersee were not included when calculating the mean hydrographs of Figures 4.12 and 4.13.

During a period of uniform hydrometeorological conditions, favouring sustained ablation from 1-15 July 1974, large variations of parameters describing diurnal hydrographs of the Gornera occurred from day to day (Table 4.2). Daily maximum hourly discharge increased from 10.20 to 18.32 $m^3 s^{-1}$ in this period, showing the superimposition effect of Martinec (1970), and daily minimum hourly discharge increased from 4.60 to 12.36 $m^3 s^{-1}$. t_{max} oscillated randomly from 15.00 - 19.00h, and $Q_{max} - Q_{min}$ increased and then decreased. The actual discharge accounting for the peak diurnal flow varied within close limits ($0.13 - 0.35 \times 10^6 m^3$), but as a proportion Q_k ranged from 14.0 - 27.9 per cent. The shape index varied from 0.23 to 0.87 despite visually similarly-shaped curves. In this case, the shape index varies strongly with the absolute value of $Q_{max} - Q_{min}$, making it fluctuate widely, whereas it failed to show visually significant changes in sharpness of hydrograph peak for the Feevispa. An index of curvature would probably provide a superior measure of shape.

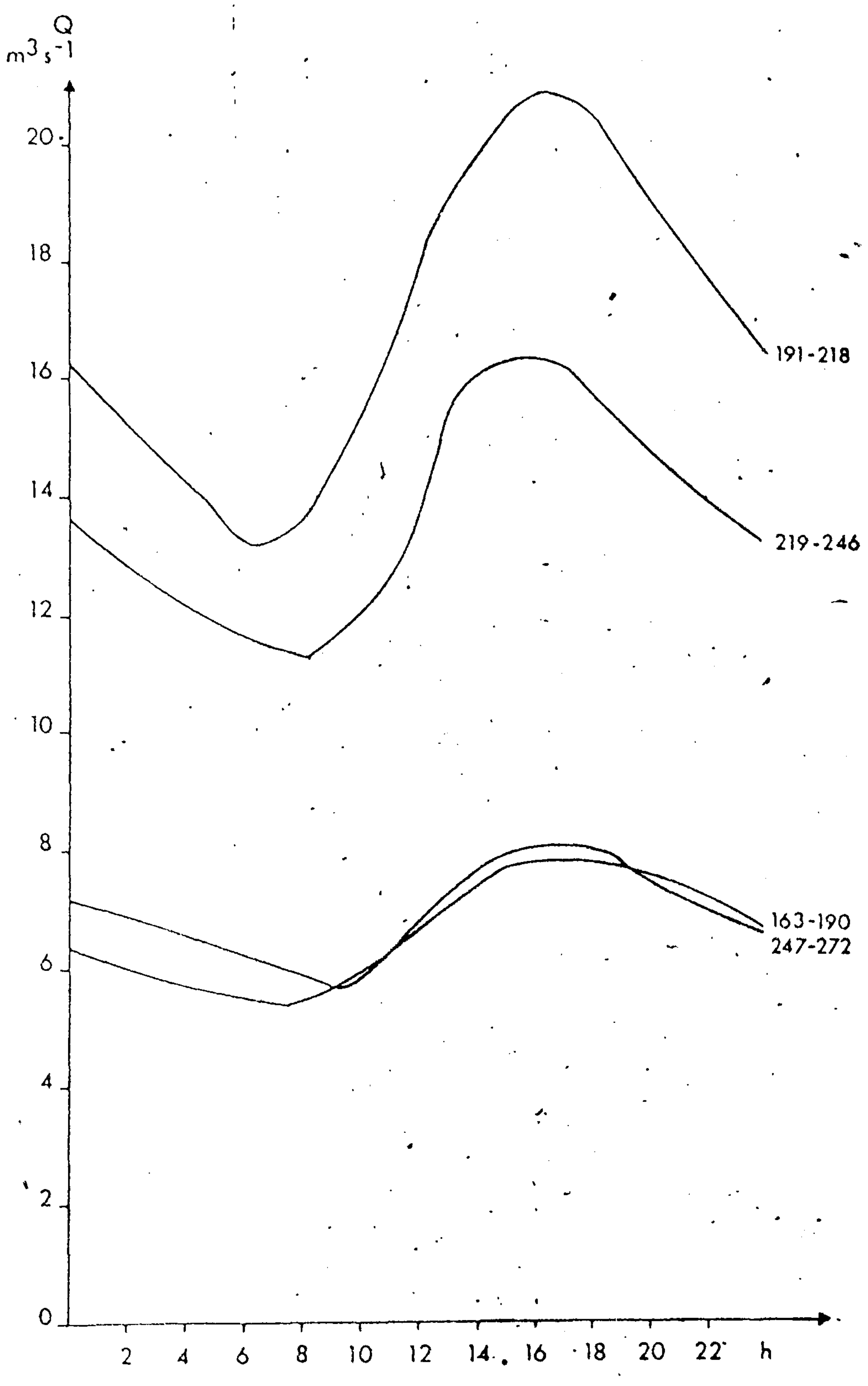


Figure 4.13 Four-weekly mean diurnal hydrograph of the Gornera during the ablation season of 1971.

TABLE 4.2 PARAMETERS OF DAILY DISCHARGES OF THE GORNERA DURING A PERIOD OF SUSTAINED ABLATION FROM 1-15 JULY 1974

Date July	Minimum discharge $m^3 s^{-1}$	Minimum discharge time h	Maximum discharge $m^3 s^{-1}$	Maximum discharge time h	Maximum-minimum discharge $m^3 s^{-1}$	Total daily discharge $x\ 10^6 m^3$	Discharge contributing daily peak $x\ 10^6 m^3$	Discharge contributing daily peak: Proportion of daily total %	Shape index
1	4.60	4-5	10.20	20-21	5.60	0.61	0.13	21.4	0.23
2	6.45	8-9	11.60	18-19	5.15	0.79	0.16	20.8	0.32
3	8.00	9-10	11.10	16-17	3.10	0.81	0.18	21.8	0.57
4	6.67	8-9	12.00	16-17	5.33	0.79	0.20	25.1	0.37
5	7.05	8-9	12.80	17-18	5.15	0.86	0.19	22.8	0.38
6	8.40	8-9	11.00	15-16	2.60	0.83	0.19	22.6	0.72
7	6.45	8-9	12.95	17-18	6.50	0.83	0.23	27.9	0.36
8	7.40	8-9	13.30	17-18	5.90	0.89	0.21	23.2	0.35
9	8.40	8-9	14.75	18-19	6.35	1.02	0.23	22.4	0.36
10	9.85	8-9	15.60	16-17	5.75	1.08	0.20	18.9	0.35
11	10.60	8-9	17.00	18-19	6.60	1.19	0.30	25.0	0.45
12	10.30	8-9	17.00	16-17	6.70	1.22	0.27	21.8	0.40
13	11.70	7-8	18.20	15-16	6.50	1.32	0.20	14.8	0.30
14	12.36	24-1	18.31	15-16	4.05	1.43	0.35	24.5	0.87
15	10.80	8-9	18.32	17-18	7.52	1.25	0.33	26.0	0.43

4.5.5 The impact of the drainage of the Gornersee

The sudden catastrophic drainage of a large volume of water through the internal hydrological system of a glacier should permit an assessment of the mechanisms controlling the usual daily discharge variations through the glacier. The increased flow of water appears to dramatically increase melting of conduit icewalls (Mathews, 1973; Nye, 1976) and, subsequently as flow decreases, either deformation closure occurs immediately or over a period of several days. Consequently, the widening of passages might be expected to influence hydrograph shape immediately after drainage of an ice-dammed lake.

Weekly mean diurnal hydrographs of the Gornera for the ablation seasons of 1970 and 1971 prior to the draining of the Gornersee show the same development pattern (Fig. 4.14). After draining, absolute discharges changed because of changing meteorological conditions but weekly mean diurnal hydrographs maintained similar average shapes (Fig. 4.15). High absolute discharges appear to result from enhanced ablation rather than from changed conduit characteristics.

Four-weekly mean diurnal hydrographs for the Gornera in 1970, excluding the period of the draining of the Gornersee, show the expected increase in discharge from June to July, but hydrograph shape remained remarkably similar before and after (Fig. 4.16). Mean diurnal hydrographs for the two weeks preceding the draining of the lake were similar in shape to the respective curves for the two weeks following (Fig. 4.17), although discharges were increased after the draining in both 1970 and 1971. No obvious change of shape of individual diurnal hydrographs was occasioned by the 1974 lakeburst (see Fig. 4.7) nor that of 1975 (Fig. 4.8).

Since the large discharge of the Gornersee appears to be accommodated by the conduit system without affecting subsequent diurnal hydrographs, other than some irregularity of peaks in 1974, it would appear that little persistent change was effected in either structure or capacity of the internal drainage system. There are several possible and plausible explanations. First, the conduits may have rapidly closed following the draining of the lake, as postulated by Nye (1976) for the outlet tunnel of Grimsvötn, Iceland. Secondly, the main subglacial drainage outlet may have widened by melting and not closed down rapidly, but the restrictions on the normal drainage of the Gornergletscher are located away from the major drainage canal. This is supported by the possibility of open channel flow in englacial conduits, although unlikely in the long term at depth in subglacial channels. An exciting possibility

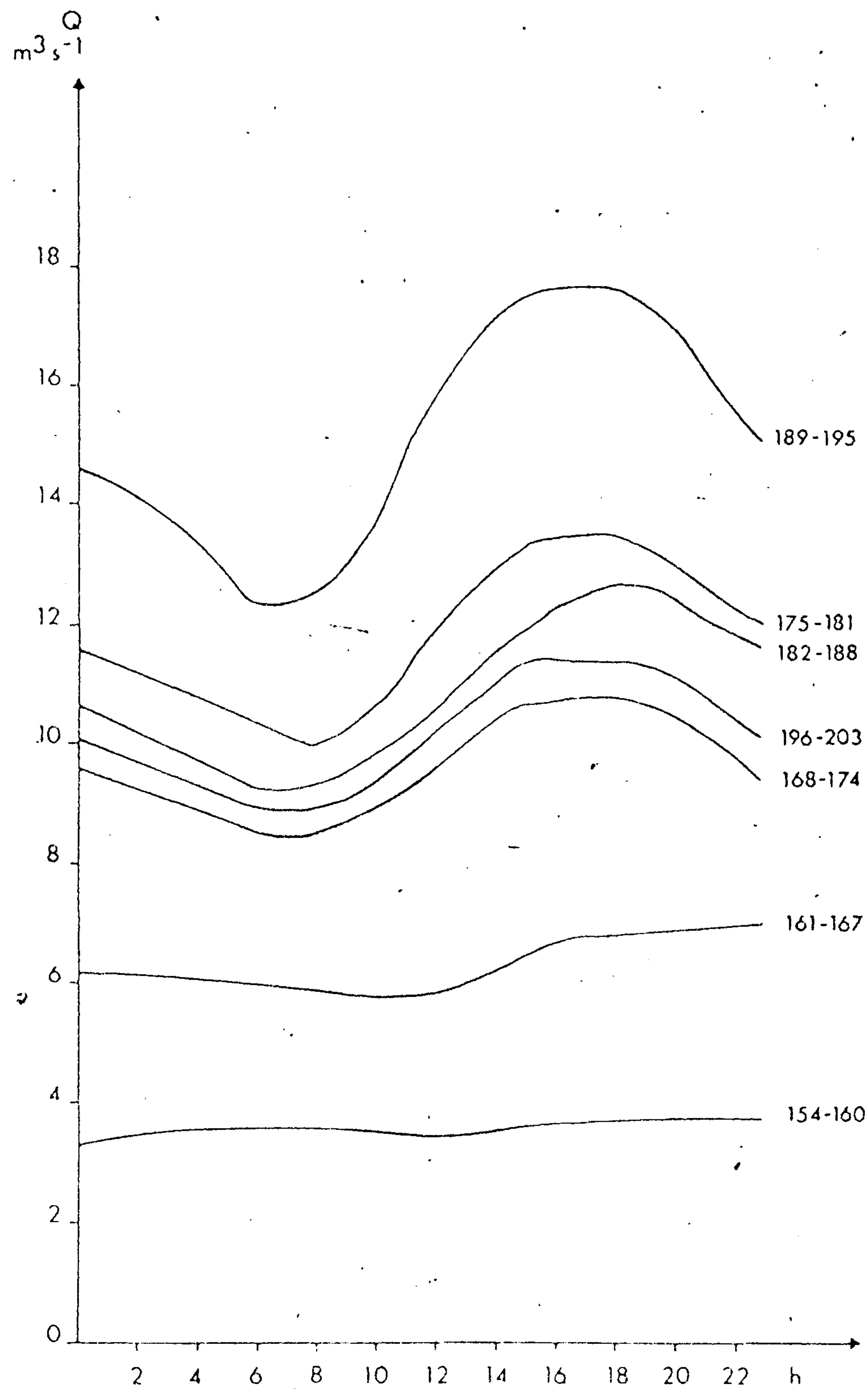


Figure 4.14 Weekly mean diurnal hydrographs of the Gornera before the draining of the Gornersee 1970.

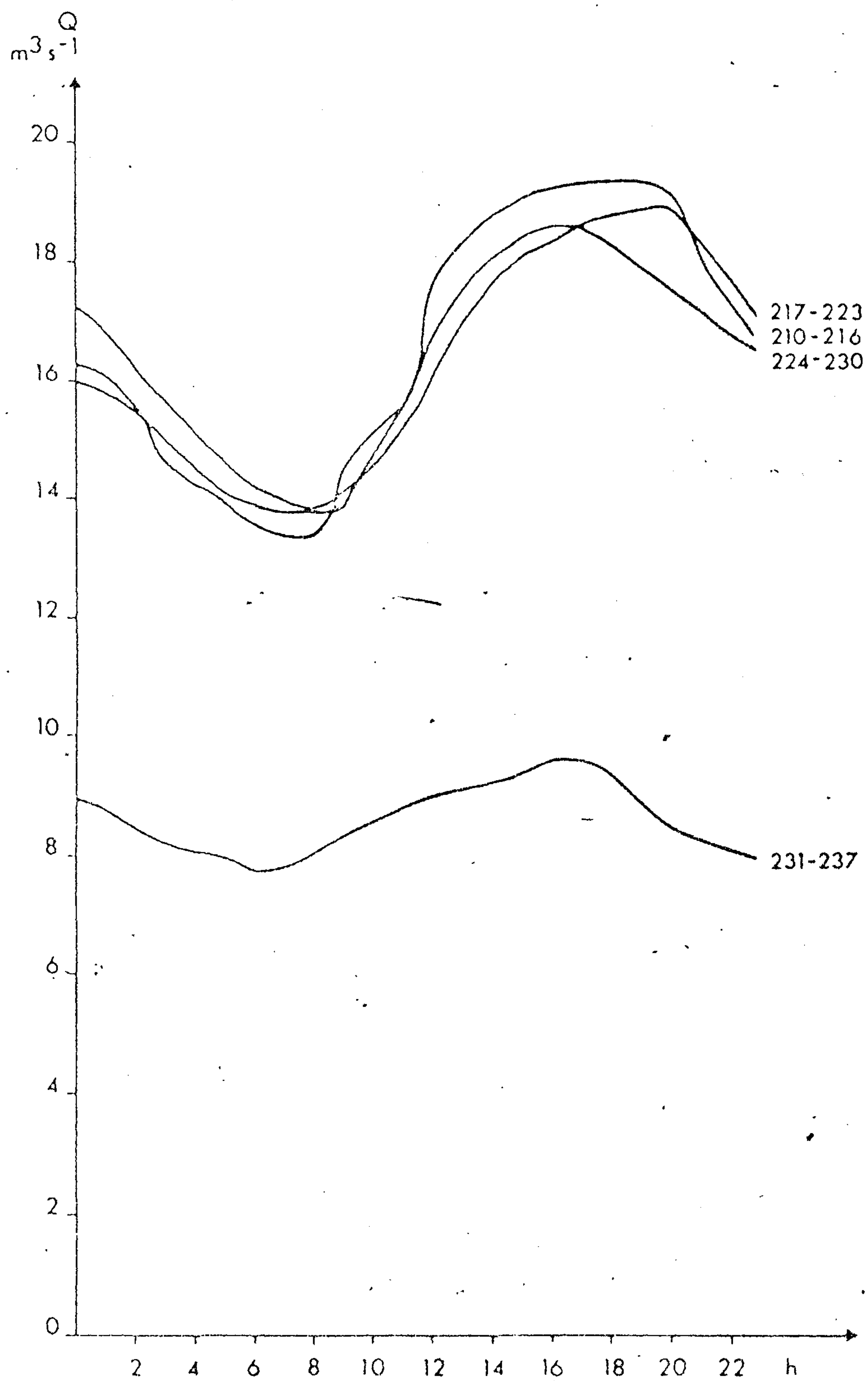


Figure 4.15 Weekly mean diurnal hydrographs of the Gornera after the draining of the Gornersee 1970.

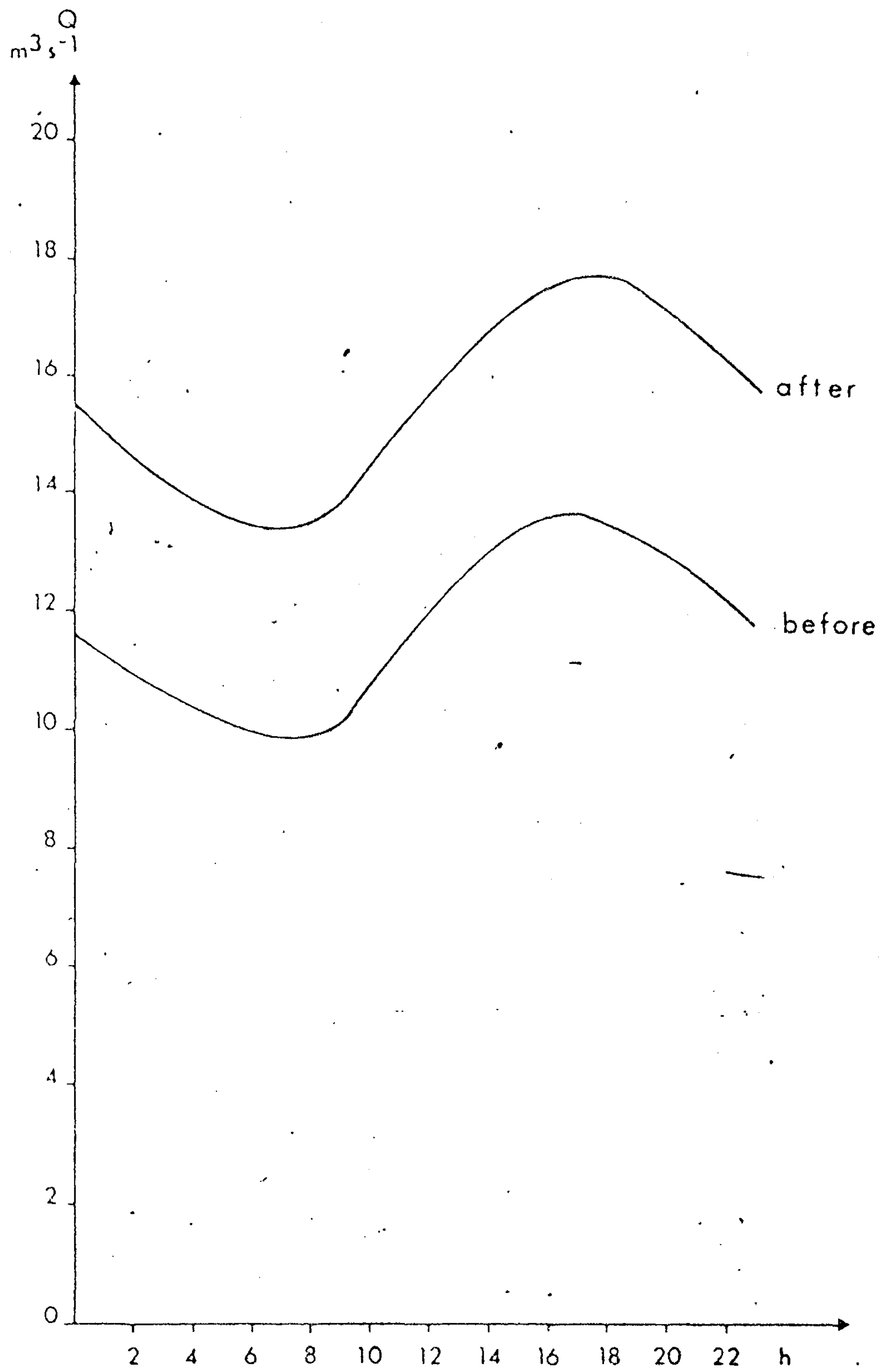


Figure 4.16 Four-weekly mean diurnal hydrographs of the Gornera for the 28-day periods before and after but excluding the draining of the Gornersee in 1970.

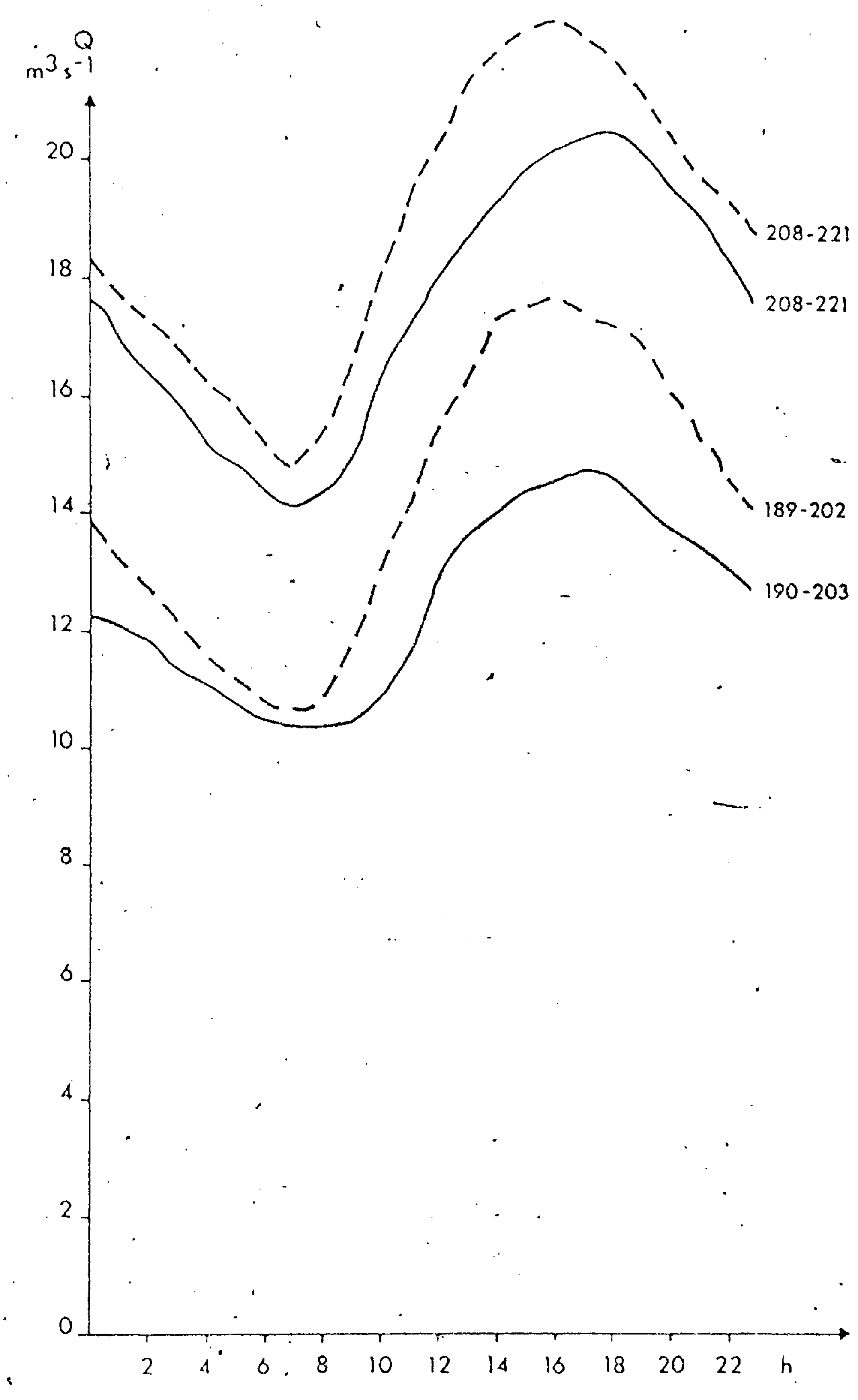


Figure 4.17 Two-weekly mean diurnal hydrographs of the Gornera before and after, but excluding the draining of the Gornersee in 1970 and 1971.

(——— 1970; ------ 1971)

remains the creation of either many new channels, or a spread of water across the bed, 'flooding', temporarily effectively widening the conduits, until following the lakeburst, the glacier returned to its bed. Sadly, analysis of hydrographs provides no further diagnostic information to test these hypotheses. The possibility of the creation of new channels or flooding would lead to increased subglacial debris transport, and this idea is examined in Chapter 5.

4.5.6 Volumes of water stored within Feegletscher and Gornergletscher

Minimum estimates of volumes of water stored within Gornergletscher were calculated for seven major periods of depletion following summer snowfall in the years 1970-1975 from discharge records of Gornera. In 1971 and 1972, only four periods of depletion were found in the flow of the Feevispa, and these were of shorter duration than those at Gornergletscher (Table 4.3). The volumes of water determined by this method depend on both the ranges of flow from initial maximum to final minimum and on the length of the depletion periods and are therefore minimum estimates of storage capacity. The large volumes of water stored within the Gornergletscher compare well with Elliston's (1973) estimate for 29 June - 1 July 1959 of 1.41 x $10^6 m^3$. The amount of water in the glacier available to maintain runoff is independent of season and has considerable range from 0.69 - 2.23 x $10^6 m^3$ ($\bar{x}$ = 1.40).

Between 0.35 - 0.46 x $10^6 m^3$ of water were held within the Feegletscher at the start of four depletion periods in 1971 and 1972 ($\bar{x}$ = 0.40 x $10^6 m^3$). For comparative purposes, specific storage per unit area of glacier bed was calculated, without differentiation of ablation and accumulation areas, for both Feegletscher and Gornergletscher. Mean specific storage at Feegletscher was 4.63 x $10^4 m^3 km^{-2}$ and at Gornergletscher 3.88 x $10^4 m^3 km^{-2}$, suggesting that overall glacier size is not the major control on internal water storage. Although the quantities of water stored appear large, they are sufficient only to maintain the usual daily discharges for about one day from Gornergletscher and for about 12h from Feegletscher. Much of the stored water will be held up in the firn area, some will be water draining out of the conduits, and the remainder presumably stored in englacial pockets or subglacial cavities. Unfortunately, hydrograph analysis does not permit separation of the origins of water by place of storage.

4.5.7 Anomalous discharges

Rainfall was frequently responsible for short-term positive and

TABLE 4.3 VOLUMES OF WATER STORED WITHIN GORNERGLETSCHER AND FEEGLETSCHER CALCULATED FROM DEPLETION HYDROGRAPHS OF GORNERA AND FEEVISPA

Date of depletion	Maximum discharge $m^3 s^{-1}$	Minimum discharge $m^3 s^{-1}$	Storage $x\ 10^6 m^3$	Specific storage $10^4 m^3 km^{-2}$
GORNERGLETSCHER				
20-24 August 1970	20.00	2.80	2.23	6.18
29 June - 2 July 1971	12.12	2.72	1.33	3.68
11-21 September 1972	6.50	0.13	1.63	4.53
20-25 June 1973	15.70	2.17	2.19	6.06
31 August - 1 September 1973	10.30	3.20	0.69	1.91
18-20 July 1974	10.60	3.00	0.81	2.25
22-27 August 1975	14.37	1.60	0.93	2.58
FEEGLETSCHER				
29 June - 1 July 1971	4.30	1.20	0.35	4.05
10-12 September 1971	5.30	1.30	0.40	4.63
18-20 August 1972	4.30	1.80	0.46	5.32
2-4 September 1972	4.70	1.40	0.39	4.51

negative deviations from the usual diurnal hydrograph. Examples of rain-induced anomalies were described in 4.5.1 and 4.5.2. The effect of precipitation on flow of the Feevispa was often to adjust the size and width of peak flow. However, the major effect of precipitation was to raise background flow, often greatly. The time of precipitation was not determined, but the anomalies suggest that precipitation runoff merely adds to the bulk of the water in the glacier, and since there were very few individual peaks, it appears that runoff from rainfall is delayed in passing through the glacier. A noticeable exception occurred on 12 July 1971. In view also of the large non-glacierised area, it is suggested that runoff is delayed in crossing the rock and morainic sediments of the lower part of the catchment area.

Since towards the end of the ablation season, peaked diurnal hydrographs with low background flows suggest little internal restriction on runoff from Feegletscher, the lack of precipitation peaks appears to be contradictory. However, earlier in the season, when heaviest precipitation was received, the runoff system was not so well developed, and restricted flow may have prevented immediate runoff from precipitation inputs.

In contrast, at Gornergletscher, where the hydrograph remains similar, with rounded peaks throughout the summer, suggesting flow always constricted, in 1974 precipitation frequently led to an individual small peak on the hydrograph as an accessory to the main diurnal peak. It appears that runoff from the limited non-glacierised catchment and from the bare-ice ablation area is rapidly concentrated through the lower part of the glacier to produce excess runoff over that of the usual diurnal peak. The same behaviour occurred in 1975, although in some cases background flow was increased overall when precipitation was continuous for several hours. Some system for preferentially allowing rapid flow from the ablation area to the portal must exist at Gornergletscher, which is not present in Feegletscher.

Anomalous hydrograph shapes also occurred when meteorological variation could not be held responsible. On the Feevispa, in 1971, several hydrograph anomalies were recorded in July and early August only, within the period when flow through the conduit system was first increasing (see Fig. 4.5). On 11 July, sudden termination of the rising flow in mid-afternoon, for about 3h, was followed by a steep rise to a maximum higher and later than on the previous three days. Twin peaks characterised maximum discharge on the evening of 25 July. On 1, 6 and 8 August, irregular falling limbs of the diurnal hydrographs were characterised by either flow being maintained or slightly increased during the early morning. Severe blocking of either minor conduits or minor blockages of arterial canals within the glacier may account for sudden drops in flow, followed by increases. These may be caused by either collapse of ice from the tunnel roof and sides or from accumulation of sediment. Water backs up at the restriction to flow, water pressure rises, and clears the offending blockage allowing discharge to be suddenly and rapidly restored. Maintenance of flows at times during daily recession flows probably results from pockets of stored water being released into the conduits as discharge decreases, and if under pressure, pressure decreases.

In 1974, hydrographs of the Gornera were characterised by irregularity (see Fig. 4.7). Twin peaks surmounting the daily peak occurred on 21, 22, 25 June, 3, 12, 28 July and extremely large twin peaks on 28, 29 and 30 August. Subsidiary peaks occurred on the falling limb on 10 days (9, 11, 12, 15, 23, 24 July; 4, 15, 16 August). Overnight on 13-14 July, overnight flow was much enhanced above the usual minimum for the period. In contrast, few anomalies occurred in 1975 (Fig. 4.8), twin peaks at maximum flow on 9 and 29 July and 2 August, a falling limb peak 4 August and enhanced background flows on 14-15 July, 16 August and 21-23 August.

These anomalies indicate instability in the englacial and subglacial conduits during times of maximum discharge, with blocking and subsequent unblocking of the conduits. Often, maximum discharge of the Gornera in late afternoon was associated with the presence of huge numbers of small rounded ice particles (also noted by Bezinge and others(1973) and termed "ice flotation cobbles"). Their roundness points to an origin some distance under Gornergletscher. It is suggested that blocks of ice calve from tunnel margins under the pressure of high water flows, and may temporarily close some conduits to flow, and restrict total discharge of the Gornera. Subsequent break-up returns flow to normal and releases ice flotation cobbles into the Gornera. Small peaks on the falling limbs of diurnal peak hydrographs may result from the sudden release of stored water as at Feegletscher. Large magnitude flows draining from englacial or subglacial water bodies can account for anomalously high background flows maintained over several hours or even days.

During a period of anomalous flows from Gornergletscher, a series of marginal crevasses on the south flank of the trunk glacier between the junction of the Schwärzegletscher and Unterer Theodulgletscher with the Grenzgletscher icestream was noticed for the first time to be full of water during late afternoon on a warm clear day, 13 August 1975. Flow in the Gornera was particularly low on the morning of 13 August, and by 11.00h discharge remained at 7.8 $m^3 s^{-1}$, rising only to 10.6 $m^3 s^{-1}$ at 17.30h. The filling of the crevasses thus appeared to be a back up of water created by some blockage beneath the glacier which restricted flow of the Gornera. During the day, many new cracks were propagated across the width of the Gorner and Grenz icestreams from the zone of the water-filled crevasses to the Riffelhorn.

Subsequently, qualitative observations of the water levels in crevasses were made between 05.00h - 07.00h and 16.00 - 19.00h each day. The results of the observations are given in Table 4.4, where "full" and "empty" refer to the presence or absence of water. Melt etching of high watermarks on the ice of the crevasse walls suggested that water levels attained a level of up to 15m from the surface of the glacier.

On the morning of 14 August, the water had disappeared from view in the crevasses, but by late afternoon, refilling of the crevasses occurred by the time of maximum flow. The same cycle repeated on 15 August during a storm and 16 August. High background flow on 16 August may have resulted from removal of the blockage or constriction because flow of the Gornera returned to normal on 17 August, and the crevasses remained empty.

On 20 August, the crevasses refilled during late afternoon but failed to refill after draining on 21 August. The background flow of the Gornera on 21 August was much increased, presumably because of the discharge of water held back by the blockage having reformed. The crevasses are upglacier of the bottom lip of the lower depression in the long profile of Gornergletscher, and water may have accumulated in this basin as a result of a blockage of outlet conduits draining across the lip. The blockages may have resulted from tunnel roof collapse or from ice movement impinging on channels across the lip of the depression.

4.6 Evaluation

4.6.1 Evaluation of methods of hydrograph analysis

The method of comparative hydrograph analysis has several serious disadvantages in the form used in this study and in relation to Alpine glacial meltstreams. The measures of peak amplitude and shape were not sufficiently sensitive to changes in overall hydrograph shape and peak curvature in particular. Temporal variations of flow from day to day

TABLE 4.4 OBSERVATIONS OF WATER LEVELS IN MARGINAL CREVASSES OF GORNERGLETSCHER, 13-21 AUGUST, 1975

Date	Time	Status
13 August	p.m.	Full
14 August	a.m.	Empty
	p.m.	Full
15 August	a.m.	Empty
	p.m.	Full
16 August	a.m.	Empty
	p.m.	Full
17 August	a.m.	Empty
	p.m.	Empty
18 August	a.m.	Empty
	p.m.	Empty
19 August	a.m.	Empty
	p.m.	Empty
20 August	a.m.	Empty
	p.m.	Full
21 August	a.m.	Empty
	p.m.	Empty

due to changing meteorological conditions prevent the sensible use of mean weekly and four-weekly diurnal hydrographs. The short periods of uniform conditions, selected in this study on the basis of hydrograph characteristics, were not sufficiently uniform for generalisation of hydrograph shapes. It is suggested that a better analysis would result from comparative hydrograph analysis in association with measurement of climatic data, especially over sequential periods of 4-5 days, during, for example, build-up and decline of flow. Although average hydrographs would suffer from more irregularities, increasing variance, if the 1h filter were removed, studies of hydrograph shape require more closely-spaced data, perhaps an average for every 15 minutes. Changes in shapes of peaks may become more apparent at this lower smoothing interval. Also, dimensionless analysis, as recently proposed by Bezinge (1978), would probably improve this method of hydrograph analysis.

4.6.2 Evaluation of meltwater stream hydrograph analysis as a method of investigation of the internal hydrology of glaciers

Hydrograph analysis provides a useful source of information concerning internal storage of water, and also discharge anomalies. While pointing to the internal storage of water, no further detail of the location of the storage is available, nor of the actual volume, but a minimum value of the volume is reliably obtained. Discharge anomalies suggest mechanisms within the glacier to account for sporadic blocking, back-up and release of meltwaters within glaciers, but hydrograph analysis can not distinguish between them. Some non-equilibrium tendencies in glacial drainage systems are strongly indicated.

The question of the hydraulics of flow within glaciers, and control of flow by either surface inputs or by restricted flow, cannot be answered from hydrograph analysis. The two models of internal hydrological systems suggested in 4.3 produce diurnal hydrographs and seasonal variations of daily hydrographs which are reasonably similar, and it is not surprising that hydrograph analysis fails to provide evidence for the existence of one or the other at Feegletscher and Gornergletscher. Both systems probably exist together. They are end members of a series, and many intermediate combinations of open channel and closed pipe flow are possible. However, analysis of hydrograph shapes has shown that change in the nature of flow may occur, and that this may have been associated not with an increase of conduit capacity following rainfall, but with flow falling beneath a pre-existing capacity.

This particular form of analysis requires a better knowledge of inputs, over the entire glacier surface preferably. Otherwise, daily variations of hydrograph dimensions resulting from changing meteorological conditions cannot be identified. The use of mean hydrographs for several days, weeks or months, is subject to wide variation in the distribution about the mean. Rather than showing temporal variations of conduit networks, mean weekly and monthly hydrographs probably better reflect changing frequencies of different magnitudes and types of meteorological controlled inputs during the ablation season. Certainly, the time of occurrence of maximum discharge each day is determined by antecedent flow conditions and daily surface inputs rather than by the state of evolution of the internal drainage system.

4.6.3 Evolution and structure of glacier internal drainage systems

A sudden late season change of hydrograph shape was apparent for Feegletscher, whereas Gornergletscher appears not to suffer such changes. Precipitation peaks are infrequent in the Feevispa, but common in the Gornera, suggesting possible different structures to drainage systems. The nature of an internal drainage system responds both to surface inputs and to its internal hydraulics. Hydrograph analysis indicates that in both glaciers some delay to runoff occurs, and that restrictions to flow are present somewhere in their internal drainage systems. It is probable that in the late ablation season, arterial canals are able to transmit all the water supplied to them. Elsewhere restrictions remain, probably in englacial or subglacial conduits, and between firn and the conduit network. Perhaps conduit restrictions are localised, rather than the entire conduit network being adjusted to some mean discharge. The localised zone of restriction may migrate upglacier as the channels widen and the ablation area extends in early summer. Restricted conduits in limited lengths of the network would be unlikely to widen since the distance for heat exchange from water to ice would be minimal. Water pressure may be present only during highest discharges.

The stability of shapes of hydrographs and the slow fluctuation of background flows suggest that immediate melting of conduits by increased flows of water (as in lakebursts) is unlikely. Either melting is not so rapid, or it is not the limiting factor, and closure of conduits may dominate under some conditions. Restriction of flow cannot hold up lower flows at night, unless conduit closure by deformation occurs extremely rapidly. Evolution of the network may result from increasing surface catchment areas, or from a progressive widening of the conduit network upglacier, and subsequent shrinkage of length in the fall. The major drainage event of the ablation season at Gornergletscher provides no lasting effect on the internal drainage system, suggesting rapid adjustment to increased flow, and subsequent rapid readjustment.

Hydrograph analysis hints at several of the possibilities, but is inconclusive with respect to the exact nature of the internal drainage systems of Alpine glaciers.

4.7 Conclusions

The following conclusions may be inferred from the analysis of hydrographs of the Feevispa and Gornera:

1. Following the maximum flow for the year through Feegletscher, background flow dropped and spiked diurnal peak components of runoff appeared after a probable sudden change in the internal drainage.

2. The effect of the drainage of the Gornersee through Gornergletscher was of little importance after the event, although new channels were opened up concurrently with the escape of lake waters.

3. No evidence for temporal evolution of the structure of Gornergletscher was obtained.

4. Rainfall peaks in the discharge from Gornergletscher suggest a route of preferential rapid runoff under the ablation area.

5. About 40 per cent of total daily flow of the Feevispa accounted for the diurnal peak in contrast to 25 per cent for the Gornera, suggesting more restrictions to flow within Gornergletscher.

6. Considerable quantities of water remain stored within both glaciers, although the location of storage cannot be determined from hydrograph analysis.

7. Conduits beneath the glaciers block temporarily, but blockages are subsequently purged. Blocking may result from collapse of ice from tunnel margins, or from sediment accumulation.

8. Irregular blocking of a major conduit within 2 km of the snout of Gornergletscher ponded back such large quantities of water that backing up occurred to within 15m of the glacier surface.

9. The analysis presented here largely supports Röthlisberger's (1972) assertion that "the interpretation of hydrological data... is largely ambiguous". Several factors affect magnitude and shape of the diurnal hydrograph, and analysis of hydrographs cannot separate the effects due to individual factors.

5. SEDIMENT CONCENTRATION IN MELT-WATERS IN THE GORNERA

5.1 Introduction

Meltwaters emerging from the portal of an Alpine glacier have acquired many of their quality characteristics during passage through the internal hydrological system of the glacier. The nature of these waters is interesting because analyses of water quality may provide more insight into the behaviour of water flowing through the glacier than can be obtained from hydrograph data alone. The suspended sediment content of meltwaters already suggests that meltstreams flow at the glacier bed. They may also provide a rich variety of other information about hydrological and erosional conditions at the soles of glaciers.

While direct observations in natural cavities at glacier beds and remote sensing of basal conditions through boreholes have provided considerable insight into the nature of subglacial hydrological and erosional processes, the nature of subglacial conduit flow and the processes by which sedimentary materials are transferred from sites of origin at the ice-bedrock interface to meltwater streams beneath Alpine glaciers remain largely unknown. The interaction of basal meltstreams with the products of glacial erosion is of interest since measurements of the quantities of suspended sediments and solutes evacuated from partly glacier-covered catchments have been used to provide estimates of gross rates of denudational lowering by glacial erosion (Østrem, 1975) and chemical weathering (Reynolds and Johnson, 1972) and of identifying the relative significance of various subglacial processes (Vivian and Zumstein, 1973). Observation of the quality of water draining from glacier snouts can permit investigation of the nature of hydro-glaciological processes integrated over large areas of glacier bed, effectively sampled by flowing meltwaters.

Measurements of suspended sediment concentrations in meltwaters have usually been made to determine rates of transport of suspended load, often in connection with water resources and hydro-electric developments. This aspect of applied hydroglaciology has received considerable attention in Norway (Østrem, 1975), where meltwaters transport much silt into lakes used for hydro-electric storage purposes. Also, particles in suspension in meltwaters increase cavitation erosion of turbine and pump blades in hydro-electric plants (Bezinge and Schafer, 1968). Rates of sediment transport have also been investigated in Alaska (Slatt, 1972; Borland, 1961), Alberta, Canada (Mathews, 1964c), East Greenland (Hasholt, 1976), and Baffin Island (Church, 1972). Diurnal and seasonal variations of sediment concentration have been investigated in several glacial meltwater streams (Mathews, 1964c; Østrem and others, 1967; Church, 1972), often based on three or four samples each day, supplemented by occasional 24h periods of intensive sampling. The transport of sediment from beneath glaciers appears to depend on factors related to discharge, and on the supply of sediment either subglacially or washed in from marginal morainic deposits.

Complex relationships between suspended sediment concentration and discharge, with large variations in sediment content both dependent on discharge fluctuations and occurring as random events (Østrem, 1975) suggest that close-interval sampling of meltwater quality characteristics should allow interpretation of the nature of subglacial interactions of water flow and erosional sediment supply. Using measurements of sediment concentration and discharge every few hours throughout 24h periods, Liestøl (1967) demonstrated that meltstreams beneath Storbreen, Norway, frequently changed course.

The present investigation was designed to use hourly observations of suspended sediment concentration to provide detailed information concerning the interaction of meltwaters in basal conduits with subglacial sources of sedimentary material. It was intended to assess the relationship between sediment concentration and discharge and so to investigate the character of subglacial drainage. A programme of detailed observations of suspended sediment concentration in the Gornera was initiated in 1974, and continued in 1975, with the intention of measuring hourly variations of sediment transport during the ablation season, as close as possible to the glacier snout. The study was designed specifically in order to see if useful information about hydrological and erosional conditions at the glacier bed could be so obtained.

5.2 Sample collection and processing

5.2.1 Procedures

In 1974, samples of meltwater and sediments were collected at hourly intervals for selected periods at a site 50m from the glacier portal, in order to minimise effects of channel scour and fill, and about 3m from the channel bank, using a depth-integrating DH-48 sediment sampler. In July and August 1975 a sample was collected every hour throughout each 24h period by a North Hants Engineering Company automatic liquid sampler. A modified sampling nozzle, consisting of 24 10.0mm I.D. polyethylene tubes bound together with wire, was fixed in the stream so as to remain below the water level at the lowest stages of flow, orientated at an angle of 45° from the water surface upstream. The nozzle varied in depth at differing stages of flow, from 0.1 - 0.7m beneath the average level of the turbulent water surface, and remained 1m from the channel bank at a site 250m from the glacier snout. Using a vacuum of 460-480mm Hg, 0.7 - 0.9 litre samples were usually drawn up. Each sample bottle was connected by an individual tube of length 3m to the nozzle, so that samples received no contamination from those collected in previous hours. Occasionally, at times of high sediment concentration, tubes of the North Hants sampler became blocked by sediment particles larger than 10mm diameter becoming sucked into the end of the hose, preventing water and sediment from reaching the sample bottle. Samples of volume less than 0.7l were discarded. After every 24h sample cycle the clear polyethylene tubes were examined, and a sample rejected if particles had remained in the tube. Over 80 per cent of the possible number of samples was collected successfully.

In both 1974 and 1975 volumes of samples were determined in measuring cylinders. Sediment samples were separated from waters in the field by filtration through Whatman 542 hardened cellulose filter papers which had previously been numbered, dried and weighed individually, under pressure from a handpump. Samples were returned to the laboratory in sealed bags, oven dried at 105°C for 8h, and the quantity of sediment determined gravimetrically. No organic material was present in the samples. Some fine particles ($< 2.7\mu m$) smaller than the initial penetration pore size, may have passed through the filter papers. The sediment processing leads to errors of $\pm$20mg, and the measurement of volume $\pm$5ml, giving overall error of about 5 per cent.

In 1977, a Partech SDM10 photo-electric sediment monitor was used to record short-term variations of sediment concentration in the Gornera. The light source and photo-sensitive receptor probe was mounted about 1m beneath the lowest water level in the upstream flume of the prise d'eau gauging station, where mains electricity was available. The flume is designed to separate coarse bedload from meltwaters by reducing flow velocity and turbulence and some coarser saltation and suspended load become deposited during lower discharges. Calibration of a reliable rating curve to relate actual concentrations of suspended sediment determined gravimetrically to the analogue meter scale of the monitor was not achieved, since most of the range of sediment concentrations was accounted for by only 5 per cent of the scale range. The range was set before the field season on the basis of calibration with formazin turbidity standards. Poor calibration probably resulted from the few largest sediment particles, which contribute a large proportion of the weight of a sample, but which cause only minor disturbance to the transmission of light, in comparison with the scattering caused by the large number of smaller particles.

5.2.2 Evaluation of sampling methods

In turbulent meltstreams, suspended sediment is almost uniformly distributed with depth (Østrem, 1975), although the actual concentrations are probably variable between sites downstream and across the width of the channel at a site. Comparative measures of sediment concentration derived from samples collected using DH 48 and North Hants samplers were highly correlated, but the actual values differed considerably. This may be as much related to conditions at the sample point locations in a wide, highly turbulent, high velocity stream with shifting bed, as to the characteristics of the nozzles of the different samplers. Further, sample volumes were extremely small (0.8 l) in comparison with the instantaneous stream discharge (10-20 $m^3 s^{-1}$). Although changing depths of water varied the position of the automatic sampler nozzle relative to the water surface, error should result only from the effects of changing velocities in the nozzle vicinity, which may either increase or decrease the quantity of sediment in a sample in comparison with the true concentration in the stream (Federal Inter-Agency Study, 1941). The sediment concentrations observed are probably not accurate representations of the actual quantities of suspended sediment in the Gornera. Rather, the results provide useful data of relative temporal variability of sediment concentration for each year, but should not be compared between years because of different sampling technique.

5.3 Results and analysis

5.3.1 Suspended sediment concentration

Temporal variations of suspended sediment concentration during a period of sustained ablation from 28 July - 3 August 1975, shown in Figure 5.1, ranged between 94-1919 mg l^{-1}, which both occurred on 3 August, though on the other days, concentrations ranged only from 100-810 mg l^{-1}. Daily sediment concentration maxima occurred within several hours of daily peak discharge, on some days preceding the time of discharge peak, and others following, although 3 August presented an anomalous occasion. Every day, the peak discharges were accompanied by minimum concentrations of suspended sediment. Precipitation was of low intensity and infrequent throughout the period. Extremely high sediment concentration during the early hours of 3 August appears to have been related to an unusually high minimum discharge. While this discharge remained steady, sediment concentration fell by 95 per cent. Irregularity of sediment concentration suggests rapid injection of sediment impulses into subglacial streams followed by exhaustion, recurring independently of rhythmic variations of diurnal discharge.

Low temperatures and continuous cloud cover reduced both absolute discharge of the Gornera and the daily amplitude of the diurnal rhythm of flow from 11-13 August (Fig. 5.2). Suspended sediment concentration varied in phase with discharge on 11 August, but lower flow on the following day produced no sediment peak, and concentration remained below 360 mg l^{-1}. Rainfall during this period showed no relationship to sediment peaks, suggesting that subglacial sources contribute much greater quantities of sediment than marginal ice-free morainic slopes. From 14 August, both discharge and sediment concentration increased, but concentration occurred out of phase with flow, lowest concentrations being timed simultaneously with diurnal discharge maxima. The highest suspended sediment concentration in this period (2234 mg l^{-1}) occurred overnight 16-17 August, following an unusually shaped hydrograph peak which may have resulted from temporary restriction of subglacial conduit flow (see Chapter 4). A further high sediment concentration peak was produced during the lowest daily flow on 19 August. Subsequently, daily sediment concentrations were in the range 100-1000 mg l^{-1}; daily minima were followed in two or three hours by daily maximum values of sediment concentration, 3-6h after the times of maximum water discharge. Snowfall from 22 August caused reduced inputs of meltwater to the Gornergletscher, and

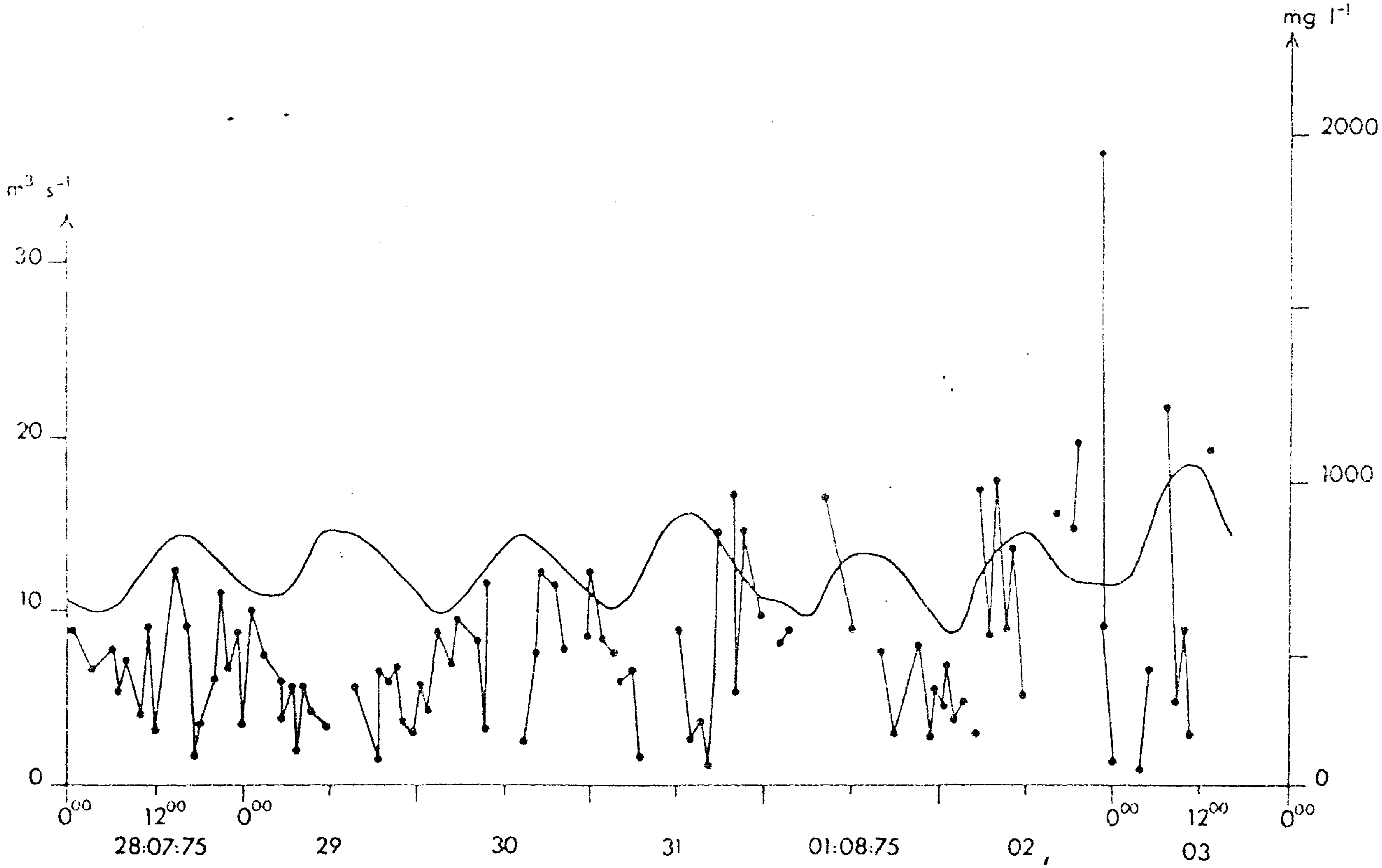


Figure 5.1 Temporal variations of discharge and suspended sediment concentration in the Gornera from 28 July - 3 August 1975. Instantaneous sediment concentrations were obtained for samples collected by a North Hants Engineering Company automatic liquid sampler. Sequential hourly samples have been connected to provide a curve of suspended sediment concentration. Sediment concentration peaks occurred both before and after times of peak daily discharge which were associated with minimum daily sediment concentrations during this period of sustained ablation. An anomalously high overnight discharge on 2-3 August was associated with high suspended sediment concentration.

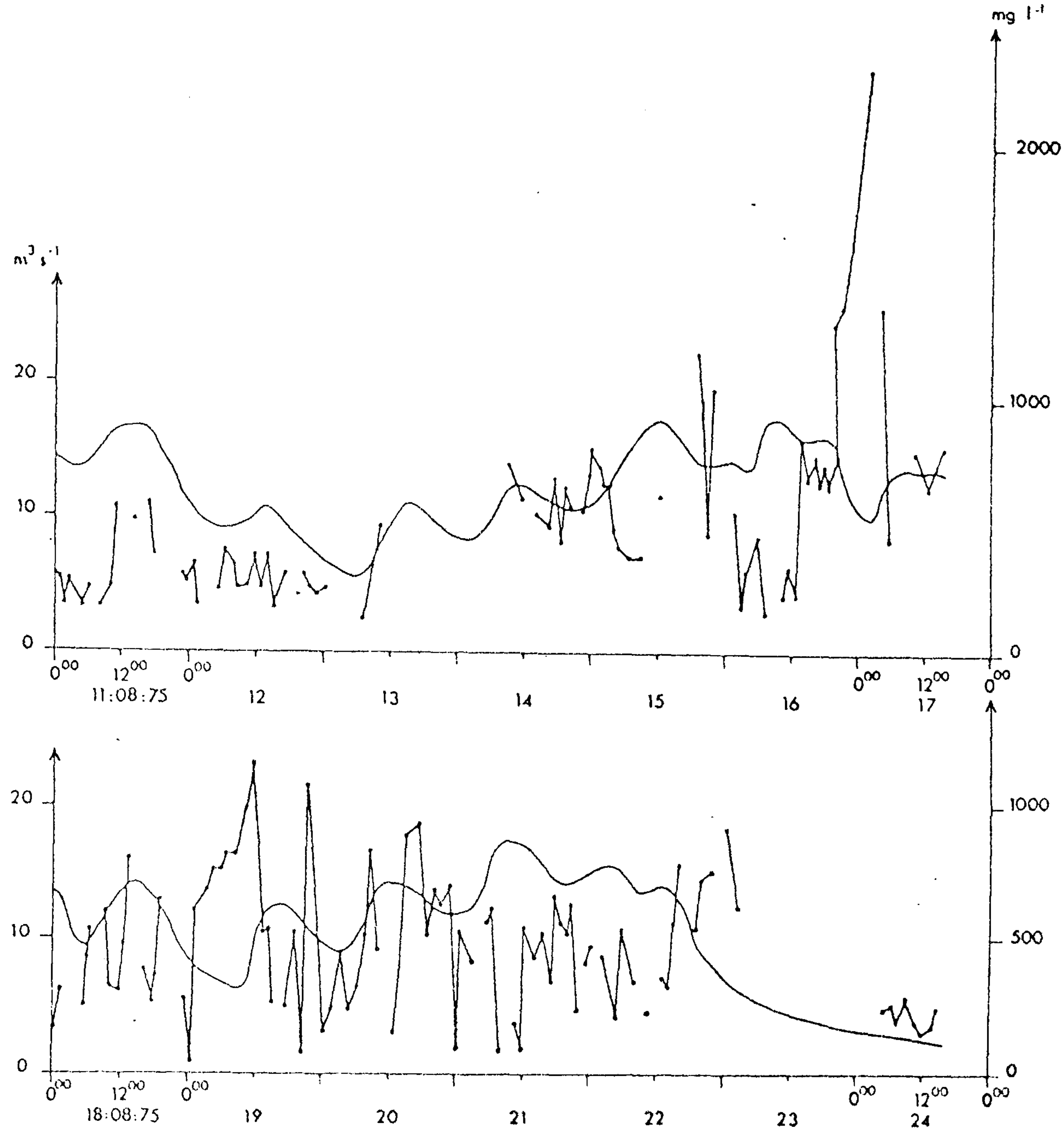


Figure 5.2 Temporal variations of discharge and suspended sediment concentration in the Gornera from 11 - 24 August 1975. Instantaneous suspended sediment samples were collected by a North Hants Engineering Company automatic liquid sampler. Discharge and sediment concentration declined from 11 - 13 August during a cool overcast period. Restored ablation produced a slow rise in peak and minimum discharges. High sediment concentration overnight on 16-17 August followed an unusual peak flow,which probably resulted from blocking of subglacial conduits. Release of water subsequently provided large quantities of sediment to the Gornera.

recession flow of the Gornera was associated with first increased followed by low (114-271 mg l^{-1}) sediment concentrations. Flow in subglacial streams decreased with declining discharge, probably either causing temporary deposition of sediment into channel storage or leaving the channel margin ice-sediment interfaces out of contact with water.

In 1974, consecutive hourly observations were undertaken for such periods as possible before, during and after the draining of the Gornersee. The usual pattern of sediment-discharge relationships occurred on 26-27 July before the beginning of the drainage (Fig. 5.3). The first release of water from the lake occurred in the early afternoon of 29 July, when the usual decrease of flow was replaced by the rising limb of the lakeburst hydrograph. Sediment concentration increased from 2900 mg l^{-1} to 5750 mg l^{-1} in 2h. On 30 July, sediment concentration was irregular, but never declined beneath 4000 mg l^{-1}, and reached a maximum of 7215 mg l^{-1}. The highest discharge (54 $m^3 s^{-1}$) during draining resulted from the superimposition of the maximum flow from the lakeburst on the usual highest diurnal flow of the late afternoon on 31 July (Fig. 5.4). Sediment concentration continued to rise to a maximum of 11 800 mg l^{-1}, two hours after peak discharge, and remained relatively high, suggesting continued availability of sediment throughout 1 August as the normal diurnal component of flow reappeared on the falling limb of the lakeburst hydrograph. On 2 August, when sediment concentration showed a direct in phase relationship with discharge, the sediment peak occurred about 2h before peak discharge. By 3 August, although suspended sediment concentration remained greater than 2000 mg l^{-1}, the usual dilution effect was associated with maximum discharge suggesting that easily-worked sediment had been flushed from the conduit system.

Occasional large sudden fluctuations of suspended sediment concentration were recorded by the photo-electric sediment monitor in 1977 (Fig. 5.5). Usual variations of sediment concentration in inverse phase with discharge occurred throughout the observation period, with occasional short-lived increases, usually occurring at the time of daily minimum discharge or maximum sediment concentration. A particularly large peak of sediment concentration persisted for 30h on the 3-4 July, with subsidiary peaks as the concentration declined. Discharge showed the usual diurnal fluctuations from 24 June - 6 July, and no rapid hydraulic changes were observed which would have accounted for the sudden changes in concentration. Similar sediment 'clouds' were described for Nigardsbreen, Norway, by Østrem (1975).

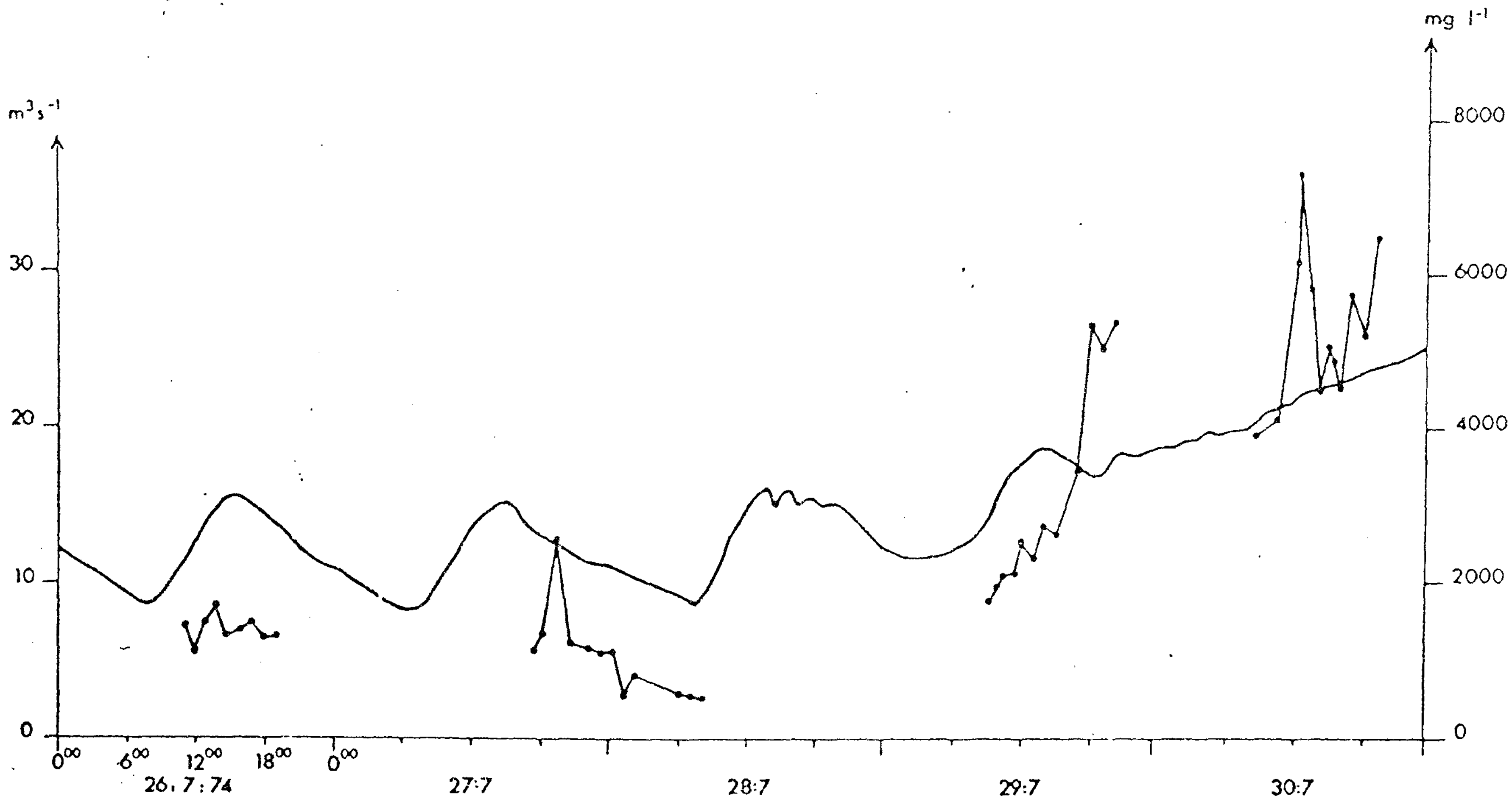
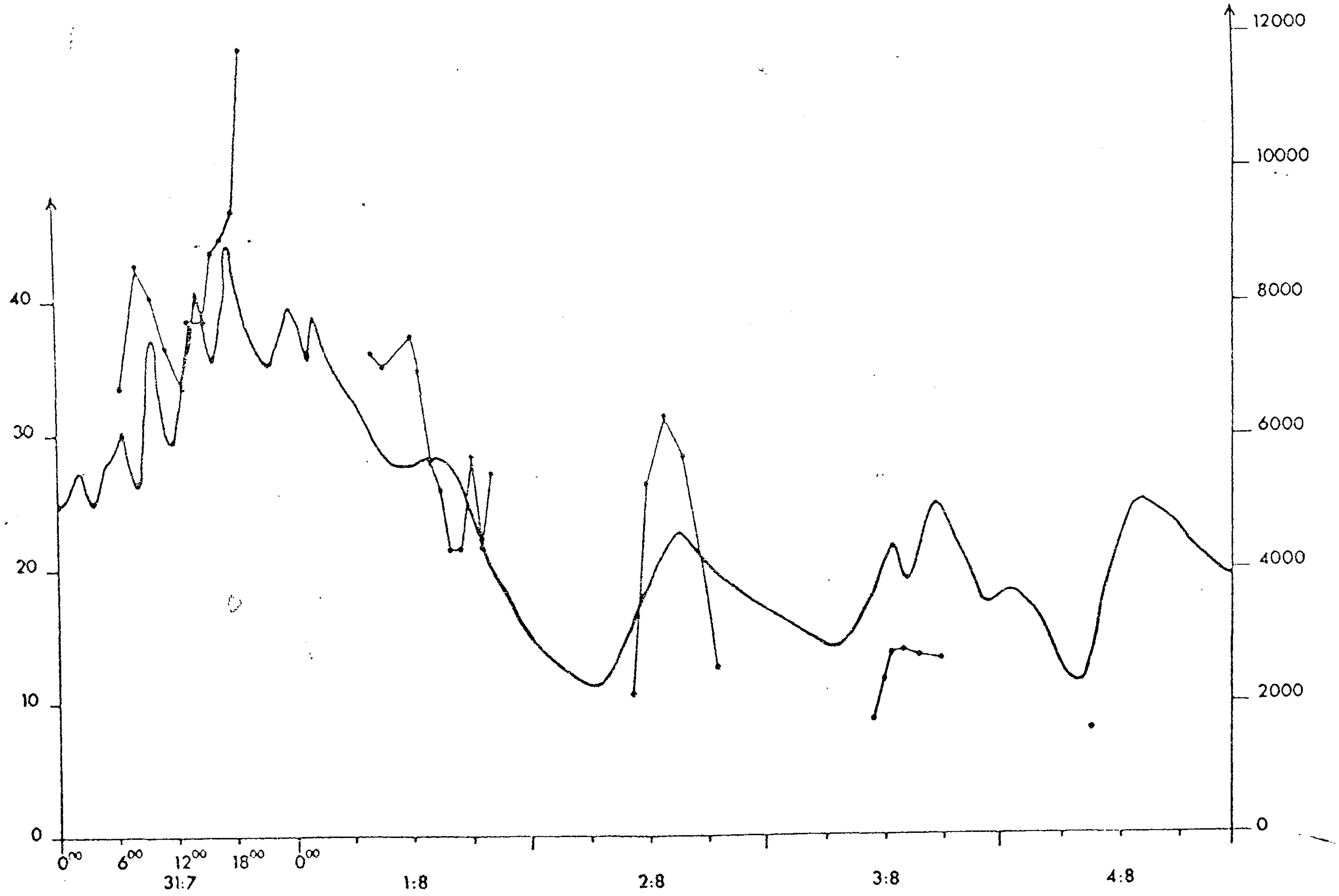


Figure 5.3 Temporal variations of discharge and suspended sediment concentration in the Gornera from 26 July - 30 July 1974, before and at the start of the drainage of the Gornersee. Water first escaped from the lake in the afternoon of 29 July.



<u>Figure 5.4</u> Temporal variations of discharge and suspended sediment concentration in the Gornera from 31 July - 4 August, during and after the emptying of the Gornersee. Draining continued until 1 August. No sediment exhaustion was observed during drainage and sediment concentration remained high on 2 August with no reduction at the time of maximum discharge.

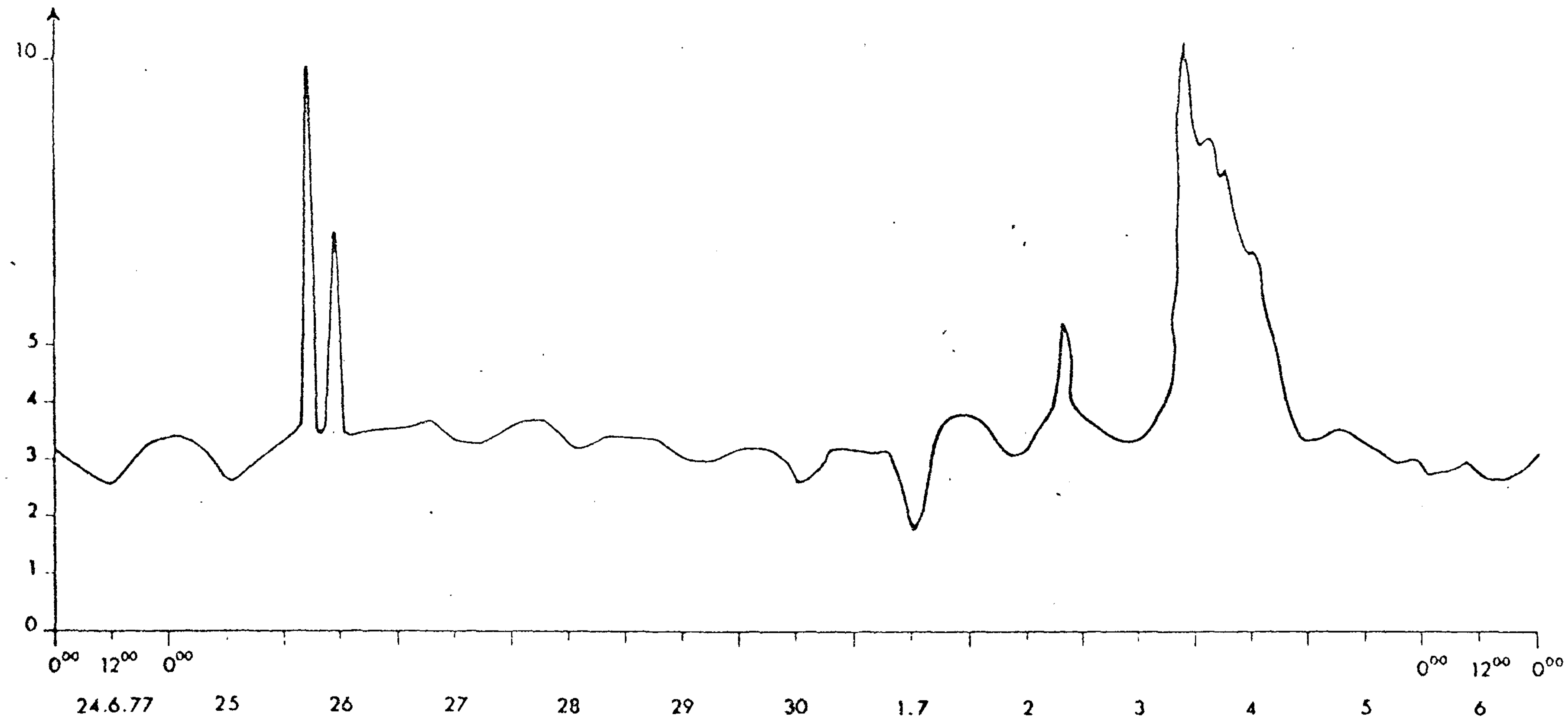


Figure 5.5 Variations of suspended sediment concentration in the Gornera determined by a Partech SDM 10 photoelectric sediment monitor 24 June - 6 July 1977. The scale was uncalibrated and ranges from 0 - 10 (f.s.d.). Occasional sediment 'clouds' were common, recorded here on 26 June and 3-4 July.

5.3.2 Suspended sediment concentration-discharge relationships

In order to assess the nature of sediment supply beneath the glacier and the interaction of water flow with sediments at the bed, the relationship between suspended sediment concentration and discharge was investigated. Suspended sediment concentration-discharge relationships of the form $S_s = a\ Q^b$ where S_s is suspended sediment concentration, Q discharge, and a and b best-fit estimated parameters, were fitted to data collected in 1974, using r^2 as an index of goodness of fit of the model. The range of best-fit parameters and low degrees of fit indicate that the relationship between sediment concentration and discharge in the Gornera is non-stationary, and varies between rising and falling limbs of diurnal hydrographs (Table 5.1). Better fit of this model but applied to relationships between suspended sediment <u>transport</u> and discharge in glacial meltwater streams (Church, 1972; Østrem, 1975) probably results from the use of the statistically spurious association between discharge and sediment transport (Benson, 1965). Use of the master rating curve to estimate suspended sediment concentration for periods when samples are not collected would result in considerable inaccuracy. In non-glacial catchments, gross errors in the assessment of sediment load have been found to arise from the use of sediment rating curves, especially when hysteresis is present (Walling, 1977).

The effects of hysteresis dynamics in the relationship between sediment concentration and discharge in the Gornera are illustrated by rating loops for 18-19 August 1975, cycling in a clockwise direction and including involutions (Fig. 5.6). Clockwise hysteretic loops result from greater concentrations of suspended sediments on the rising limb of the diurnal hydrograph than at equivalent discharges during the falling stage, resulting from the flushing out of sediment collected at margins and beds of subglacial streams during low flows. A distinct loop occurred each day during periods of sustained ablation, often with figure-of-eight subloops and involutions, reflecting irregularity in sediment availability. More regular relationships in which daily peaks of sediment concentration precede discharge peaks by several hours have been shown for glacial meltstreams in Norway and on Baffin Island (Østrem, 1975; Østrem and others, 1967).

5.3.3 Suspended sediment transport

Instantaneous suspended sediment transport (kg s^{-1}) in the Gornera was derived from discharge x sampled sediment concentration for those

TABLE 5.1 PARAMETERS OF THE MODEL $S_s = aQ^b$ FOR SUSPENDED SEDIMENT CONCENTRATION-DISCHARGE RELATIONSHIPS IN THE GORNERA, DETERMINED FOR RISING AND FALLING LIMBS OF DAILY HYDROGRAPHS DURING THE 1974 ABLATION SEASON

Date	Hydrograph limb	Suspended sediment-discharge relationship		
		a	b	r^2
19. 7. 74	Falling	0.10	4.65	0.64
21. 7. 74	Rising	0.13	5.22	0.88
22. 7. 74	Rising	3.47	2.59	0.81
22. 7. 74	Falling	20.76	1.90	0.78
26. 7. 74	Rising	739.52	0.29	0.09
26. 7. 74	Falling	73.11	1.08	0.79
27. 7. 74	Falling	3.62	2.29	0.61
1. 8. 74	Falling	37.45	1.53	0.64
3. 8. 74	Rising	64.20	1.19	0.61
10. 8. 74	Rising	39.10	1.08	0.40
10. 8. 74	Falling	186.79	0.48	0.21
11. 8. 74	Rising	39.81	1.09	0.72
All data	Rising and falling	9.20	1.91	0.78

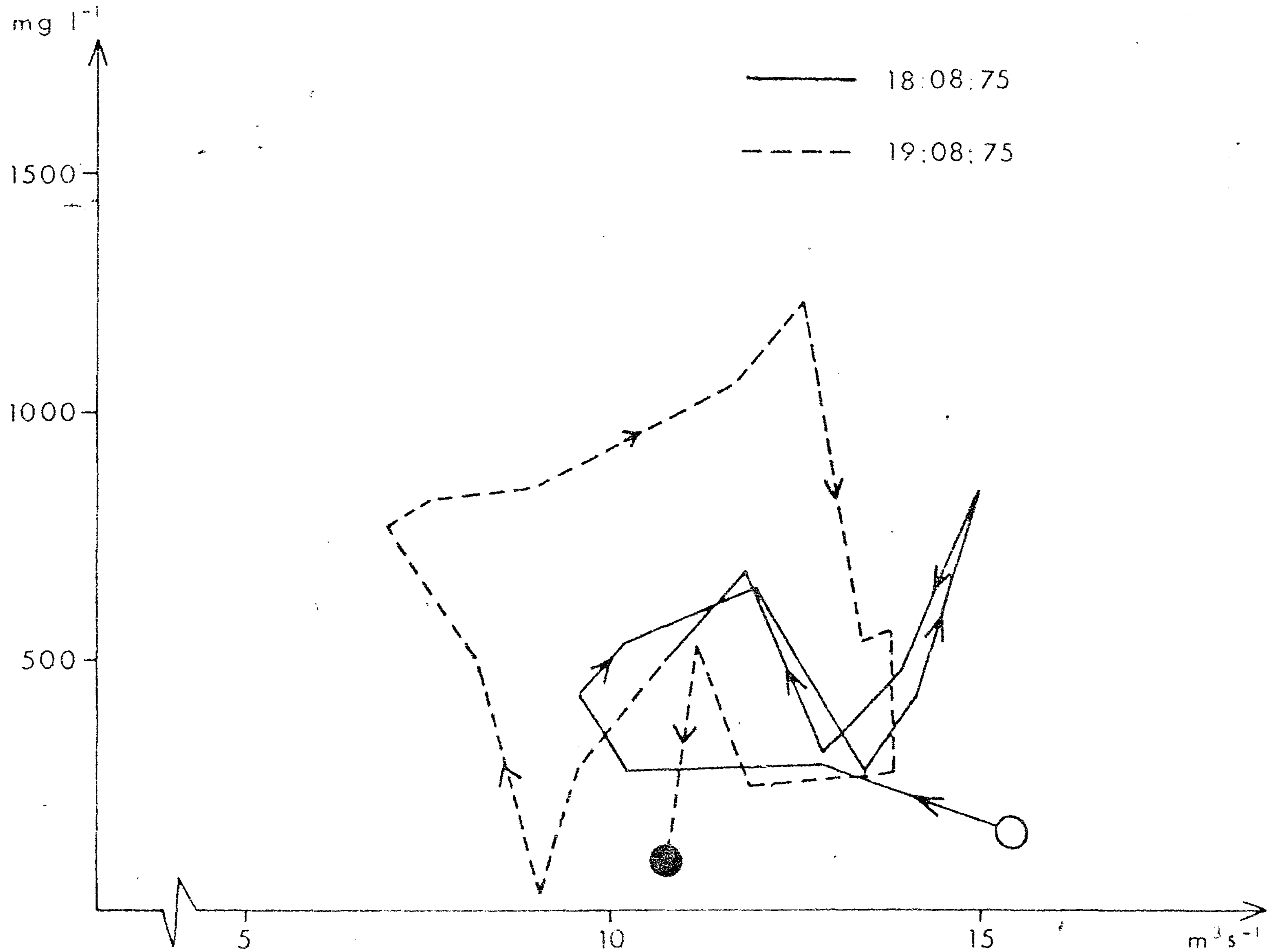


Figure 5.6 Hysteresis rating loops for suspended sediment concentration with discharge in the Gornera for 18 and 19 August 1975. Clockwise loops and involutions occurred on both days.

hours for which data were available. Temporal variation in the evacuation of sediment from beneath Gornergletscher was extremely irregular (Fig. 5.7). Diurnal ranges of suspended sediment transport were variable, and values fluctuated by over 100 per cent in only one or two hour periods. Instantaneous suspended sediment transport ranged between 0.001 and 32.932 kg s^{-1} during the study period (20 July - 2 September 1975). Greatest sediment transport rates were associated with lower flows of the diurnal regimen of discharge.

Daily totals of suspended sediment transport in the Gornera were calculated from those calculated hourly instantaneous values available for each day in 1975 (Fig. 5.8). Daily total sediment transport was variable, with a minimum during the sampling period of 9.63 tonnes during recession flow, to a maximum of 1170.51 tonnes during a period of sustained ablation. Some exhaustion of sediment supply was observed in late August, but low suspended sediment transport resulted from the occurrence of low discharges following summer snowfall. Subsequently, sediment transport was restored as flow increased but never rose to former levels. A significant proportion of the total transport during the observation period was achieved on several days with unusually high sediment concentrations, though not necessarily high discharges. Some inaccuracy in these data results from the lack of availability of samples for every hour throughout each 24h period.

5.4 Discussion

5.4.1 Rapid temporal variations of suspended sediment concentration

Rapid erratic fluctuations of sediment concentration may result from samples unrepresentative of conditions in the Gornera at the time of collection. Occasional random inclusion of a few large sediment particles, which account for a large proportion of sample weight, may introduce apparent increases of sediment concentration not experienced in the stream. At higher discharges, when larger particles become suspended, sediment concentration may be overestimated by samples. Rudolph (1961) calculated centre-weighted averages from values adjacent to each data point to smooth temporal variations of sediment concentration, but data have not been filtered in this study. Sudden variations in concentration were also detected by the photo-electric monitor, suggesting that some, if not all, erratic behaviour characterises sediment dynamics in the Gornera. Such rapid fluctuations characterise meltstreams as they have been

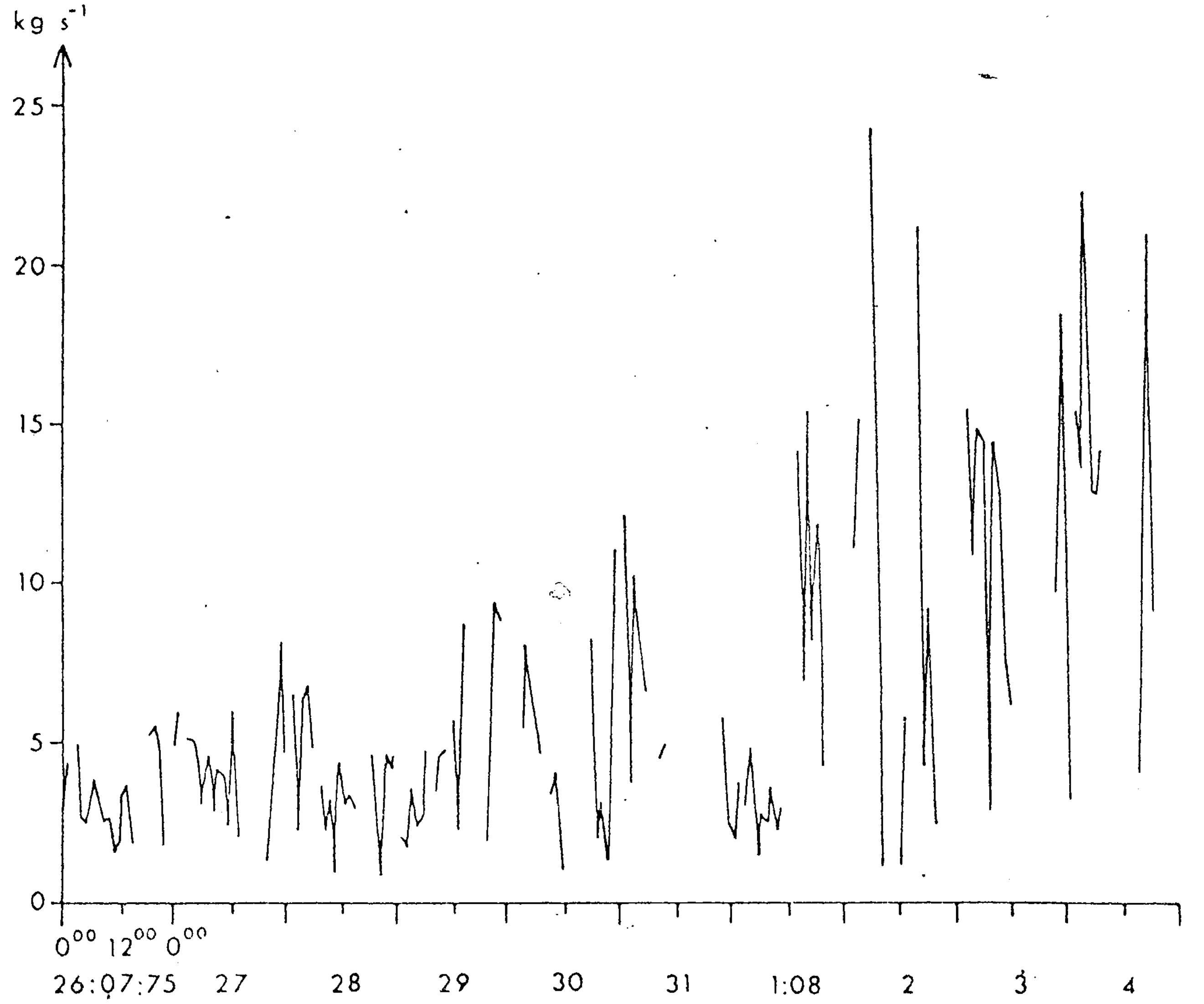


Figure 5.7 Curve of suspended sediment transport in the Gornera from 26 July - 4 August with instantaneous suspended sediment measurements connected only for sequential hourly determinations. Extreme irregularity in suspended sediment transport results from variations in sediment concentration.

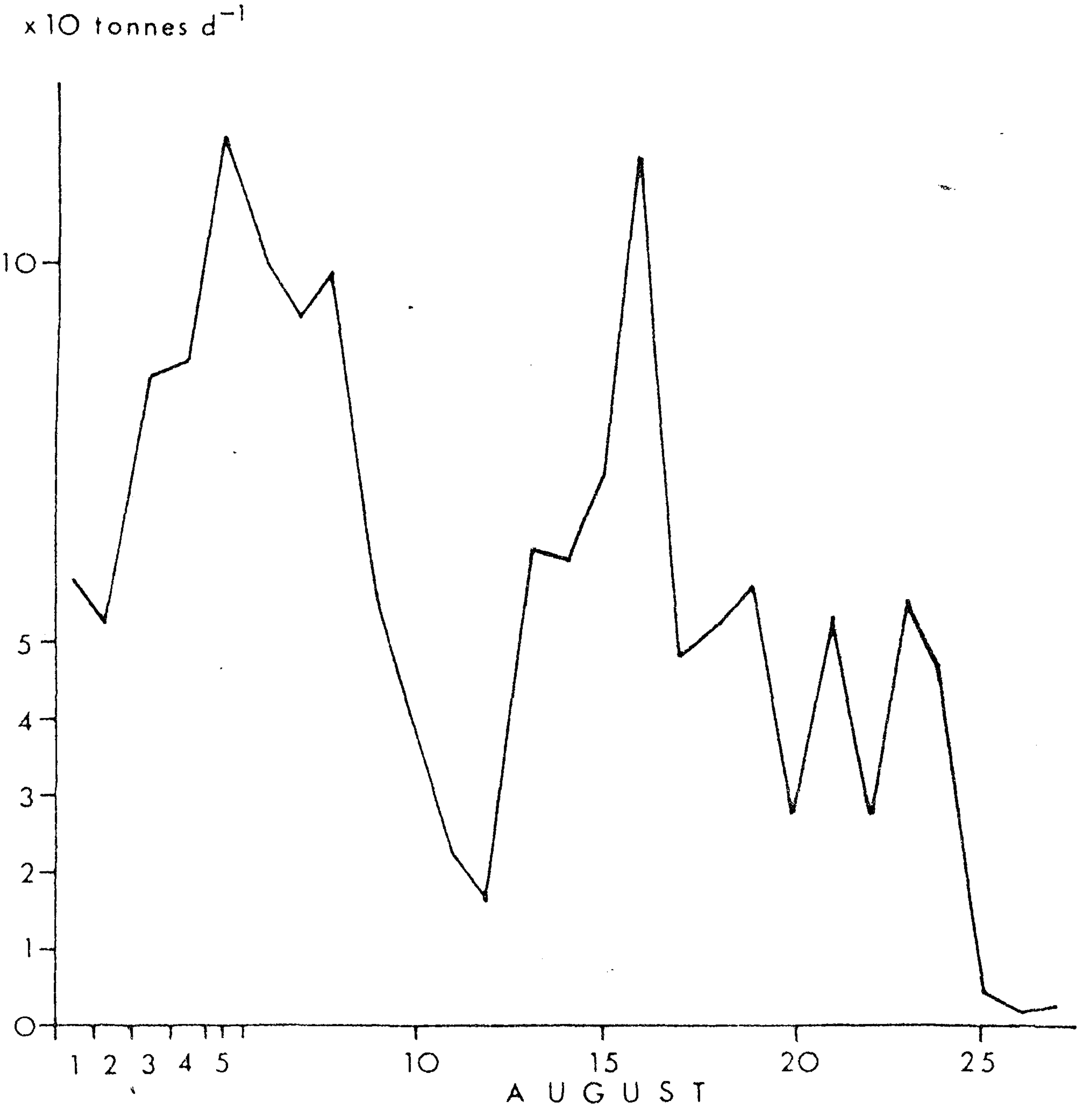


Figure 5.8 Fluctuations of total daily suspended sediment transport in the Gornera 1 - 27 August 1975.

observed also by Mathews (1964) at Athabasca Glacier, Canada, and by Østrem (1975) at Nigardsbreen, Norway.

Sudden large magnitude variations of sediment concentration suggest subglacial instability beneath Gornergletscher. Random injection of sediment impulses may result from migration of basal streams during re-organisation of subglacial drainage channels. Sediment impulses were often associated with the presence of large quantities of cobble-sized ice particles floating in the Gornera, suggesting that re-organisation is of a sufficiently large scale to fracture large volumes of basal ice. During migration, channels impinge on unworked pockets of sediment stored at the ice-rock interface, providing ready but short-lived supplies of sediment load. Slumping from unstable morainic conduit margins may also produce sudden increases in sediment concentration followed by rapid exhaustion.

5.4.2 Subglacial sediment transfer processes at Gornergletscher

Temporal variations of suspended sediment concentration and transport and concentration-discharge hysteresis relationships suggest that the overall rate of sediment delivery to the subglacial hydrological system is variable on a diurnal basis and from day to day during the ablation season. Subglacial streams flowing in large arterial conduits probably incised into bedrock (Röthlisberger, 1972) should transport all sediment supplied to them, and higher discharges of the diurnal regimen ensure sediment removal from major pipes of the hydrological network. Supply of sediment to the hydrological system from sites of production by erosion over wide areas of the glacier bed is probably achieved through smaller unstable conduits tributary to the arterial network.

Since basal moraine may consist of material incorporated in ice and as layers between ice and bedrock, relative movement of ice by sliding and channels by melting of their walls during expansion and migration provides sediments to the smaller subglacial streams by changing contact zones. The thick basal layer of sediments under Gornergletscher (Bezinge and others, 1973) would provide a reservoir of sediment for supply to streams, and may be contributed by deformation into conduits, particularly at times of low water pressures, under the hydrostatic pressure of overlying ice. During the highest diurnal discharges in late afternoon, the rate of sediment supply fails to maintain the concentration in increasing volumes of flow suggesting that increased shear stress at conduit margins is offset by increased volume - wetted perimeter ratios.

Disproportionate increases in flow volumes in channels incised in bedrock over those in smaller conduits, or stable sedimentary margins to conduits, would account for decreased sediment concentrations at high discharges. However, low flow sediment contributions and rapid variations of concentration point to conduit margin instability, and suggest a flow-related reduction in the rate of sediment supply. Increased water pressure during high discharge may lessen the amount of deformation of basal sediments into conduits and some water may be forced into bank storage in basal moraine, to be returned later, during lower discharges, aiding collapse of conduit margins. Superimposed on this basic flow-related pattern, sudden conduit course migrations, probably initiated by blocking of conduits by sediment accumulation or by collapse of ice-walls, integrate unworked zones of sediment with water flow.

5.4.3 Subglacial processes during drainage of the Gornersee

The rate of supply of sediment to subglacial streams increased throughout the emptying of the Gornersee. Enlarging conduit capacities during draining caused by melting of icewalls (Röthlisberger, 1972) would expose a decreasingly small area of sediments to possible entrainment relative to increasing discharge causing sediment concentration in meltwaters to peak and begin to decline before the time of maximum discharge. The large and sustained increase in sediment concentration throughout the rising flow of the lakeburst suggests a major change in the subglacial drainage network, with the probable creation of many new channels beneath Gornergletscher or the possibility of flooding of the glacier bed. Continued expansion of the network over wider areas of the bed permitted continuing contact with unworked zones of sediment throughout this major drainage event.

5.5 Conclusion

Investigation of temporal variations in sediment concentration in meltwaters and its relationships with discharge provides a useful method of sampling subglacial conditions in the vicinity of conduits dispersed over large areas of a glacier bed, from which the nature of subglacial sediment transfer processes and hydrological networks can be inferred. Although meltwater has a significant role in sediment evacuation from the ice-bedrock interface at Gornergletscher, away from conduits, material not in transit in ice is accumulated in a thickness of subglacial moraine.

Sediment concentration in meltwaters depends on sediment supply and hydrological conditions. Most sediment is delivered to the smaller unstable conduits in the basal drainage network. Since it is unlikely that the rate of sediment production by erosion equals the rate of sediment transport by meltwaters, expressed per unit area of glacier bed, accurate estimation of the rate of glacial erosion requires detailed close-interval samples of sediment concentration in meltwaters over many annual cycles of discharge.

A basal hydrological system beneath Gornergletscher of small unstable conduits leading to major arterial Röthlisberger-canals incised into the bed is suggested. Unstable conduits may change locations rapidly and frequently. During the draining of the Gornersee, the subglacial conduit network drastically changed, and water spread into new positions on the glacier bed. This suggests that the draining of the lake occurred subglacially, but may not have enlarged existing channels. Instead, new channels were probably created, by waters forced along the ice-rock interface by high pressures in conduits. The same mechanism forcing meltwaters during highest discharges each day out of conduits may account for sudden decreases in sediment concentration with rising flows. Sediment is prevented from reaching conduits under these conditions by water flowing down a temporary hydraulic pressure gradient from the conduits to the surrounding areas of bed.

6. H Y D R O C H E M I S T R Y O F M E L T W A T E R S

I: METHODS AND EVALUATION OF TECHNIQUES

6.1 Introduction

The chemical composition of glacier runoff is of interest from several viewpoints. Not only has chemical weathering been demonstrated to occur beneath Alpine glaciers, but analyses of calcium (Ca^{2+}) and silica (SiO_2) concentrations in subglacial meltwaters from Glacier d'Argentiere, French Alps, also show enhanced solutional activity in winter (Vivian and Zumstein, 1973). The relatively high concentration of solutes in winter discharge from glacier snouts has suggested the existence of subglacial groundwater systems, although the question of the contribution of spring waters beneath temperate glaciers remains undetermined (Lütschg and others, 1950; Stenborg, 1965).

Rainwater and Guy (1961) considered that solutes were contributed to meltwaters during seepage into silty till, with some contribution from the ice-rock interface, suggesting a two-component sub-division of total flow into water passing slowly through the ground environment, and meltwater and precipitation running off rapidly, without undergoing chemical change. Diurnal variations of solute concentration in waters of the portal meltstream reflected the dilution by relatively pure meltwaters from ablation during the day of slower-moving water percolating through moraine where it had become chemically enriched. The variation of meltstream composition resulted from changing proportions in the total discharge of water flowing from different hydrochemical environments.

In Baffin Island, increasing glacierisation of catchments appears to be associated with increased concentration of dissolved materials, some derived from the ground environment around and under the ice, and some added from suspended sediments (Church, 1974). Diurnal variations of solute content in glacially-fed streams have been indicated by only occasional short term investigations during 24h periods (Rainwater and Guy, 1961; Behrens and others, 1971; Church, 1974). Reynolds and Johnson (1972) attempted to derive the annual rate of chemical weathering in a glacierised catchment from dissolved loads of the meltwater stream.

Meltwater chemistry is also important at the ice-bedrock interface, where both quantity and quality of subglacial water affect the dynamics of glacier movement. Accretions of precipitates of calcite on the beds of Alpine glaciers (Ford and others, 1970) and of silicate deposits (Hallet, 1975) suggest that the concentrations of solutes in meltwaters at glacier soles reach high levels. Relatively high concentrations of solute at the bed will significantly reduce the ice melting temperature and hence the heat flow which is critical for regelation sliding, as recognised by Lliboutry (1971). Hallet (1976) has attempted to quantify the effects of solutes on basal sliding.

This study was designed to provide basic hydrochemical data for meltwaters draining from heavily glacierised catchments, and to investigate the relationships between discharge and chemical characteristics. Comparison with analytical data for other meltwaters was intended to identify environmental variables affecting glacier runoff hydrochemistry. Solute dynamics were investigated with a view to assessing the role of subglacial hydrochemical environments as sources of dissolved load in the runoff from mountain catchments. Chemical characteristics of glacial meltwaters were investigated during the ablation season. In particular, it was hoped that the observations might permit the separation of components of total discharge taking different routes through Alpine glaciers on the basis of their chemical composition. Thus, the chemical characteristics of meltwaters may provide a technique for the investigation of the location, structure and behaviour of glacier internal drainage systems.

6.2 Sampling strategy

6.2.1 Aims

The sampling strategy was designed to overcome two basic problems which were apparent during the first field seasons, 1971 and 1972. The first was concerned with sample preservation, storage and analysis procedures, summarised in the question "What methods are appropriate for accurate determinations of the actual field chemical characteristics of Alpine waters?". The second relates to providing a sufficiently detailed closely-spaced temporal sample collection framework to allow accurate characterisation of the diurnal variations of chemical quality observed by Rainwater and Guy (1961) at Chamberlin Glacier, which are probably present in all meltwater streams.

6.2.2 Background

The choice of sample processing techniques is usually made on the basis of empirical tests. Because of fine rock particles contained in large concentrations in Alpine meltwaters, and their low salinity, samples present problems at several stages in chemical analysis. Similar problems in other waters are not so critical, since suspended sediments are not held in such high concentrations in comparison with those of solutes. Accurate determination of the chemical composition of an Alpine water sample as it was at the time of collection is made more difficult by the long periods of storage time necessary after collection and prior to analysis. Usually, in natural water chemistry samples are transported to the laboratory immediately after collection rather than attempting field determinations by titration or using specific ion-electrode methods. However, Rainwater and Guy (1961) recommended that field measurements of electrical conductivity should be used in future work, in addition to laboratory determinations of major anions and cations. Considerable and variable time delays occur between the collection of individual field samples and subsequent analytical batch processing, enforcing storage for periods of up to three months' duration (Reynolds, 1971; Church, 1974). Chemical changes during storage may result in the samples having contents of dissolved material when analysed in the laboratory which are quite different from those actually present in streams at the time of collection. Altered sample composition may be caused by physical and chemical changes, and by biological processes, the effects of which depend on temperature, exposure to light (Slack and Fisher, 1965), concentrations of sedimentary and organic materials, duration of storage period and the type of storage container (Rainwater and Thatcher, 1960).

For unpolluted waters, the American Public Health Association (1965) suggests a 3d maximum time delay between collection and analysis. Field determinations of pH, alkalinity and specific conductance were shown to be generally higher than laboratory determinations of the same variables made within one month of the time of collection for samples of waters from non-glacierised Californian and New Jersey watersheds (Roberson and others, 1963). Field determinations were considered more representative of the waters in their natural environments than the laboratory measurements. Johnson (1971) found that adequate representation of the chemical composition of river water could be achieved by laboratory determinations, provided that pH and conductivity were measured as soon as possible on return from the field. Other analyses should have been completed within six days, though Johnson (1971) noted that precipitation of solutes and settling of fine suspended material would affect results.

Comparative results of analyses of pairs of samples of meltwaters from Alaskan glaciers, one of each of which was immediately passed after collection through a 0.22 µm millipore filter in the field, were given by Slatt (1972). All were stored at room temperatures for between 2 and 120d, those with included sediment being occasionally agitated, and then filtered before analysis. Increased ionic concentrations in the samples stored unfiltered suggested that partial dissolution of suspended load occurred during storage, and that immediate field filtration of samples is essential for accurate determinations of the chemical composition of glacial meltwaters. No evidence was found to suggest that cation exchange reactions were important. The dominant ion in Alaskan meltwaters, Ca^{2+}, also showed the greatest absolute increases in concentration during storage.

Not only are Alpine waters stored for longer periods than samples from most other environments, they also suffer temperature changes after collection at field temperatures usually in the range 0.1 - about 10.0° Celsius. In storage, they may pass through room temperature (20°C), refrigeration (3-5°C) to be deep frozen (-18°C). The rates of solution of particulate material will increase with increasing storage temperature, whereas dissolved gas content decreases. The greatest percentage changes probably occur in the first few days of storage. Golterman (1969) recommended freezing to prevent changes in samples due to temperature fluctuations, precipitation of ions and biological activity. However, Rainwater and Thatcher (1960) state that freezing should be avoided, since the original chemical character of the water may not be completely restored when the sample thaws.

Separation of suspended material from ionised constituents in true solution in water samples is particularly important in glacial meltwaters. Membrane filtration of particles larger than about 0.5 µm under pressure or vacuum separates suspended from dissolved constituents, but releases nitrogen, phosphates and organic compounds from the membrane to the filtrate (Golterman, 1969). Colloidal particles may remain in suspension, having passed through the filter membrane, and analytical assay will tend to represent the total ionic concentration in the fraction of the total sample taken, regardless of whether the constituent is in solution or suspension (Rainwater and Thatcher, 1960).

During even short processing times cations adsorbed on the surfaces of mineral particles are able to migrate into solution (Souchez and others, 1973). This desorption mechanism, of which ion-exchange is a special case, can affect water samples at the time of separation and during storage.

Sediments in suspension may play an important part in determining the chemical composition of meltwaters. Lorrain and Souchez (1972) showed that significant proportions of the major cations transported from Moiry Glacier, Switzerland, were adsorbed on the surfaces of suspended sediment particles. Partial dissolution of suspended load was shown to release ions to meltwaters by Slatt (1972), and was suggested as an important source of solute in streams draining from active glaciers (Church, 1974).

During instrumental analysis of Alpine waters by atomic absorption spectrophotometry, fine particulate material may be aspirated into the flame, where it contributes to the absorption due to ions in true solution. Results of comparative analyses by atomic absorption and ion-selective electrode methods for Na^+ and K^+ showed higher ionic concentrations in determinations by atomic absorption (Reynolds, 1971). The samples contained noticeable turbidity, but suspended sediments had settled out by the time of analysis, three months after collection. Fine silt at concentrations up to 200 mg l^{-1} caused no measurable effect on electrode response. Reynolds and Johnson (1972) considered that atomic absorption data for glacially-derived waters were so unacceptably high that the determinations were eliminated from further consideration. For waters transporting no glacial sediments, significant discrepancies between atomic absorption and ion electrode methods averaged ± 13 per cent for both Na^+ and K^+, which suggest error from some source other than aspiration of colloidal sediment into the flame.

A water sample should be collected, stored and analysed in such a way that the final laboratory determinations of its ionic content provide accurate representation of the chemical composition of the hydrological environment from which the sample was taken. While the precision of analytical methods can be assessed by replicate laboratory determinations, estimation of accuracy is more difficult. If the effects of storage were uniform for all samples, then systematic error would be present but concealed. The removal of such a possibility is difficult unless complete sample analysis can be performed in the field. Reynolds and Johnson (1972) made a comparison of the chemical stability of Alpine water samples in storage in terms of concentration of HCO_3^-. Titrations in the field and in the laboratory some months later were highly correlated, increases of concentrations of bicarbonate ions during storage being about 5 per cent of the field measurement.

6.2.3 Choice of parameters and procedures for sample processing

Electrical conductivity was selected for use as a measure of the total dissolved solids content of meltwaters, since it can be determined with portable field instruments, and is suited to continuous monitoring in the field for observations of temporal variations. It was realised in 1972 that samples collected every hour for a few 24h periods in a field season could not be used to characterise the range of diurnal variations of meltwater chemical composition. Preliminary tests at Hintereisferner, Ötztal Alps, Austria, suggested that conductivity was a useful indicator in studies of glacial hydrology (Behrens and others, 1971).

Leaching of solutes from filter papers of different types into double-distilled de-ionised water was investigated in the laboratory. Cellulose acetate papers, nylon membranes and glass-fibre papers were investigated. Oxoid 0.45 μm membrane filters were selected as the least undesirable, with a pore diameter small enough to remove fine sediments. Refrigeration was all that was possible for storage of water samples before analysis. Storage periods were different for all samples within an analysis batch. Atomic absorption spectrophotometry was the only technique for chemical analysis available in the laboratory. Hence, only cations were determined in the laboratory analyses, although analysis of anions would have enhanced the value of the study. The major cations, Na^+, K^+, Ca^{2+} and Mg^{2+}, were selected for analysis.

6.2.4 Sampling programme

Several samples were collected from the two meltstreams draining from the Nordzunge of Feegletscher in the summer of 1972, in order to evaluate measurement techniques. Subsequently, refined techniques were used in a preliminary investigation of meltwater chemistry in the Gornera between 20 July and 12 August 1974, when the measurement and processing techniques were again evaluated. A comprehensive field programme was undertaken during the summer ablation season of 1975 from 15 July - 2 September, at Gornergletscher, with some subsequent observations in that catchment. Electrical conductivity was continuously monitored on the

Gornera at a site 250m from the glacier portal and on a major supraglacial stream on the Gornergletscher. Samples of meltwaters representative of major hydrochemical environments were collected for field determination of conductivity and subsequent laboratory analysis of the major cations. The role of suspended sediment in meltwater chemistry was investigated, on account of its interest as a source of solute (Slatt, 1972) and its citation as a cause of interference in atomic absorption spectrophotometry (Reynolds, 1971).

In 1977, electrical conductivity of meltwaters in the Findelenbach was recorded continuously at a site 20m from the ice margin, from 1-24 August. Samples of meltwaters were not collected for laboratory analysis. At all glaciers, samples were collected, and continuous recording apparatus located so as to minimise the influence of runoff from the non-glacierised parts of the catchments on solute contents of the portal meltstreams.

6.3 Measurement procedures

6.3.1 Electrical conductivity

At all stations at which continuous measurements of electrical conductivity were recorded, the identical instrumentation was used. Conductivity was determined with a Walden Precision Apparatus CM 25 conductivity meter to which was attached a Sproule electrolytic dip cell. The cell (constant = 1.0) of carbon electrodes in a resin probe was positioned to remain always in the turbulent main flowline of the stream away from boulders in transit on the bed. Frequent removal for inspection ensured that no suspended sediment became deposited in the cell. The calibration of the cell was checked against 0.01 M KCl at 25°C before and after the field observations, and showed no change through time. A Rustrak model 288 6v portable chart recorder was harnessed to the conductivity meter. Chart time-keeping and levels of battery charge were checked daily. A shielded thermistor was located on the steam-bed, and temperatures recorded at 3h intervals.

Field electrical conductivity of samples was also determined with a WPA CM 25 conductivity meter, equipped with a range of accurately calibrated platinum-electrode glass dip cells. The observed electrical conductivity in the field was determined in the presence of suspended sediment load.

6.3.2 Sample treatment and analytical methods

Samples of meltwaters from the Gornera were collected frequently at most stages of flow during the observation periods. Samples were also collected occasionally from meltwaters on the surface of Gornergletscher (Fig. 6.1). Samples were collected from the fastest-flowing streamline at all sites to ensure complete turbulent mixing. Samples were taken and stored in polyethylene bottles, which were pre-washed in double-distilled de-ionised water. Immediately on collection, at a temperature less than about 3^{o}C, the electrical conductivity of a sample was determined. The sample was then filtered through a pre-washed Oxoid 0.45 μm membrane, in a washed perspex cylinder, under the pressure of three or four strokes of a bicycle pump. A storage bottle was washed with the first small quantity of filtered sample, which was discarded, before collection of about 300 ml of filtrate. The samples were refrigerated for periods of between two days and two months after collection, before return to the laboratory for analysis.

In order to evaluate the effects of suspended sediments on solute content, many samples were collected in duplicate. One sample of each pair was immediately filtered in the usual manner following collection. For some samples, conductivity was measured before and after filtration. The unfiltered samples were vacuum-filtered in the laboratory, through pre-washed Oxoid 0.45 μm membranes, immediately prior to analysis.

In 1972, samples of meltwaters were not filtered in the field, but after storage at temperatures beneath 10^{o}C for periods between 7 days - 3 months, they were filtered through Whatman GF/C glass fibre filters, of initial penetration pore size 2.0 μm, before analysis.

In the laboratory, the filtered samples were analysed for sodium, potassium, calcium and magnesium by atomic absorption spectrophotometry. Samples from 1972 and 1974 were determined with an Evans Electroselenium 240 atomic absorption spectrophotometer, and from 1975 using a Perkin-Elmer 403 instrument, in both cases operating under standard conditions. All material passing through a 0.45 μm filter membrane is defined as dissolved, and was subjected to assay in these determinations. To assess reproducibility of results, multiple replicate determinations were made on aliquots of the same sample, for each of several samples.

6.4 Evaluation of analysis techniques

6.4.1 Conductivity measurements

Comparative results of conductivities of samples determined before

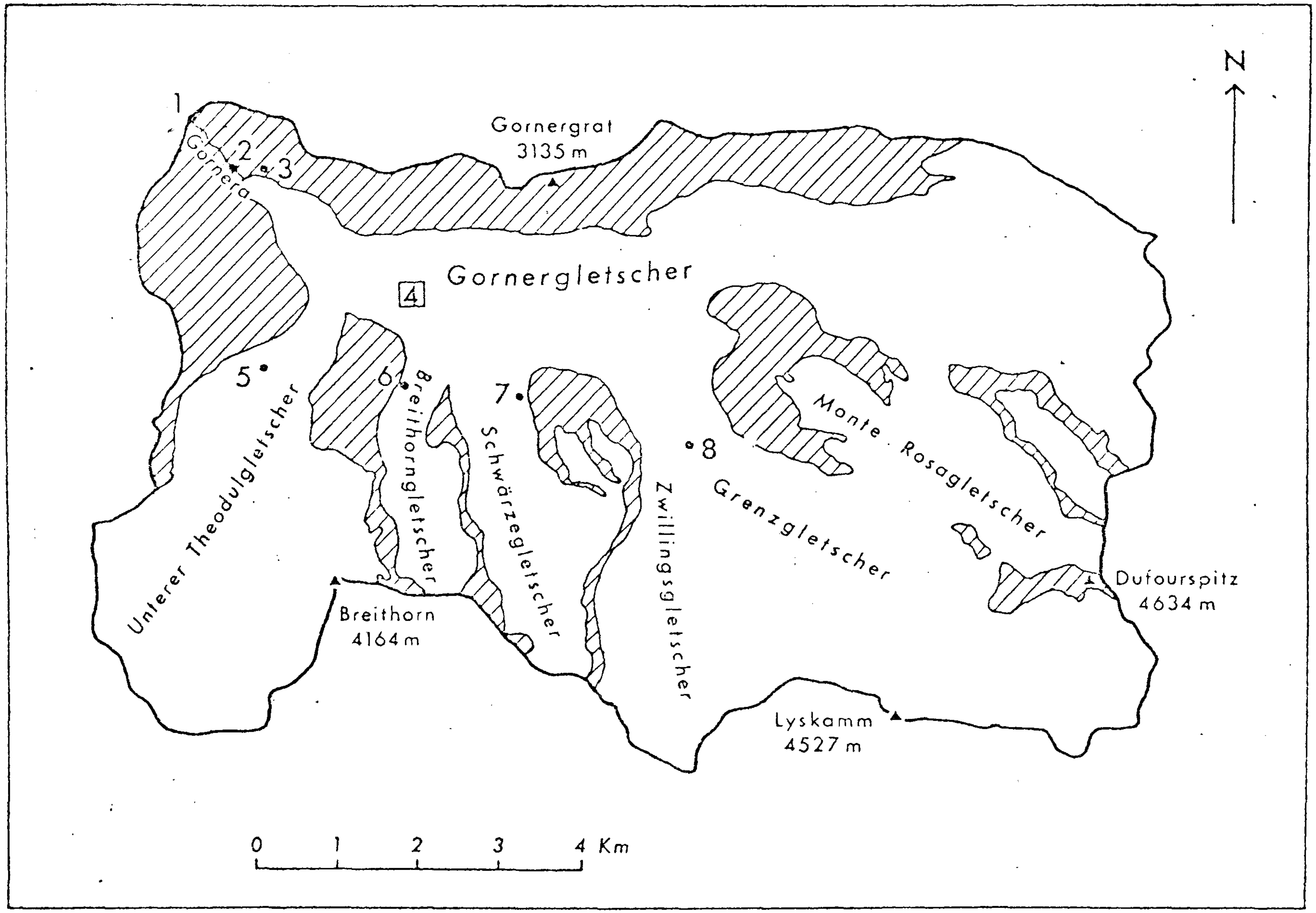


Figure 6.1 Map of the Gornergletscher catchment area showing locations of sampling sites: 1. Prise d'eau 2. Measurement site on Gornera 3. Seepage in lateral moraine 4. Surface icemelt streams on Gornergletscher 5 - 8. Supra-glacial sampling sites.

and after filtration in the field are shown in Figure 6.2. A point located above the 45° line represents a pair of measurements in which conductivity determined after filtration was greater than that of the unfiltered sample. For the majority of samples conductivity increased during filtration, and in no case reduced. The increases range from 2.4 to 47.8 per cent ($\bar{x}$ = 18.0 per cent). Increases of such magnitude are unlikely to result from leaching of ions from filter membranes, and although samples warmed up during the filtration process, all determinations were made at the same temperature. A probable explanation is that ions become desorbed from the surfaces of sedimentary particles collected on the membrane during the filtration process (Lorrain and Souchez, 1972). As continuous monitoring of conductivity had to be undertaken in sediment-laden waters, all conductivities reported in this study are determinations of unfiltered waters. Laboratory tests showed that interference by suspended sediment on measurements of conductivity was negligible. Facilities for the analysis of dissolved gases were not available, and the probable minor effect of dissolved CO_2 on conductivity measurements was not investigated.

Because electrical conductivity increases with increasing temperature, it is usual to standardise measured values to a reference temperature (18°, 20° or 25°C). Filtered samples should be warmed to the reference temperature on water baths before measurement in laboratory determinations (Mackereth, 1963; Allen and others, 1974). For measurements made at field temperatures, it is usual to use tables of correction factors based on the temperature-conductivity curves of 0.01 M KCl and $NaNO_3$ solutions (Golterman, 1969), or to use a conductivity meter which automatically compensates for temperature. Both methods assume increases in conductivity of about 2 per cent per degree Celsius. Tabled correction factors are usually presented for measurement temperatures 3-30°C, and give standardisation approximately equivalent to that derived from:

$$C_{25} = 1.02\ C_t^{(25-t)} \qquad (6.1)$$

where C_t is measured conductivity at temperature t°C, and C_{25} standardised conductivity at 25°C.

The rate of increase is greater than 2 per cent per degree at low temperatures, especially near the freezing point 0°C, and also varies for different meltwaters (Østrem, 1964). In order to determine correction factors, conductivity and temperature were measured on 13-litre samples of meltwaters from the Gornera and a surface icemelt stream on the

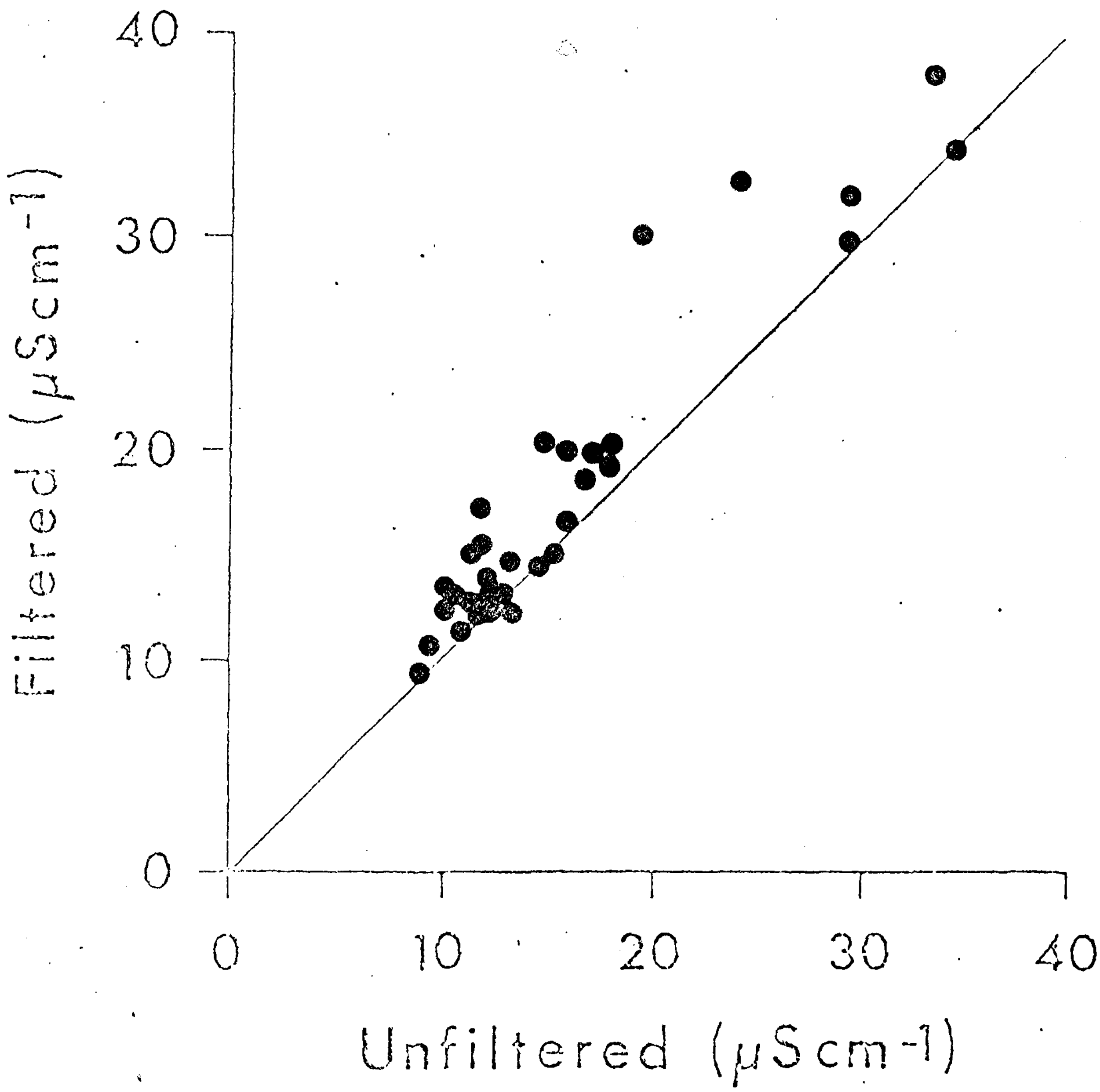


Figure 6.2 Comparative determinations of electrical conductivity of samples of meltwater from the Gornera before and after filtration. For explanation see text.

Gornergletscher were warmed and stirred in polyethylene containers. Small sub-samples were collected during the warming procedure for analysis of the major cations.

On warming, all samples increased in conductivity at a rate greater than expected from the usual correction factors for natural waters (Fig. 6.3). Both filtered and unfiltered samples showed increases at the same rate. The highest percentage increases per degree were shown by supraglacial meltwaters, containing no detectable suspended sediment. Samples of the same meltwaters increased in conductivity at different rates and it was not possible to determine reliable correction factors. Measurements of electrical conductivity are reported in this study at the measured temperature, in most cases between 0.1 and 1.2^{o}C. The maximum error due to temperature variation within this range is about 8 per cent of the determined conductivity. The effect of error is to reduce the diurnal range of conductivity, since temperature varies in phase with discharge. Conductivity meters which automatically compensate for temperature should not be used for determinations of glacial meltwaters. Specimen percentage increases of electrical conductivity during warming up of unfiltered meltwaters from the Gornera (sample 5 of Fig. 6.3) are given in Table 6.1. Large percentage errors would result from attempts to standardise at the conventional temperatures of 20^{o} or 25^{o}C, using usual procedures.

During the warming up of the filtered sample, no change occurred in the concentration of the ions Mg^{2+}, K^{+} and Na^{+}, but a slight reduction of Ca^{2+}. In contrast, Mg^{2+} and Ca^{2+} increased in concentration by 10 and 16 per cent respectively, and Na^{+} decreased 40 per cent in an unfiltered sample (Fig. 6.4). Since the sediment and meltwater formed a closed system, changes in ionic concentration must reflect either cation exchange between water and sediment or sorption phenomena on the surfaces of particles, and accounts for the rates of increase of conductivity observed for unfiltered samples. Particles of suspended sediment finer than 0.45 μm are probably present in the filtered sample.

6.4.2 Storage and filtration of meltwaters prior to chemical analysis

For the pairs of identical samples collected from the Gornera, one of each was filtered immediately after collection, and the other stored unfiltered until immediately before analysis. The results of determinations of Na^{+}, K^{+}, Ca^{2+} and Mg^{2+} of the pair of samples are shown in Figure 6.5. Data points below the 45^{o} line indicate that the sample stored unfiltered

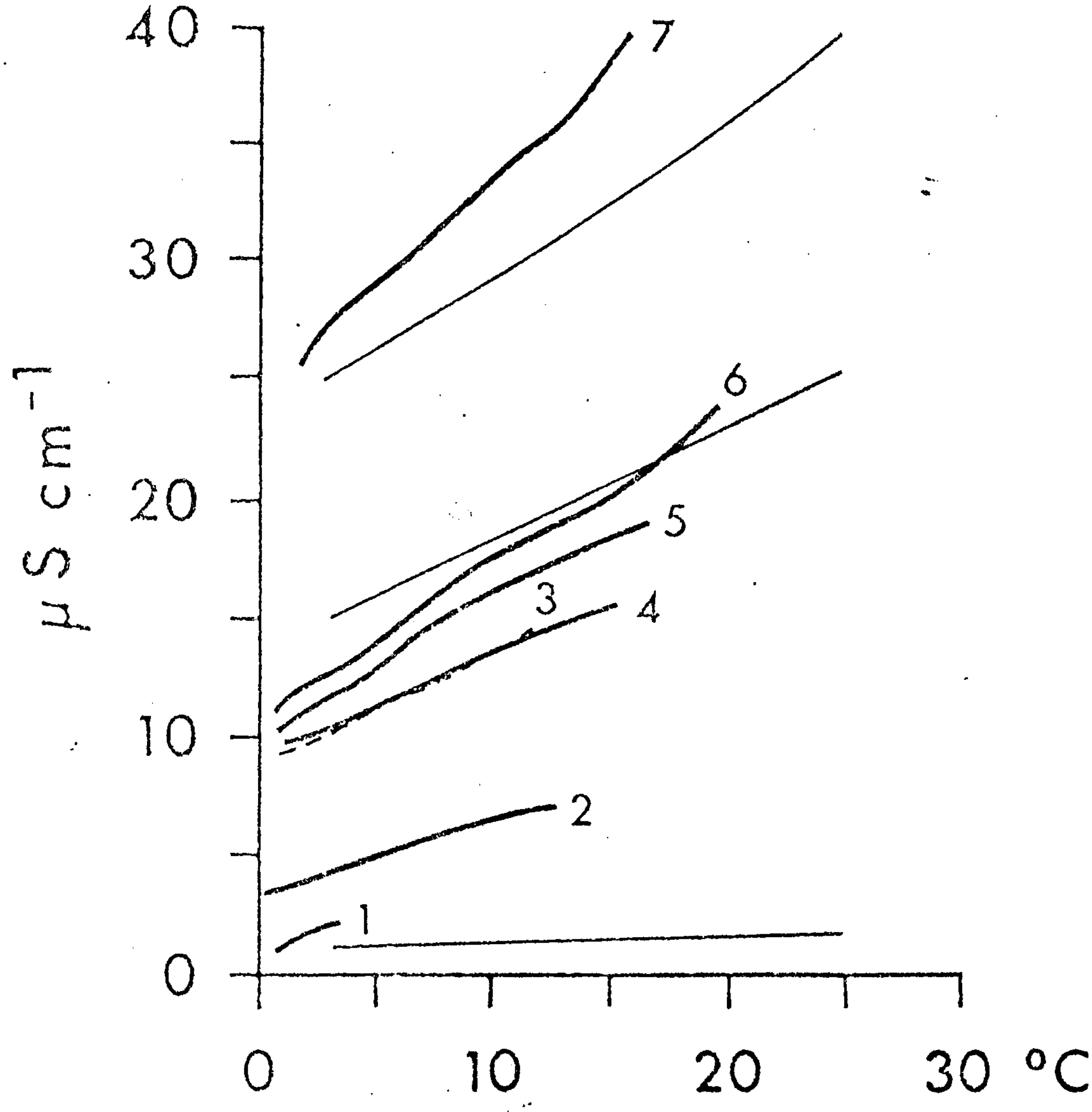


Figure 6.3 Curves showing the increase of conductivity on warming meltwater samples from Gornergletscher sites:
1,2 : unfiltered supraglacial stream waters
3,4 : simultaneous samples from the Gornera, unfiltered (3), filtered (4).
5 - 7: unfiltered meltwaters from the Gornera. The other curves give the increase in conductivity with temperature expected for natural waters (after Golterman, 1969).

TABLE 6.1 PERCENTAGE INCREASE OF ELECTRICAL CONDUCTIVITY FOR UNFILTERED MELTWATERS FROM THE GORNERA WHEN TEMPERATURE IS RAISED 1°C

Temperature change of 1°C from °C	Increase of electrical conductivity %
1	6.1
2	4.1
3	4.0
4	5.3
5	4.3
6	4.8
7	4.6
8	4.4
9	4.2
10	3.5
11	3.3
12	3.7
13	3.1

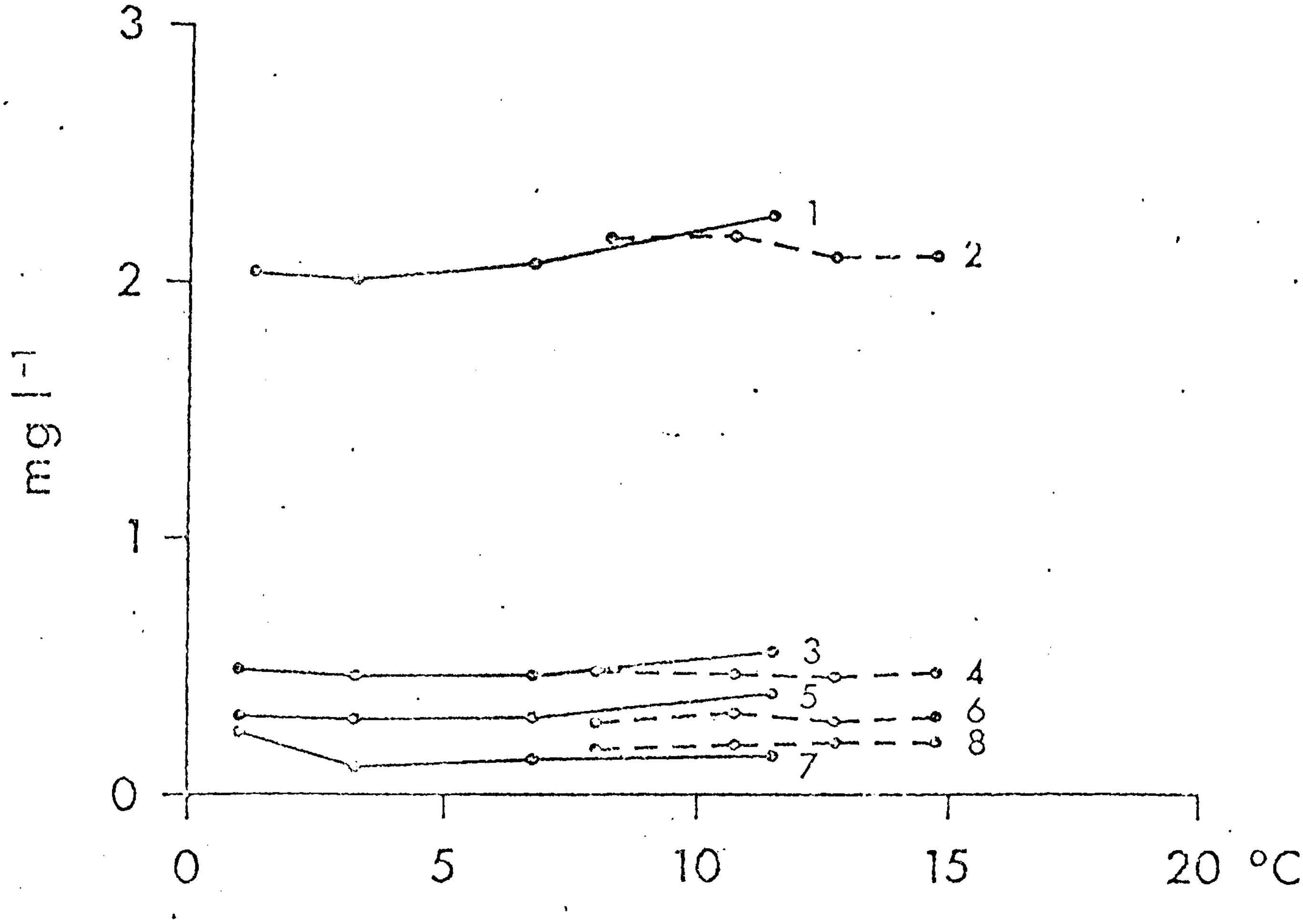


Figure 6.4 Changes in ionic composition of meltwaters from the Gornera on warming filtered and unfiltered samples: Ca^{2+} (unfiltered/filtered) - 1/2; Mg^{2+} - 3/4; K^{+} -5/6; Na^{+} - 7/8.

had a higher concentration of an ion than the other of the pair filtered immediately on collection; points plotted above the line show those filtered samples which had a higher concentration of an ion than the unfiltered. For all pairs of samples, the concentrations of Mg^{2+} and K^+ were considerably higher in the sample stored unfiltered. In the majority of pairs, the concentration of Na^+ was higher in the unfiltered sample, but in some cases it was higher in the sample stored filtered. The concentration of Ca^{2+} was lower in the unfiltered sample in about half of the pairs of samples analysed.

Relative changes in concentrations of individual ions in the waters must be due to interaction with sediments either during filtration, or in the case of unfiltered samples, in storage, though some very fine particulate material may remain in the filtered samples.

Ionic concentration changes could be caused by either partial dissolution of sediment or by cation exchange processes and sorption phenomena. Direct solution would result in relative increases of all ions in the waters stored unfiltered. Solution has been suggested as a process contributing ions to meltwater streams in Alaska (Rainwater and Guy, 1961; Slatt, 1972). Cation exchange reactions or sorption processes would account for relative increases in concentrations of Mg^{2+} and K^+ accompanied by some relative decreases of Na^+ and Ca^{2+}. Lorrain and Souchez (1972) determined that quantities of the major cations were sorbed on suspended sediment particles in meltwater, with greater amounts on morainic sediments at Moiry Glacier. Calcium was found to be the most important dissolved cation in meltwaters and also the most important sorbed on suspended sediments. When morainic particles with sorbed cations come into contact with dilute meltwaters, desorption occurs, and ions are liberated into solution. In the water from the Gornera, Ca^{2+} is also the most important cation. During storage it is probable that both limited solution of particles and some desorption have occurred. In addition, Ca^{2+} and Na^+ ions have either displaced Mg^{2+} and K^+ by cation exchange reactions, or become selectively re-adsorbed on particle surfaces. These processes probably occur beneath Alpine glaciers as the waters come into contact with sediments.

Since desorption phenomena appear to occur during sample filtration, the immediate filtering of meltwaters after sampling will only minimise further changes in chemical composition during storage, and does not ensure that the ionic concentrations in the sample are the same as those in the meltwater stream at the time of collection. The error will be

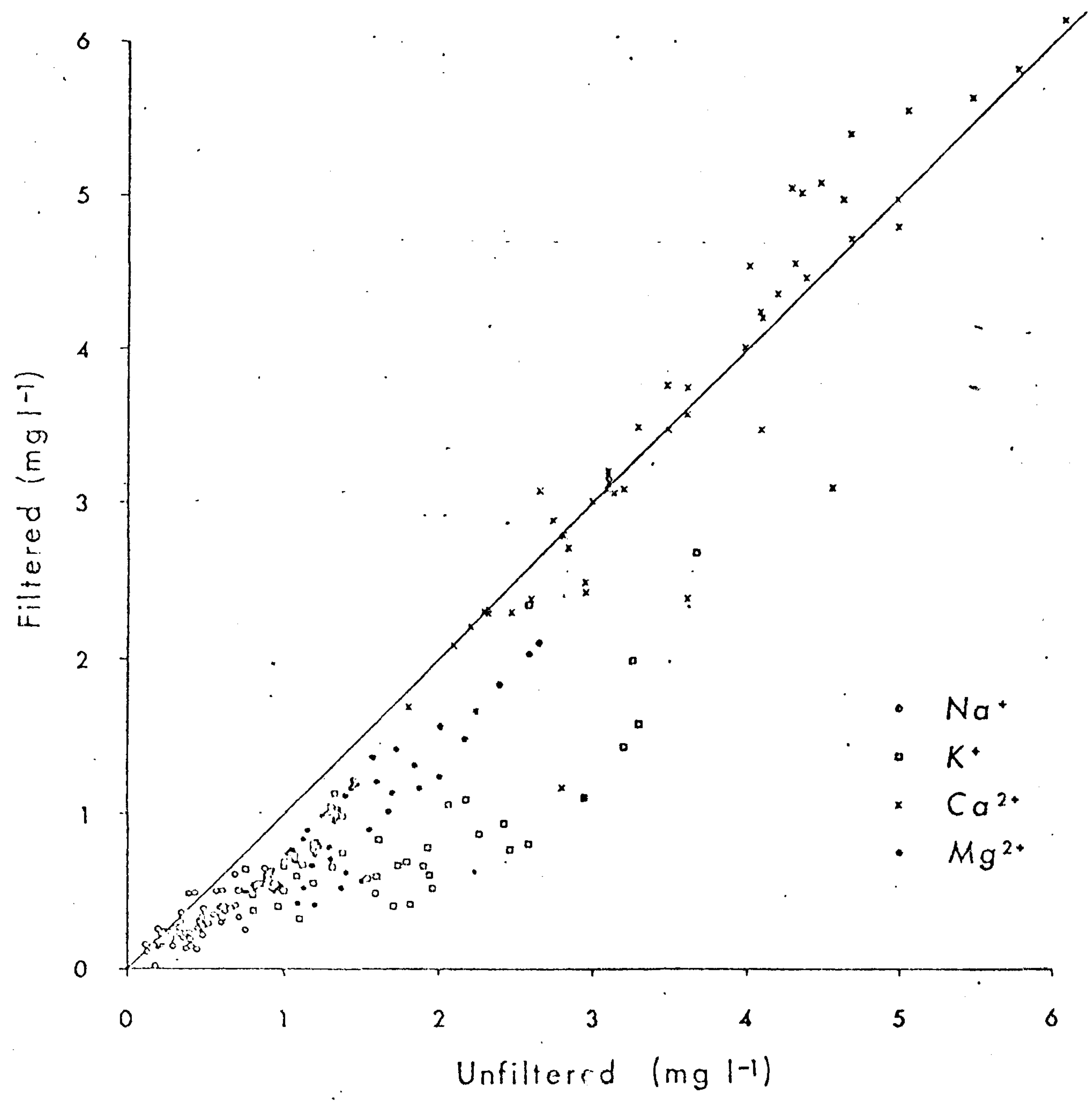


Figure 6.5 Comparative concentrations of the major cations determined for pairs of samples of meltwaters from the Gornera. One of each pair was filtered immediately after collection, and the other stored unfiltered, and filtered immediately prior to analysis. For explanation see text.

non-systematic as desorption occurs according to the law of mass action and is affected by the amount of sorbed ions on particle surfaces, the concentration and particle size distribution of suspended sediment (Kennedy, 1965), and solute content of the meltwaters. In this study, the results of chemical analyses from the Gornera are those performed on samples filtered immediately after collection, whereas from the Feevispa, all samples were unfiltered in the field.

6.4.3 Reproducibility of atomic absorption determinations

Reynolds (1971) determined cations by atomic absorption methods in samples in which suspended sediments had settled out between the times of collection and analysis. It is probable that agitation at the time of analysis caused particles to re-enter suspension, and become aspirated into the flame. In this study, the high reproducibility of results where samples were filtered at 0.45 μm suggests that atomic absorption results are at least consistent (Table 6.2). Replicate determinations were made for several samples and results are tabled for samples with concentrations around the median values for each ion, and averaged results for determinations throughout the range of concentrations of each ion. For samples filtered at 2.0 μm from the Feevispa, replicate determinations showed a much greater range, suggesting that particles between 0.45 μm and 2.0 μm, of which there are many in glacial meltwaters, interfere in atomic absorption spectrophotometry (Table 6.3).

No comparative results from a different analytical technique are available, but it is reasonable to believe that analysis of samples carefully filtered to exclude particles above 0.45 μm provide accurate determinations of the cationic content of meltwaters at the time of analysis.

6.5 Summary

The suspended sediment-solute-meltwater system provides a variety of complex interactions which make chemical analyses of Alpine meltwaters difficult. Further, the interactions which occur during storage and filtration may occur within glaciers, and to some extent determine the chemical composition of meltwaters in proglacial streams. Laboratory investigations of the sediment-water system and further sampling are required to evaluate the effects of sorption by suspended sediments on the chemistry of glacial meltwaters, and on the storage and processing of samples of Alpine waters. Other methods of separation (e.g. centrifugation)

TABLE 6.2 RESULTS OF REPLICATE DETERMINATIONS OF INDIVIDUAL IONIC CONCENTRATIONS IN SAMPLES OF MELTWATERS FROM THE GORNERA, 1975

Ion	Detection limit in atomic absorption spectrophotometry	Concentration range for entire sample batch	Determinations for a sample close to range median ($mg\ l^{-1}$)			Mean results of 2 or 3 replicate measurements on each of several samples throughout range	
	$mg\ l^{-1}$	$mg\ l^{-1}$	$\bar{x}$	σ	n_1	V(%)	n_2
Na^+	0.01	0.1 - 1.0	0.48	0.02	5	2.9	11
K^+	0.02	0.1 - 2.7	0.56	0.05	3	4.7	9
Ca^{2+}	0.10	1.8 - 9.0	4.25	0.11	6	2.3	5
Mg^{2+}	0.04	0.1 - 2.3	0.88	0.03	5	1.2	13

$\bar{x}$ = mean; σ = standard deviation; n_1 = number of replicate determinations; V = coefficient of variation; n_2 = number of samples

TABLE 6.3 REPLICATE DETERMINATIONS OF INDIVIDUAL IONIC CONCENTRATIONS IN A SAMPLE OF MELTWATERS FROM THE FEEVISPA

Ion	Percentage variation from mean	No. of determinations
Na^+	6.8	4
K^+	17.1	4
Ca^{2+}	10.7	2
Mg^{2+}	5.3	4

or field analytical techniques requiring no separation such as portable ion selective electrodes may provide more accurate data, and permit more detailed investigation of changes in chemistry of meltwater between field and laboratory.

7. H Y D R O C H E M I S T R Y O F M E L T W A T E R S
II: MEASUREMENT RESULTS AND INTERPRETATION

7.1 Hydrological and hydrochemical components of runoff in glacierised watersheds

In a catchment comprising predominantly glacier ice and almost bare rock, solutes are derived from two main sources: atmospheric and lithospheric from the bed of the glacier. Both the quantity and chemical composition of precipitation may vary seasonally, spatially and topographically. Atmospheric influences on water may be modified during storage in snowpack and glacier. Then, as water passes through the catchment, it drains through a range of lithological environments, between each of which there are differences in rate and mechanism of solute release. The hydrochemical characteristics of waters derived from different environments are sufficiently diverse to permit some discrimination between waters on the basis of their chemical compositions. Exact characterisation of the hydrochemistry of certain environments is, however, difficult, since some water from other sources is often present. Notwithstanding, snowmelt, glacier icemelt and baseflow sources of flow have been distinguished in an Alpine basin by Zeman and Slaymaker (1975).

The dissolved load of the stream draining from the portal of an Alpine glacier reflects the mixing of waters with different chemical compositions from different environments in varying proportions, in the glacier and from the non-glacierised part of the catchment. Both the actual quantities and relative proportions of runoff derived from the various sources and routed through the different environments vary temporally.

The results presented in this chapter relate only to summer, when the snow-free non-glacierised area contributes to runoff only following rainfall. Temporal variations of the hydrochemistry of meltwaters thus result from processes operating within the glacier.

7.2 Gornergletscher catchment

7.2.1 Electrical conductivity of meltwaters

Chemical composition and electrical conductivity of waters representative of the major hydrochemical environments within the Gornergletscher catchment, with the exception of the Gornera, are shown in Table 7.1. All supraglacial meltwater streams show very low electrical conductivities (0.1 to 2.7 $\mu S\ cm^{-1}$), and very small concentrations of the determined cations. No detectable chemical difference exists between meltwaters derived from snow and ice sources on the glacier surface. Large supraglacial streams have significantly higher conductivity values than the smaller streams. The relatively low conductivity of waters seeping through a lateral moraine above the level of the glacier snout suggest that they are derived from the melting of snow higher on the valley side, although a snowmelt-fed stream just outside the catchment showed a higher conductivity.

A large supraglacial stream on the Gornergletscher, on which continuous monitoring was undertaken in August 1976, showed an almost constant background conductivity of 2.7 $\mu S\ cm^{-1}$ at $0.1^{o}C$, periodically interrupted by impulses of waters showing conductivities rising to a maximum of 5.4 $\mu S\ cm^{-1}$ at $0.1^{o}C$ (Fig. 7.1). The impulses occurred between 08.00 - 10.00h and 19.00 - 21.00h, when the smaller tributary streams resumed flow after the onset of ablation and ceased to flow in the evening. At these times, the streams transported small ice crystals in increased quantities. As the crystals form in the evening, the solute concentration of the remaining meltwater is increased, but as discharge falls, the solute-rich water is held up in pools in the stream beds until its release in the morning when ablation increases flow.

Ranges of variations of electrical conductivity of supraglacial meltwaters and of the Gornera are given in Table 7.2 for periods of observations in summer ablation seasons. The dilute supraglacial waters represent the atmospheric ionic input at the time of precipitation, as subsequently modified during firnification and regelation. The minimum conductivity recorded in the Gornera was almost within the range of surface meltwater determinations, suggesting that at times, almost all the discharge of the Gornera is made up of meltwaters which have passed through the glacier without coming into contact with lithospheric sources of solutes. The high conductivities arise when chemically-enriched waters, from contact with basal solute sources contribute most of the discharge.

Results of sample determinations (1974) and continuous measurement (1975) of the conductivity of the runoff in the Gornera are shown in Figure 7.2 and Figure 7.3, together with discharge hydrographs. Occasional breaks in the record for 1975 are due to power failures in the monitoring equipment. Daily ablation of the glacier surface is clearly marked by

TABLE 7.1 CHEMICAL CHARACTERISTICS OF WATER FROM MAJOR HYDROLOGICAL ENVIRONMENTS OTHER THAN THE GORNERA, GORNERGLETSCHER CATCHMENT

Hydrological environment	Date	Temperature °C	Observed electrical conductivity $\mu S\ cm^{-1}$	Na^{+} $mg\ l^{-1}$	K^{+} $mg\ l^{-1}$	Ca^{2+} $mg\ l^{-1}$	Mg^{2+} $mg\ l^{-1}$
Small supra-glacial ice-melt streams							
Gornergletscher	22.07.74	0.1	0.2				
	24.07.74	0.1	0.1				
	24.07.74	0.1	0.2				
	18.08.75	-	-	0.0	0.4	0.1	0.0
	28.07.77	0.1	0.8				
	29.07.77	0.1	1.6				
Large supra-glacial ice-melt streams							
Gornergletscher	27.07.77	-	-	0.1	0.2	0.7	0.1
	13.08.76		2.7	0.3	0.2	0.6	0.1
	14.08.76	0.1	2.7	0.2	0.1	0.5	0.1
	15.08.76	-	2.7	0.4	0.3	0.4	0.1
Glacier surface snow-melt streams							
Theodulgletscher	26.07.74	0.1	1.3				
Breithorngletscher	11.08.75	-	-	0.0	0.6	-	0.5
Schwärzgletscher	11.08.75	-	-	0.0	0.1	0.3	0.1
Grenzgletscher	11.08.75	-	-	0.0	0.1	0.1	0.0
Seepage in lateral moraine, 150m above snout of Gornergletscher	22.07.74	5.2	22.7				
Non-glacial snow-melt stream							
Gakihaupt	03.08.77	0.8	28.0				

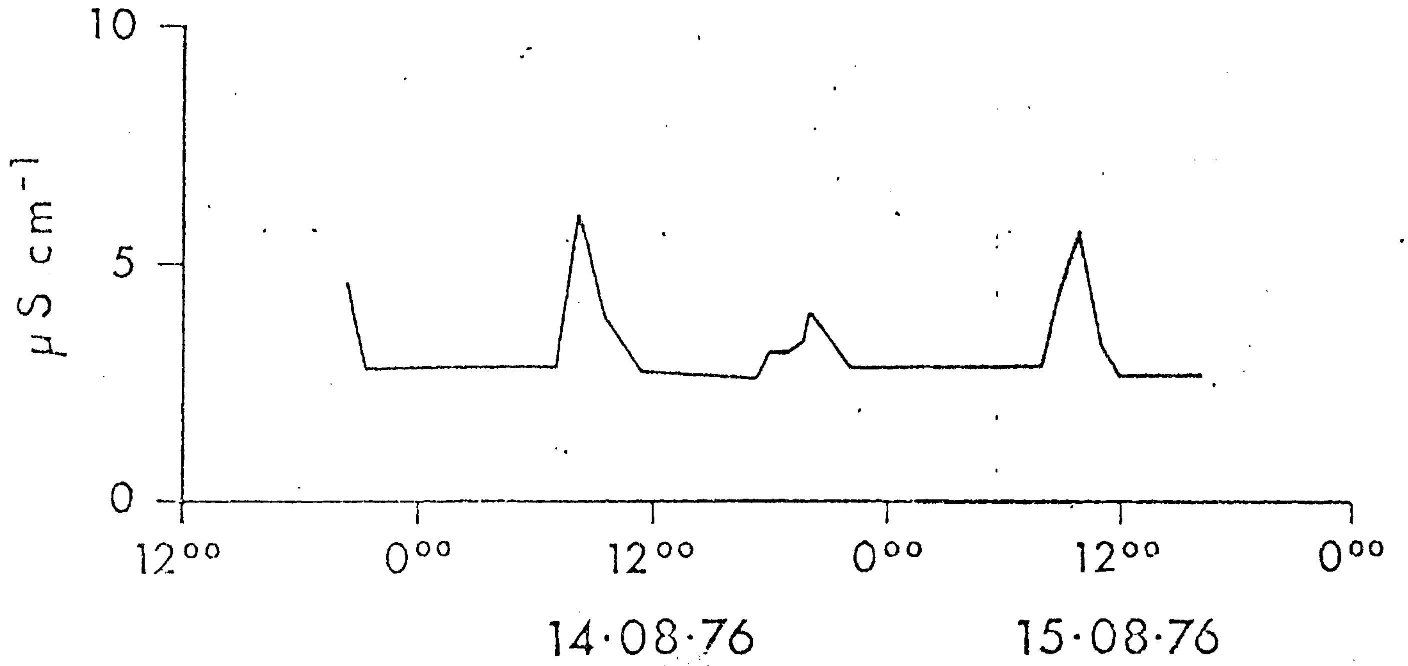


Figure 7.1 Daily variations of measured electrical conductivity of a major supraglacial meltwater stream, Gornergletscher, at site 4 (Fig. 6.1).

TABLE 7.2 SUMMARY OF MEASURED ELECTRICAL CONDUCTIVITY OF MELTWATERS IN THE GORNERA AND IN SUPRAGLACIAL STREAMS OF GORNERGLETSCHER

Meltwater	Period	Number of samples	Range of measured electrical conductivity	
			Minimum $\mu S\ cm^{-1}$	Maximum $\mu S\ cm^{-1}$
Small supraglacial icemelt streams Gornergletscher	1975-1977	12	0.1	1.6
Large supraglacial icemelt streams Gornergletscher	13.8. - 15.8.76	continuous record	2.7	5.4
Gornera	15.7. - 2.9.75	continuous record	6.5	44.0
Gornera	20.7. - 12.8.74	69	8.0	44.0

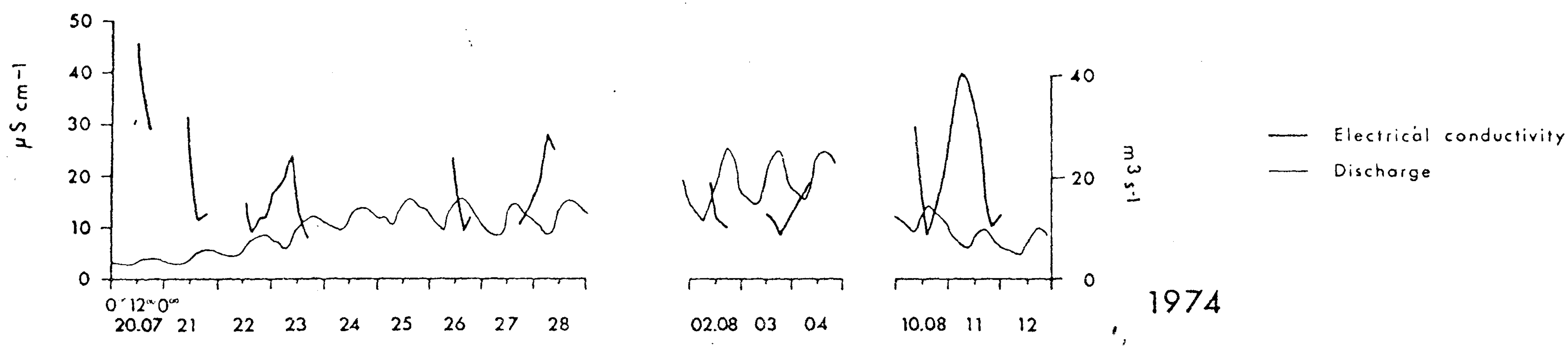


Figure 7.2 Discharge hydrographs and measured electrical conductivity of samples of meltwaters from the Gornera, 20 July - 12 August 1974.

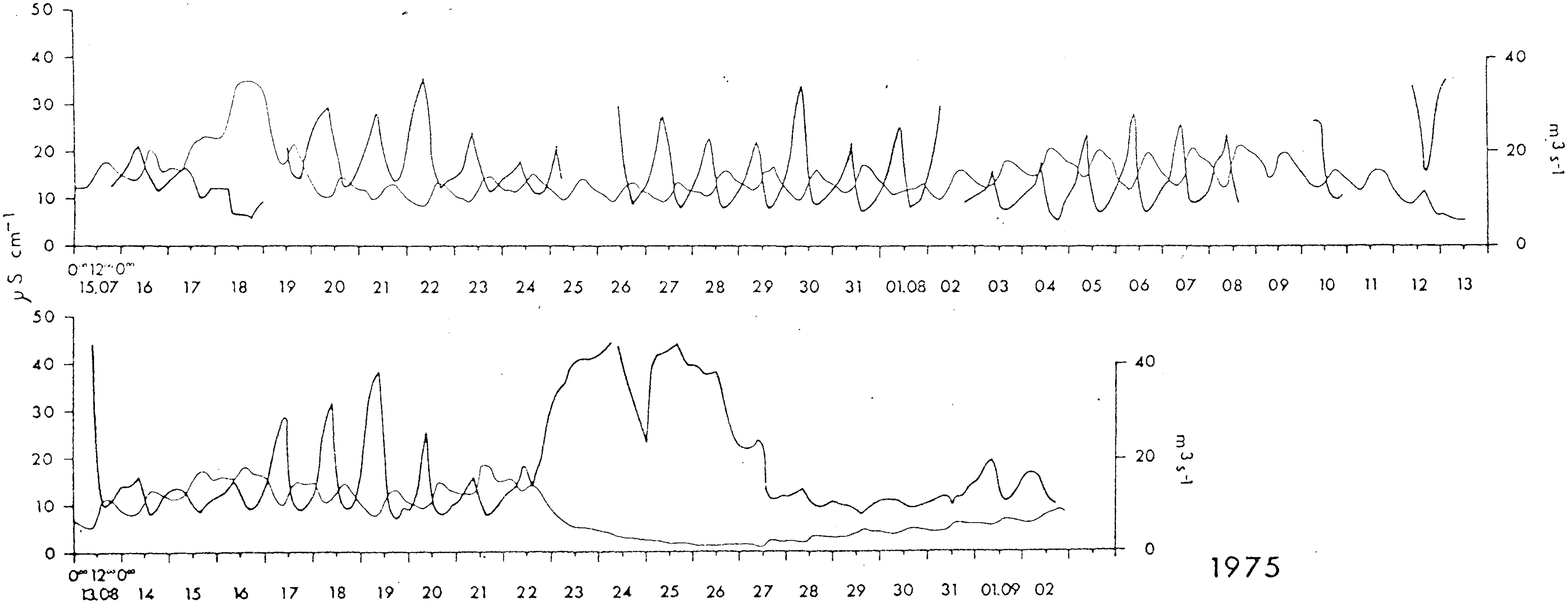


Figure 7.3 Discharge hydrographs and measured electrical conductivity of meltwaters in the Gornera, 15 July - 2 September 1975.

very sharp falls in electrical conductivity and steep rises in discharge in the afternoon. Following peak discharge, the hydrograph shows a slow fall, during which conductivity rises fairly rapidly. The minimum daily value of conductivity precedes the maximum discharge by 1-2h and the maximum conductivity occurs 2-3h after the minimum overnight flow. This diurnal pattern of a roughly phased inverse relationship between conductivity and discharge is well developed in the periods 26 July to 1 August, and 5-8 August 1975. The diurnal variations in conductivity indicate that comparative studies of meltwater chemistry between glaciers require long-term intensive sampling. On many days, the minimum conductivity was lower than 10 $\mu S\ cm^{-1}$, almost as low as the conductivity of meltwaters in supraglacial ice-melt streams (Table 7.2), evidence that at times of maximum discharge, surface meltwaters drain through the glacier quickly, almost unaltered in total solute concentration. At night, the lower discharges are still composed of surface meltwaters, delayed in flowing within the glacier, but they have become chemically enriched during transit, and do not reach the portal in increased quantities until about 12h after the maximum discharge of the Gornera. Variation of the daily ranges of conductivity values, depending on hydrological conditions, appear to mask any seasonal trend in the short period of the measurements.

The repeating periodic diurnal variations of discharge and conductivity were interrupted by the occurrence of various unusual hydrological conditions at intervals during the investigations. High discharges were produced in the Gornera during the drainage of the Gornersee on 17-19 July 1975. During the spring thawing of snow on the glacier and surrounding morainic slopes, very dilute meltwaters collect in a depression between the Grenzgletscher and trunk Gornergletscher. The minimum conductivity measured in the Gornera (6.0 $\mu S\ cm^{-1}$) was recorded during the lakeburst flood. This value is very close to that of surface snow and icemelt and implies that water from the lake has not been chemically altered either by the sediments brought into the Gornersee or by passage through the glacier. The suggestion is that the Gornersee drains through an ice-walled conduit, keeping the water free of lithospheric sources of solute. Since the highest sediment concentrations occurred during the lakeburst, it appears that solutes in meltwaters are not contributed from suspended sediment particles. In Chapter 5, sedimentary evidence suggested subglacial drainage over the glacier bed in 1974, and it is possible that the routing of meltwater was different in each of the two years. It is clear that natural water quality can be used in studies of the emptying of glacial lakes as a tracer of the flow of water through a glacier.

On several days in 1975 when the diurnal rhythm of discharge was interrupted, on 15-16 August, 20-21 August and 22-23 August, and discharge remained at the early evening level throughout the night (see Chapter 4), conductivity remained low, reaching maxima of about 16 $\mu S\ cm^{-1}$, rather than the usual 25-35 $\mu S\ cm^{-1}$. The low conductivities associated with these waters suggest a source remote from solute-rich material.

It is suggested that the low conductivities indicate that dilute meltwaters, ponded back during the day by temporary blockage of the conduit, were released. Storage had occurred englacially, away from soluble material.

During a period of low temperatures and almost continuous cloud cover between 8-13 August 1975, ablation was reduced and discharge in the Gornera decreased. The maximum conductivity recorded in the Gornera at this time was 44.0 $\mu S\ cm^{-1}$, though the minimum was about the usual, 10 $\mu S\ cm^{-1}$. Since rain fell over the catchment on each day, solutes may have been contributed to the total catchment discharge from the snow- and ice-free slopes. Increased conductivities result from decreased input of dilute ablation melt raising the proportion of solute-rich and by implication, subglacial water in the total discharge. The gradual fall in night minimum flow after 8 August may be due to a depletion of water retained but in transit in the subglacial conduits. When ablation resumed with clearing skies on 13 August, increased surface meltwater supply reduced the conductivity of water in the Gornera from 44.0 to 9.5 $\mu S\ cm^{-1}$ in 6h.

On two occasions (18-20 July 1974 and 22-27 August 1975), snowfall temporarily interrupted ablation, causing recession of discharge. Under such circumstances, draining of internal reservoirs in the glacier was thought by Elliston (1973) to account for continued flow of the Matter-Vispa (to which the Gornera is principal tributary). Conductivity values on both occasions reached the same maximum value of 44.0 $\mu S\ cm^{-1}$, which was also recorded during low discharge on 13 August 1975. This value was never exceeded, and recurred despite different contributions of meltwater from the non-glacierised part of the catchment on each occasion. It possibly represents an environment maximum concentration which is an equilibrium level for desorption and solution between sediments and solutes. Meltwater from areas surrounding the glacier produced by snowmelt would be rapidly increased in solute content to the equilibrium level on entering the basal conduits of the glacier. Melting of snow on the south facing slopes of Gornergrat on 23 August had no impact and conductivity contrived to rise. Some snow on the glacier melted on 24 August, and although streamflow continued to decline, the passage of dilute meltwaters to the portal is shown by the drop in conductivity to 24.0 $\mu S\ cm^{-1}$ at 23.00h, a delay of 5h in comparison with the arrival of the minimum value on days with usual ablation rates. The conductivity measured on the Gornera rose to 44.0 $\mu S\ cm^{-1}$ on 25 August following further snowfall. Melting of the snow from 26 August again diluted the waters of the Gornera, and large quantities of surface meltwaters passing through the englacial network maintained a stable conductivity level around 10.0 $\mu S\ cm^{-1}$. Rain over the catchment on 28-31 August did not increase the solute load by runoff from the extra-glacial areas.

7.2.2 Variations of electrical conductivity with discharge

Summary data of diurnal variations of discharge and electrical conductivity of meltwaters in the Gornera, in the form of daily maximum and minimum values of discharge and conductivity and mean daily discharges, are shown in Figure 7.4 for a period of 42 days in July and August 1975, together with daily totals of precipitation. The effect of precipitation was to reduce mean daily discharge, because all precipitation is associated with overcast skies, which limit energy supply to the glacier surface for ablation (for example, 9-13 August) and because snowfall raises albedo and limits ablation (22-26 August). At other times, variations of the ablation rate, reflecting the meteorological parameters air temperature and incoming radiation, influence both daily means and diurnal ranges of discharge. The diurnal range of electrical conductivity varied considerably during the observation period from a minimum span of 9.5 - 11.0 $\mu S\ cm^{-1}$ on 30 August to 10.0 - 44.0 $\mu S\ cm^{-1}$ which occurred on 13 August 1975. The overall range of electrical conductivity was 6.5 - 44.0 $\mu S\ cm^{-1}$. There was no seasonal trend in either maximum or minimum daily conductivity, and no systematic relationship between them. Further, no obvious relationship was detected between actual values of electrical conductivity and discharge.

Draining of dilute ablation meltwaters from the surfaces of the glaciers during the day, mixing with solute-rich basally-routed waters produces the inverse relationship between electrical conductivity and discharge in the Gornera (Figure 7.5). In non-glacierised catchments

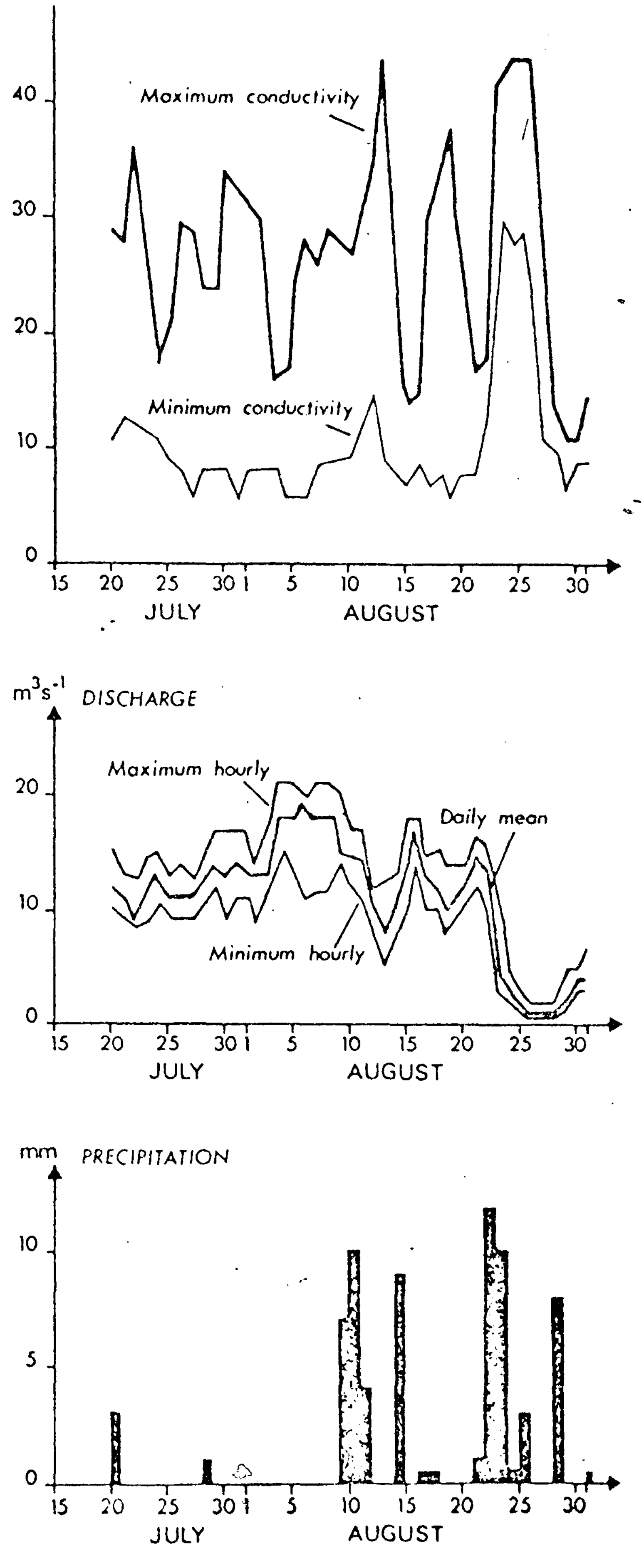


Figure 7.4 Seasonal variation of electrical conductivity and discharge in the Gornera during the summer ablation period 1975. Precipitation was recorded at a gauge at 2580m on the surface of Gornergletscher. Snowfall occured from 22-26 August.

this relation is usually described by the model $c = a\,Q^{-b}$, where c is dissolved solids concentration (electrical conductivity) and Q discharge (Hem, 1970), although this is the simplest of several mixing models (Hall, 1970). Simple models are inappropriate for the Gornera, since a descriptive function should allow for the range of electrical conductivity observations associated with a given discharge, and the observed conductivities result from the mixing of waters from different runoff sources and routings. Mass-balance equation models (e.g. Pinder and Jones, 1969) whilst of increased sophistication, are more suitable for hydrograph separation than for description of solute-discharge relationships.

The solute (electrical conductivity)-discharge relationship is better defined by the margins of a trapezium (Figure 7.5 (inset)). Side AB represents the lowest observed conductivity (6.5 $\mu S\ cm^{-1}$) which occurs independent of discharge at higher flows, and which is determined by the solute content of ice and snow meltwaters from the glacier surface at times when there is minimal subglacial outflow. Point D is located by the maximum observed solute concentration which ideally is the concentration which would be measured in interstitial waters of basal moraine. During this study period, it is likely that surface meltwaters derived from snowmelt reduced the observed maximum below that which would have occurred had total discharge been contributed by basal outflow alone. CD is positioned by lowest observed recession flows (1.3 $m^3 s^{-1}$) which result from varying proportions of surface runoff and basal outflow. When further surface contributions inhibit basal outflow, solute content is decreased (CB), as discharge rises. Some water probably restocks subglacial storage within conduits following their depletion up to the discharge represented by point C, permitting a wide range of water quality at an almost constant low flow. The upper limits of the distribution (AD) are located by daily maximum conductivities.

Points in the distribution close to AB represent meltwaters with chemical characteristics primarily derived from atmospheric inputs. Towards D, terrestrial sedimentary solute origins become dominant. This joint influence of solute origins on alpine water quality was noted by Zeman and Slaymaker (1975), and in studies of alpine catchments, the glacial meltwater component of flow should always be treated as highly variable in chemical composition. Different mixing models are appropriate for different parts of the trapezium frame, according to pertaining hydrological conditions. Unfortunately, the definition of the trapezium

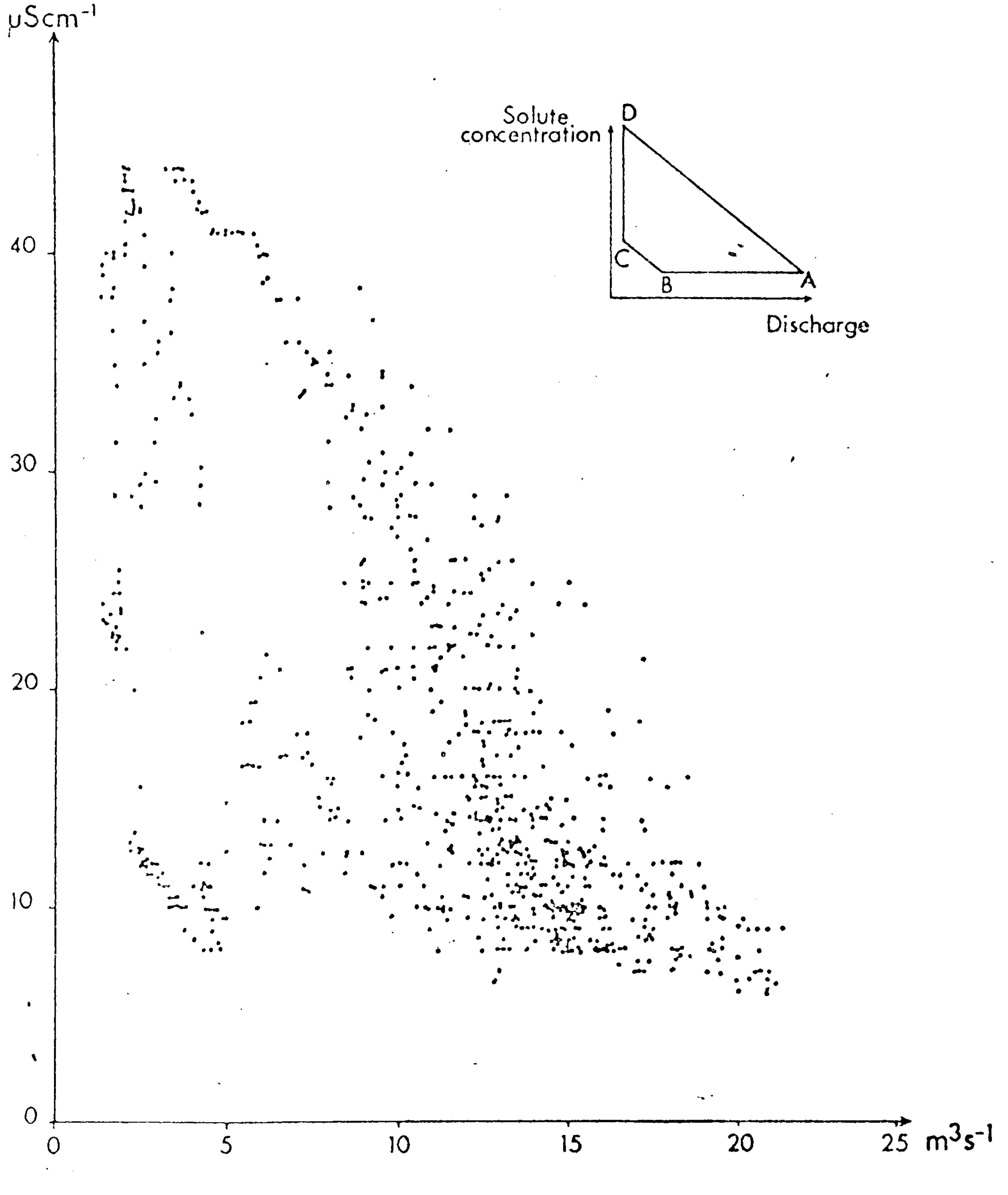


Figure 7.5 Inverse relationship between solute concentration (as electrical conductivity) and discharge in the Gornera in 1974 and 1975. Inset: trapezoidal frame ABCD which encloses the distribution.

frame does not provide a function for prediction of water quality. However, comparison of glacial meltwaters from catchments with different lithologies and varying intensities of glacierisation can only be made when the complete trapezoidal distribution has been described for each meltstream. The effects of different environmental factors, reflected in shapes and sizes of trapezia, could then be evaluated.

Hysteresis dynamics affect solute rating relationships which must be used to determine solute transport when continuous data are not available. For streams in non-glacierised catchments, the effects occur during individual flood peaks of storm events and cyclic relationships have been described consisting of both anti-clockwise hysteretic loops in Kentucky (Hendrickson and Krieger, 1964) and clockwise in Georgia, U.S.A. (Toler, 1965a), in both cases referring to graphs with solute concentration on the x axis. Rating loop relationships for the Gornera for the periof 27 July - 1 August 1975 show a clockwise hysteretic loop for each day (Figure 7.6) with solute concentration as dependent variable on the y axis. Within each loop, conductivities are lower during a period of falling stage than they had been at the same discharges on the rising stage. The decrease in conductivity associated with dilution by surface meltwaters in the early morning is postponed by the forcing out of water, which has become chemically enriched, from basal conduits. This component of discharge is proportionally and absolutely reduced as ablation meltwaters reach the portal in increasing quantities. The falling limb of the hydrograph recedes slowly since meltwater from the upper part of the glacier continues to reach the portal after ablation has ceased. At peak discharges, 'figure-of-eight' sub-loops may occur, probably as a result of discharge irregularities caused by the release of pockets of dilute englacial waters.

Since hysteresis dynamics affect solute rating relationships, it is difficult to identify a single rating relationship for solute concentration and discharge. Parameters of the model $c = a\,Q^{-b}$ where c is electrical conductivity, Q discharge and a and b best-fit parameters, were estimated for separate limbs of diurnal hydrographs for days in the ablation season of 1974 (Table 7.3). Good estimates of solute concentration can be achieved for individual limbs of hydrographs, but overall a rating curve for the season from all measurements would produce considerable inaccuracy in estimates of solute transport. Solute transport studies for glacial meltwater streams require detailed sampling or continuous recording of solute parameters if accuracy is to be maintained.

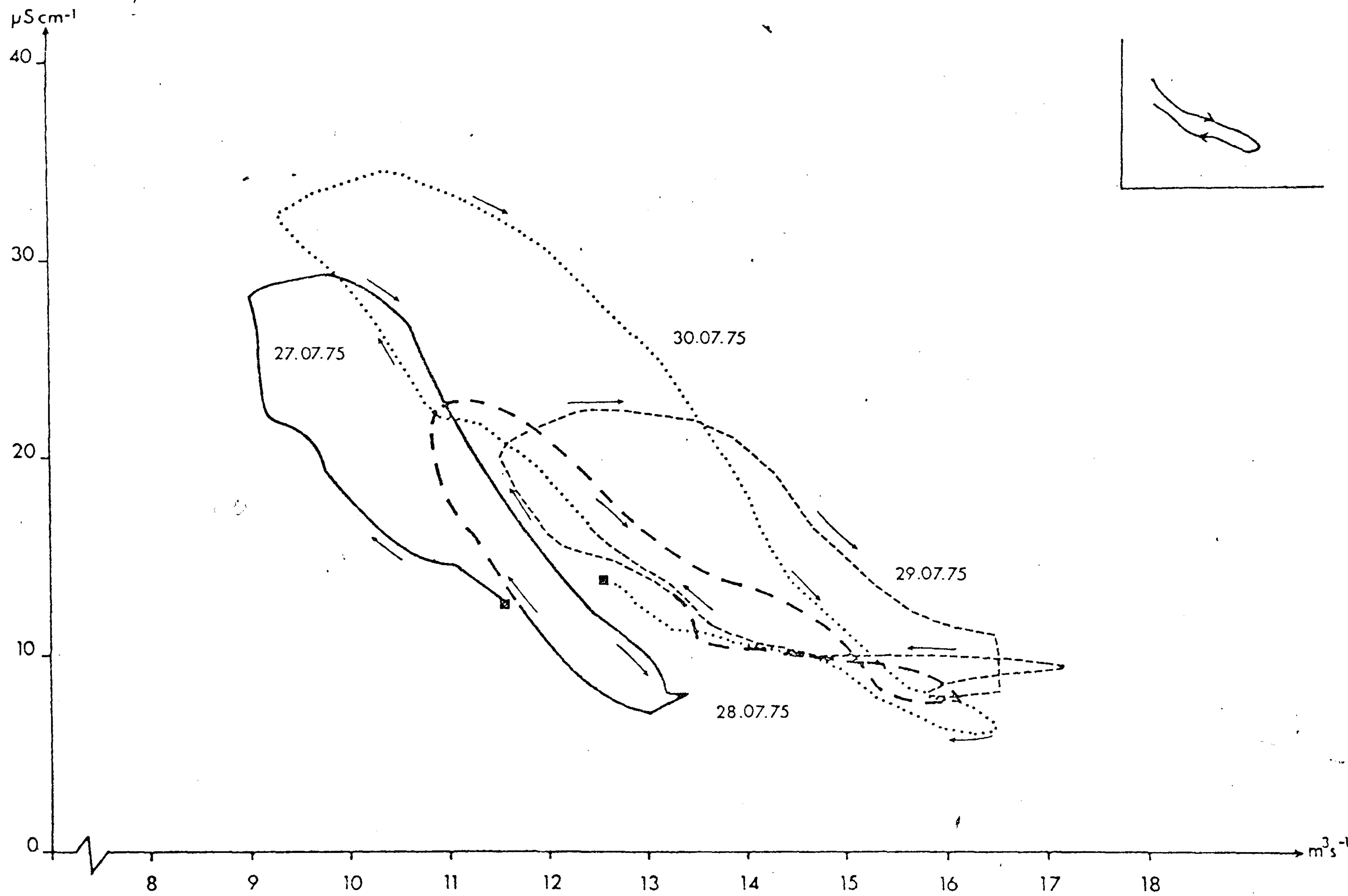


Figure 7.6 Clockwise hysteretic rating loops of conductivity and discharge in the Gornera, 27 - 30 July 1975.

TABLE 7.3 PARAMETERS OF THE MODEL $C = aQ^{-b}$ FOR ELECTRICAL CONDUCTIVITY-DISCHARGE RELATIONSHIPS IN THE GORNERA, DETERMINED FOR RISING AND FALLING LIMBS OF DAILY HYDROGRAPHS DURING THE 1974 ABLATION SEASON

Date 1974	Hydrograph limb	Parameter		Goodness of fit
		a	-b	r^2
20.7	Rising	4390.0	1.81	0.85
21.7	Rising	1880.0	1.40	0.88
22.7	Rising	1258.0	1.02	0.34
22.7	Falling	3165.0	1.31	0.79
26.7	Rising	2895.3	2.81	0.90
27.7	Falling	2285.7	1.89	0.96
2.8	Rising	2761.2	1.66	0.98
3.8	Rising	676.0	0.48	0.52
10.8	Rising	4120.0	2.69	0.92
10.8	Falling	3816.0	1.29	0.94
11.8	Rising	9570.2	2.76	0.90
All data	Rising and Falling	510.0	0.42	0.40

7.2.3 Individual cations

The samples of water for chemical analysis were collected throughout the periods of field investigations. Samples were usually collected between 08.00h and 19.00h, on the rising limb of the daily hydrograph, although some were taken during low discharges at night. This sampling strategy has not permitted the construction of diurnal curves of variation for each individual ion, nor the description of hysteretic rating loops. Further, no samples were collected during recession flow following summer snowfall. Unfortunately, analysis for anions was not possible. Determinations for each sample are listed in Appendix 1. The ranges of ionic compositions of meltwaters for the determined elements are presented in Table 7.4. The ranges represent the minimum and maximum concentrations determined for the samples rather than the population ranges which would have been observed had samples been collected at close intervals throughout the study period.

Ranges of concentrations of individual ions in the Gornera are large, and are relatively stable between years, with the exception of K^+, which showed a markedly increased span in 1975. Some of the variations in ions between years result from the timing of sampling. In comparison, snow and icemelt waters on Gornergletscher are very dilute but their composition suggests that windblown fine sediment or atmospheric fallout have supplied solutes to the glacier surface. Differences in concentration between surface meltwaters and those of the Gornera show the extent of influence of lithological enrichment of waters within the glacier.

Relative proportions of the major cations, as percentages of the total sum of determined cations, are given in Table 7.5, for the Gornera and for other glacier meltwaters. Ca^{2+} is the most abundant constituent analysed in water samples from the Gornera and in the surface snow and icemelt, constituting between 45.0 and 90.9 per cent of determined cations in the Gornera, and 50.0 - 63.6 per cent of the surface meltwaters. Ca^{2+} is followed by either K^+ or Mg^{2+}, with Na^+ the least significant. The ranges of percentages of each ion are consistent between the three observation periods. The ranges of percentage composition show that as concentration of meltwaters varies, the proportions of the various ions do not remain constant. Conductivity can only be used as an index of individual ion concentration when the relative proportions of the ions present are constant. The variability in percentage composition of ions prevents the use of electrical conductivity as an indicator of the

TABLE 7.4 IONIC CONCENTRATIONS DETERMINED FOR MELTWATER FROM GORNERGLETSCHER CATCHMENT

Meltstream	Sampling period	No. of samples	Ionic concentration (mg l^{-1}) Na^+ Range	$\bar{x}$	σ	K^+ Range	$\bar{x}$	σ	Ca^{2+} Range	$\bar{x}$	σ	Mg^{2+} Range	$\bar{x}$	σ
Gornera	July-August 1974 Ablation season	69	0.2-1.0	0.44	0.22	0.1-1.3	0.51	0.27	2.5-6.7	4.32	1.08	0.2-2.3	0.93	0.53
	July-September 1975 Ablation season including summer snowfall recession	59	0.1-0.8	0.28	0.16	0.3-2.7	0.74	0.46	1.8-7.4	3.73	1.33	0.4-2.2	0.92	0.39
Gornergletscher supraglacial icemelt streams	August 1975/6	5	0.0°-0.4	0.20	0.16	0.1-0.4	0.24	0.11	0.1-0.7	0.46	0.23	0.0°-0.1	0.08	0.04
Gornergletscher supraglacial snowmelt runoff	11 August 1975	3	0.0°	-	-	0.1-0.6	0.27	0.29	0.1-0.3	0.20	0.14	0.0°-0.5	0.20	0.26

°below detection limit (see Table 6.2); $\bar{x}$ = mean; σ = standard deviation

TABLE 7.5 SUMMARY OF CATIONIC COMPOSITION OF MELTWATERS FROM GORNERGLETSCHER CATCHMENT

Gornergletscher	Date	No. of determinations	Ranges of % as %(Na^{+}+K^{+}+Ca^{2+}+Mg^{2+})			
			Na^{+} %	K^{+} %	Ca^{2+} %	Mg^{2+} %
Gornera	July - August 1974	69	1.3-17.4	1.8-22.0	45.0-90.9	5.2-23.3
Gornera	July - September 1975	59	1.9-8.8	9.6-26.5	57.0-71.3	14.0-18.0
Icemelt	August 1975/6	5	0.0-33.3	12.5-80.0	50.0-63.6	0.0-45.4
Snowmelt	11 August 1975	3	0.0	20.0-55.0	50.0-60.0	0.0-45.0

behaviour of individual ions, except Ca^{2+}, although it is useful as an overall measure of diurnal and seasonal concentration of total dissolved solids. The changing proportions of cations suggest that the meltwaters of the Gornera are derived from several subglacial routes along each of which the water comes into contact with morainic materials of different mineral composition. The ionic composition of meltwaters beneath the glacier is determined by morainic chemical characteristics, and the mixing of waters from various subglacial zones produces variable ionic compositions. A detailed investigation of temporal variations of individual ions may lead to a better knowledge of subglacial water movement, and changing basal contributing areas.

7.2.4 Variation of individual cation concentrations with discharge

The relationships between individual ionic concentrations and discharge in the Gornera are depicted in Figure 7.7. Both Ca^{2+} and Mg^{2+} show an inverse relationship with discharge, with wide variability. The limited sampling design may account for the shapes of the figures enclosing these two distributions differing from the trapezium of electrical conductivity and discharge, when the relatively high concentrations and ionic mobilities of the bivalent ions contribute a large proportion of the total conductivity. The range of concentrations of Ca^{2+} in particular points to differential variation in subglacial chemical enrichment of individual ions at different stages of flow. In contrast, the ranges of concentrations of Na^{+} and K^{+} are independent of discharge and the dilution effect is not apparent. The stability of concentrations of Na^{+} and K^{+} suggests either a more uniform distribution of these ions in sedimentary environments beneath the glacier, or selective solution or desorption from particles in contact with increasingly dilute meltwaters.

An attempt to describe rating curves specific to each individual ion using the two simple concentration-discharge models: $c = a - b\ Q$ and $c = a\ Q^{-b}$, where c is the concentration of an ion (mg l^{-1}), was unsuccessful since the goodness of fit was very small for all ions (Table 7.6). The lack of fit of these models is evident from the ranges of ionic concentrations associated with a given discharge (Figure 7.7).

7.2.5 Temporal variation of individual cation concentrations

Temporal variations in concentration of individual cations in meltwaters of the Gornera are shown in Figure 7.8. Because electrical conductivity is the sum of conductances due to individual ions, changes in

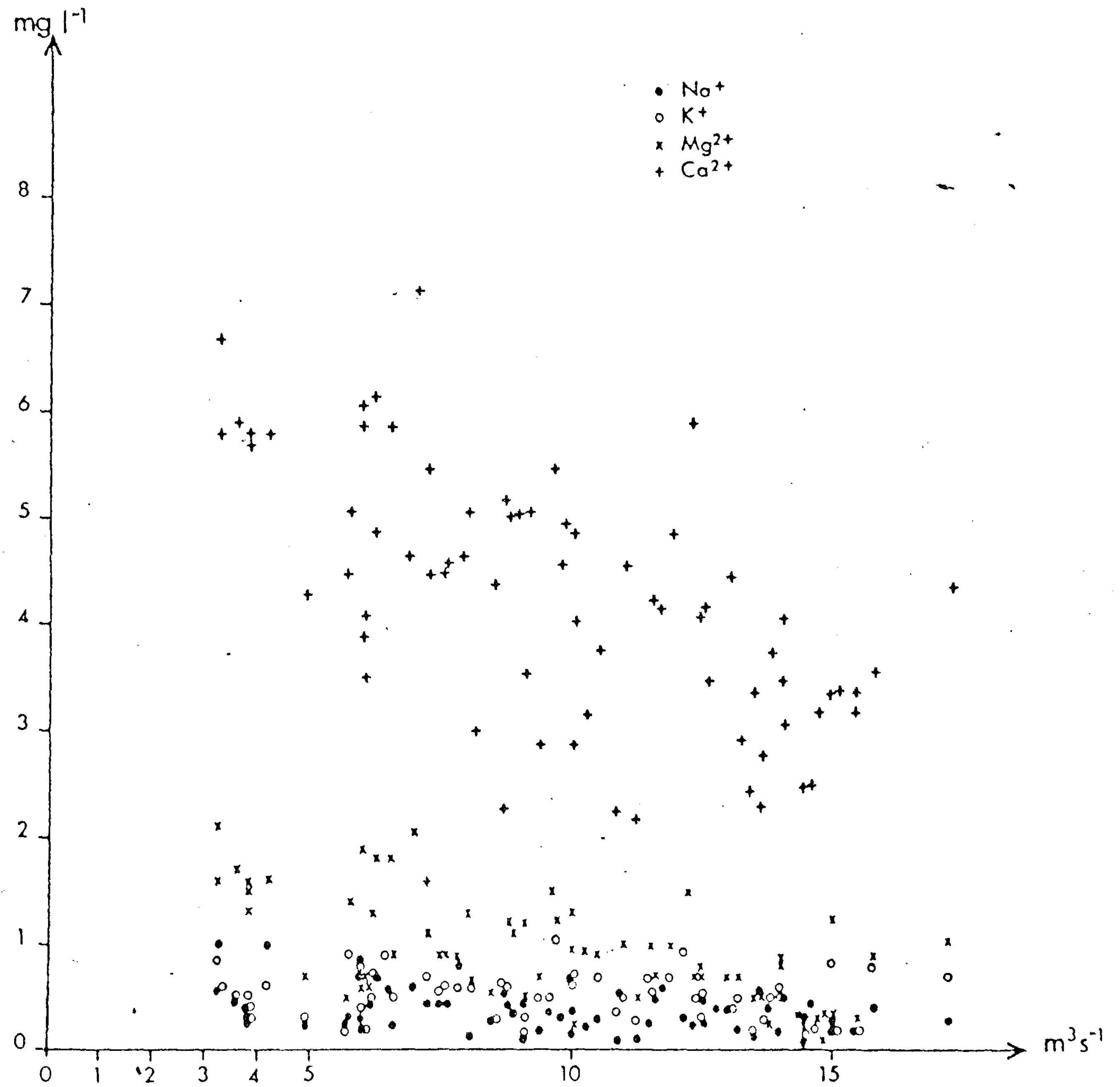


Figure 7.7 Relationships between individual cations and discharge in the Gornera during July and August in 1974 and 1975.

TABLE 7.6 PARAMETERS OF SIMPLE CONCENTRATION-DISCHARGE MODELS FOR INDIVIDUAL IONIC CONCENTRATIONS IN THE GORNERA

Ion	No. of samples	$c = a - b\,Q$	r^2	$c = a\,Q^{-b}$	r^2
Na^+	116	$c = 0.51-0.01Q$	0.02	$c = 1.10Q^{-0.62}$	0.03
K^+	114	$c = 0.70-0.01Q$	0.01	$c = 1.45Q^{-0.14}$	0.09
Ca^{2+}	116	$c = 6.21-0.21Q$	0.29	$c = 5.57Q^{-0.15}$	0.15
Mg^{2+}	117	$c = 1.72-0.08Q$	0.28	$c = 1.29Q^{-0.20}$	0.08

N.B. Some analyses of samples collected subsequently, in 1976, have been included in the calculations of concentration-discharge models.

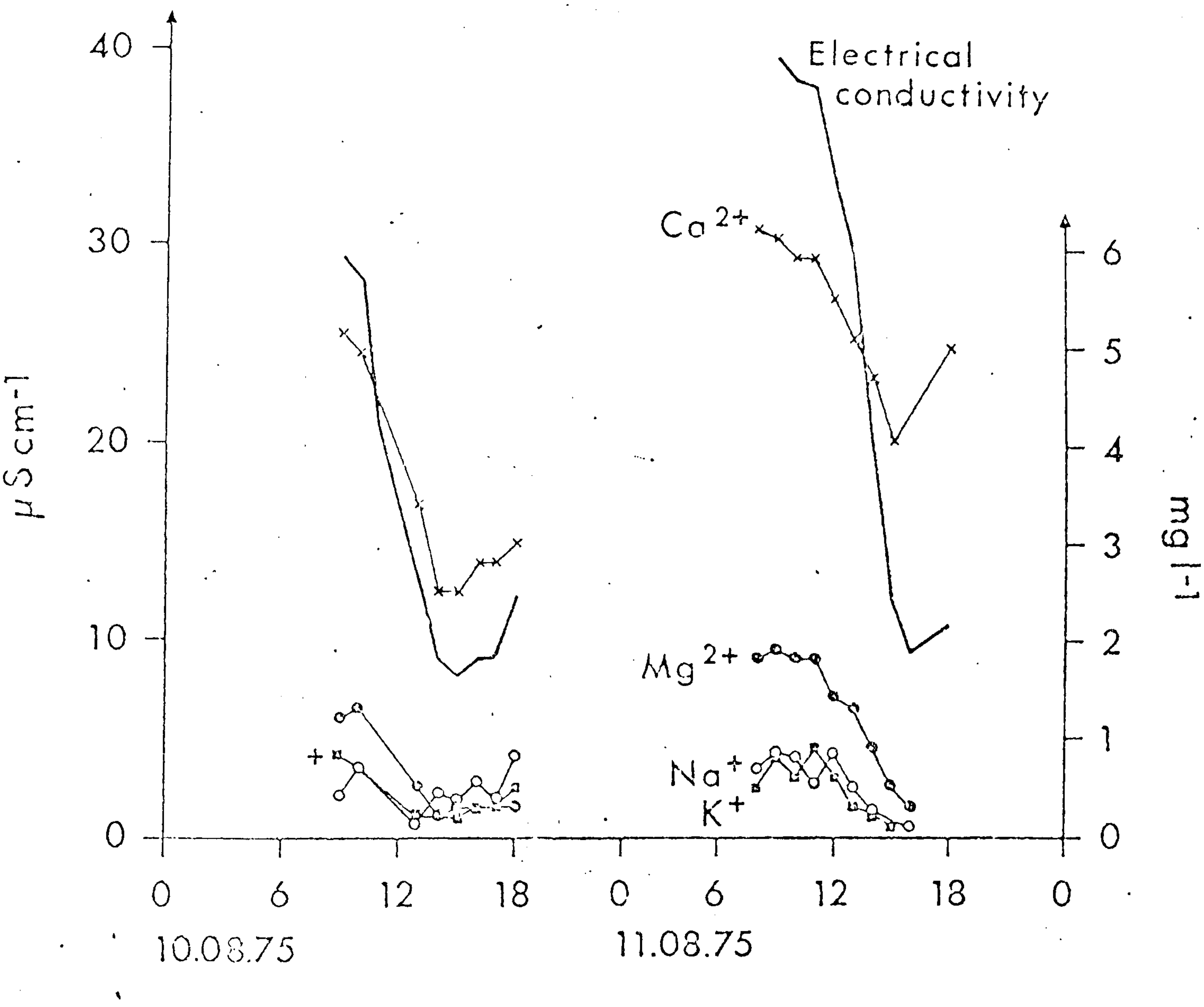


Figure 7.8 Temporal variations in concentrations of individual major catio ns and of electrical conductivity of meltwaters from the Gornera 10-11 August 1974.

the concentrations of the most important cations, Ca^{2+} and Mg^{2+}, are closely paralleled by fluctuations of conductivity. Na^{+} and K^{+} are more variable but follow the general trend in concentration of the major solutes. Electrical conductivity is a good indicator of the total behaviour of the sum of individual ions in the Gornera. However, calcium and magnesium ion concentrations would also provide useful indicators of runoff portions in glacier hydrology.

7.2.6 Relationships between electrical conductivity and individual cation concentrations

The relationships between electrical conductivity and the concentrations of individual ions are shown in Figures 7.9 and 7.10. The variation of Na^{+}, the cation of the lowest concentration, with conductivity, was irregular and variable (Fig. 7.9), together with variation of K^{+}. The most important cations (Ca^{2+} and Mg^{2+}) showed a linear increase with electrical conductivity (Fig. 7.10). Considerable scatter in this relationship shows that the proportions of individual ions do not remain constant for all observations of conductivity (Fig. 7.11). Conductivity can only be used as an index of individual ion concentrations when the relative proportions of the ions present are constant. Further, the scatter in the relationships between ions and conductance suggests that meltwaters of the Gornera are derived from sources with differing chemical compositions beneath the Gornergletscher, and that in some waters cations other than Na^{+}, K^{+}, Ca^{2+}, Mg^{2+} are important. Variations must also occur in the relative proportions of anions in glacier meltwaters, although it has not been possible to make such determinations. However, it is concluded that electrical conductivity provides a useful surrogate measure of total ionic strength.

7.2.7 Dissolved load transport

Although Hem (1970) considered that for most natural waters, total dissolved solids (in mg l^{-1}) could be estimated from electrical conductivity on multiplication by an empirical constant (0.65), determinations of total dissolved solids by evaporation to dryness were not undertaken since transport of sufficient sample volumes from the Gornera was impossible. Usually, only 40-70 ml of each sample remained after analysis of individual cations, and at least 1-2 litres would have been required. The physical basis of the empirical constant could not be demonstrated for these Alpine waters. Instead, an index (S) of the total dissolved solids in

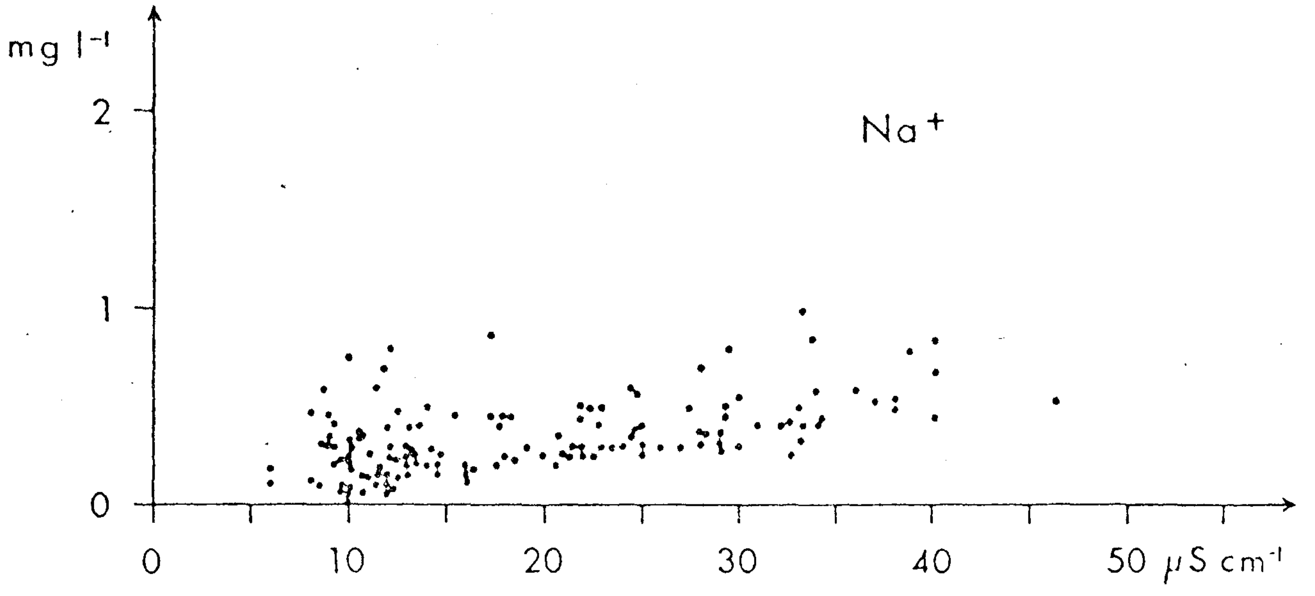


Figure 7.9 Plot of concentration of sodium against electrical conductivity for samples of meltwaters from the Gornera collected in 1975.

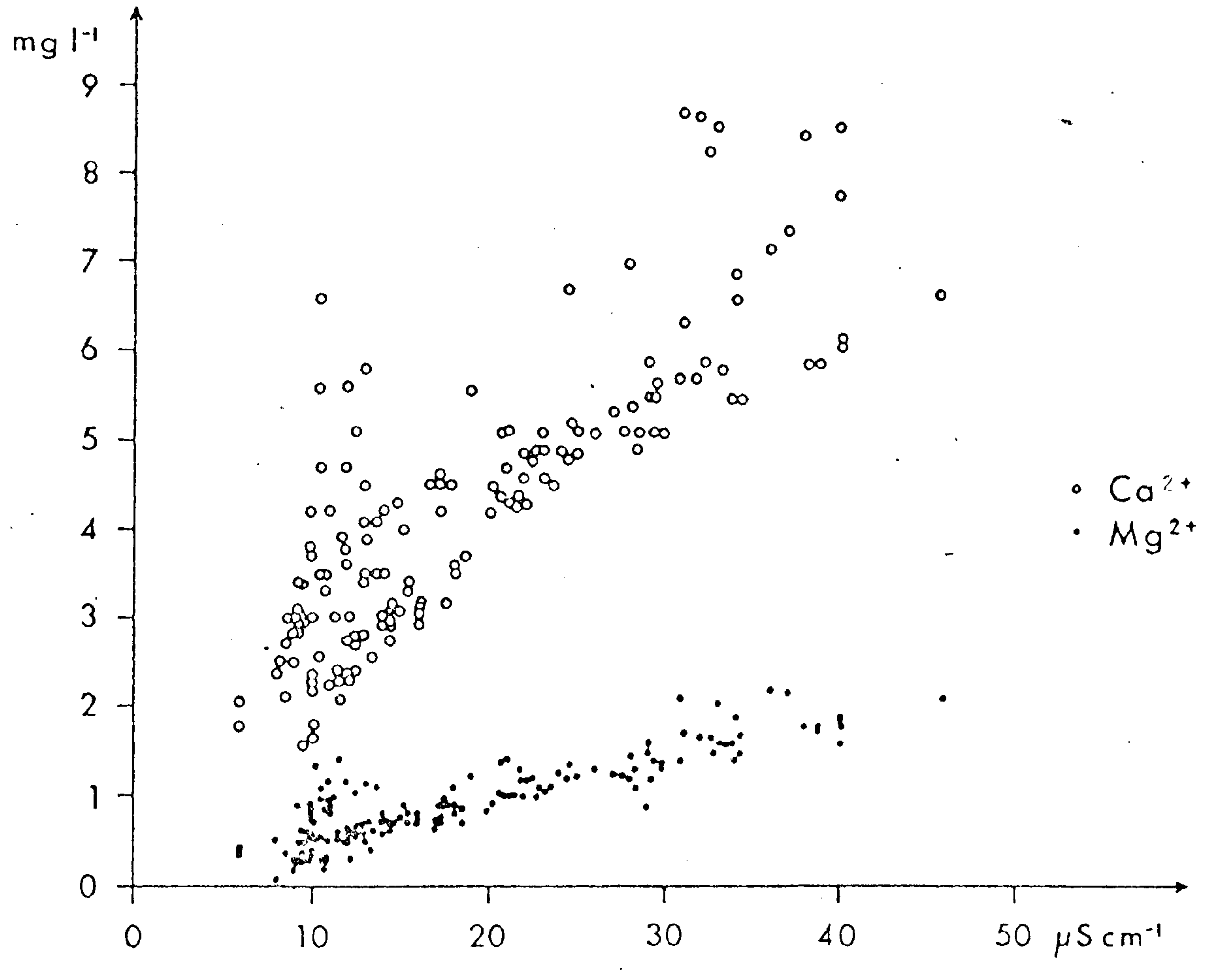


Figure 7.10 Plot of concentrations of calcium and magnesium against electrical conductivity for samples of meltwaters from the Gornera collected in 1975.

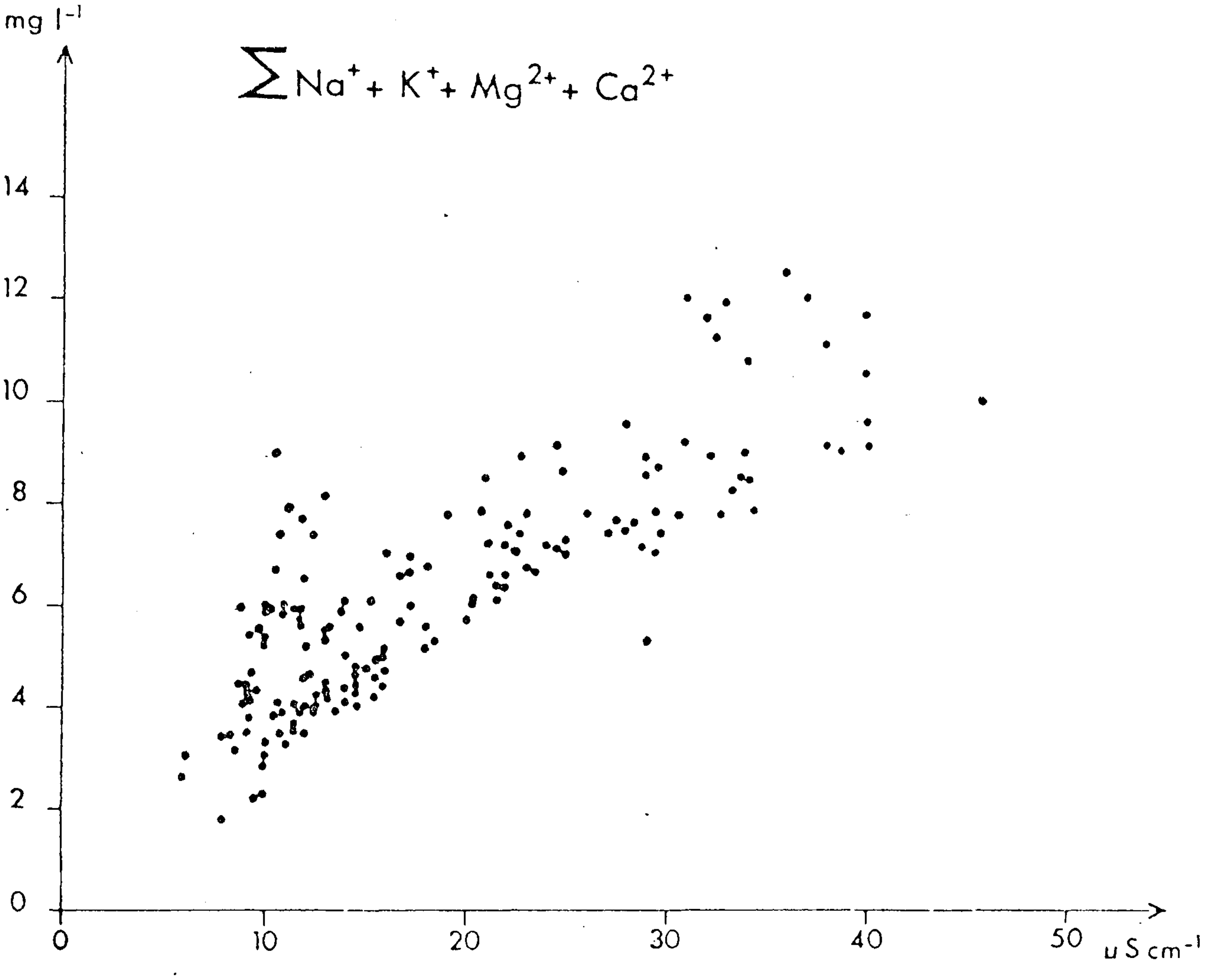


Figure 7.11 Plot of total concentration of sodium, calcium magnesium and potassium against electrical conductivity for samples of meltwaters from the Gornera collected in 1975.

water at a given time (i.e. load s^{-1}) was derived:

$$S = \text{electrical conductivity } (\mu S\ cm^{-1}) \times Q \qquad (7.1)$$

where Q is discharge ($m^3 s^{-1}$). Diurnal variation of S is shown in Figure 7.12, for the period 24 July - 4 August 1975, a period of sustained ablation. Diurnal variations of the index of solute transport showed a rhythmic repeating pattern. Minimum solute transport was associated with the highest discharges in late afternoon, and the maximum occurred between 09.00 - 12.00h each day, a few hours after the time of lowest discharge. This variation of solute transport, which is out of phase with changes of discharge, parallels the curves of electrical conductivity, with an asymmetrical slow rise to peak, followed by a steep decrease during the morning. Flows of intermediate magnitudes transport the largest quantities of dissolved load. S decreases as discharge rises indicating that the actual amount of solute supplied to the stream is reduced rather than being a constant input subjected to dilution.

7.2.8 Relationship between solute and suspended sediment concentration in the Gornera

The diurnal cycle of index S occurs out of phase with fluctuations of suspended sediment concentration (Fig. 7.12). During high discharge and high sediment concentration, the instantaneous total solute content is only about 35 per cent of that at night, suggesting that the contribution of solute released from sediment in transit is extremely small in comparison with the proportion of solute derived from beneath the glacier. This is confirmed by Lorrain and Souchez's (1972) observation that significant cationic material remains adsorbed on the surfaces of suspended particles in meltwaters after evacuation from the glacier bed.

7.3 Findelengletscher catchment

7.3.1 Electrical conductivity of meltwaters

Ranges of variations of electrical conductivity of supraglacial snow meltwaters and of the Findelenbach outwash streams are shown in Table 7.7 for the observation period in 1977. The minimum conductivity recorded in the Findelenbach was considerably higher than that determined for the Gornera, and the maximum measured conductivity of the Findelenbach is also higher than that of the Gornera. Lütschg and others (1950) considered that the groundwater component of winter discharge of the Findelenbach resulted in its having several individual ionic concentrations

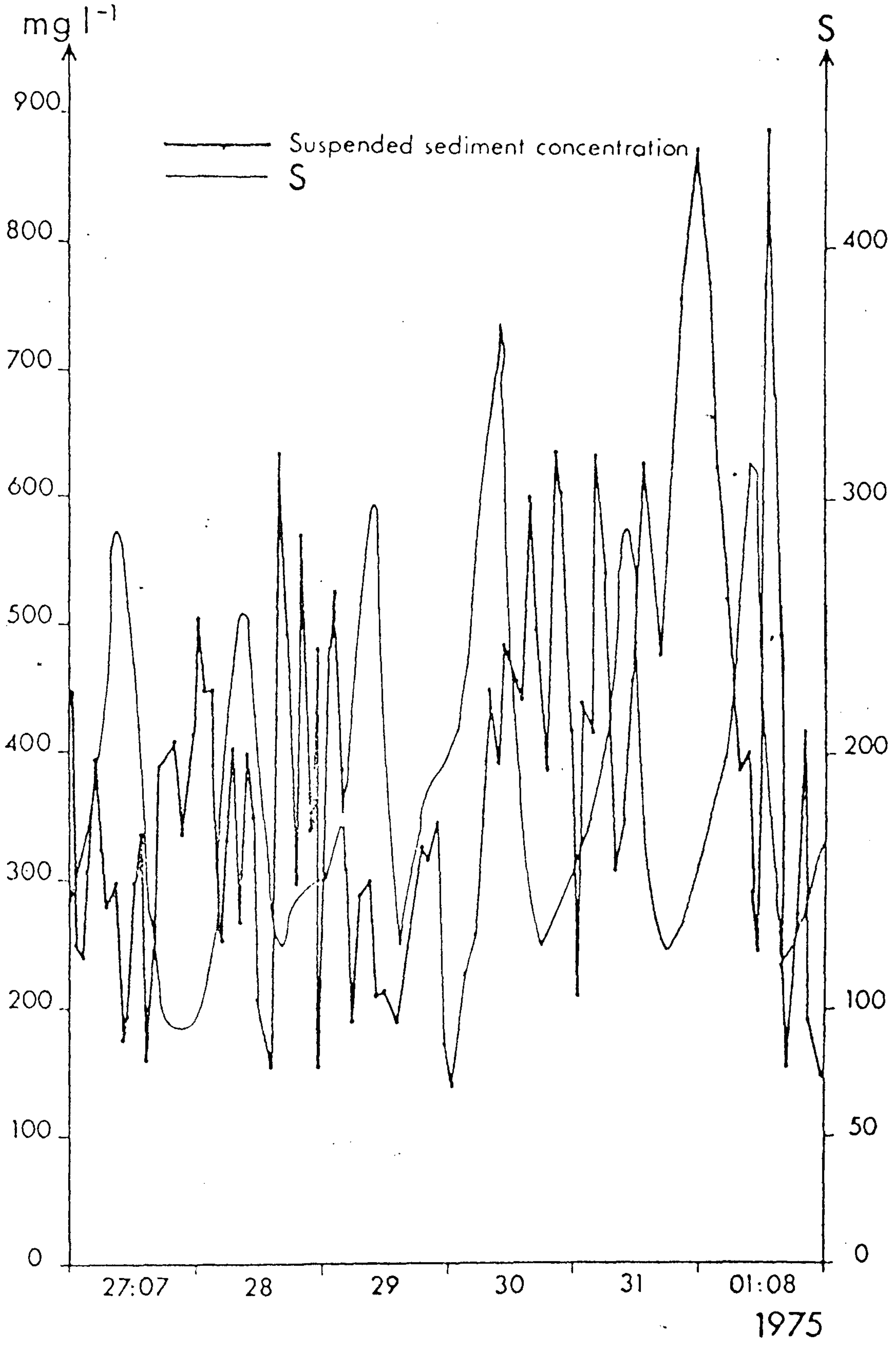


Figure 7.12 Temporal variations of an index of instantaneous solute transport (S) and suspended sediment concentration in the Gornera 27 July - 1 August 1975. For calculation of S see text.

TABLE 7.7 SUMMARY OF MEASURED ELECTRICAL CONDUCTIVITY OF MELTWATERS IN THE FINDELENBACH AND A SUPRAGLACIAL SNOWMELT STREAM ON FINDELENGLETSCHER

Meltwater	Period	Number of samples	Range of measured electrical conductivity	
			Minimum $\mu S\ cm^{-1}$	Maximum $\mu S\ cm^{-1}$
Findelenbach Findelengletscher	1.8 - 24.8.77	continuous record	18.6	68.2
Snowmelt runoff Findelengletscher	1977	6	1.3	1.6

some ten times higher than those of meltstreams draining neighbouring glaciers. The nature of the igneous and metamorphic rocks would suggest that groundwater flow is unlikely in both catchments. Slatt (1972) found that bedrock type was not an important variable determining meltstream hydrochemistry. In this study, only relative concentrations of meltwaters within each stream are of importance. No samples were taken for analysis of cations.

7.3.2 Temporal variations of electrical conductivity

Discharge hydrographs and continuous records of electrical conductivity of the runoff in the Findelenbach are shown in Figure 7.13, for the period 1-24 August 1977. Discharge exhibits the usual distinctive diurnal rhythm of flow with the daily peaks superimposed on a slowly fluctuating background flow. The hydrographs show little short-term fluctuation, and the only precipitation event to markedly influence the discharge occurred between 0-1h on 17 August, when 2.5mm of rain fell over the catchment. Diurnal hydrographs are asymmetrical, showing a rapid rise to peak in response to the daily increase in energy supply for ablation, followed by a slower decline. Maximum discharge occurred between 17-19h and minimum flow between 8-10h. Daily variations of conductivity of meltwater occur in inverse phase compared with discharge. As flow increases, conductivity decreases rapidly as surface ablation waters pass quickly to the portal. During the night, solute concentration builds up slowly as the proportion of chemically-enriched subglacial water increases.

7.4 Feegletscher catchment

7.4.1 Individual cation concentrations

Samples of meltwaters from the two Nordzunge tributaries of the Feevispa were collected between 08.00h and 20.00h whenever possible during the field season of 1972. The sampling was adequate neither to allow investigation of temporal variations nor to identify the trapezoidal distributions of individual ions. In any case, samples were not filtered in the field, and the precision of atomic absorption determinations was much lower for all cations than for samples collected from the Gornera.

Results of determinations of the major cations for invididual samples from Feegletscher meltstreams are given in Appendix 2. The analyses indicated that the two streams had a common source beneath the rockfall

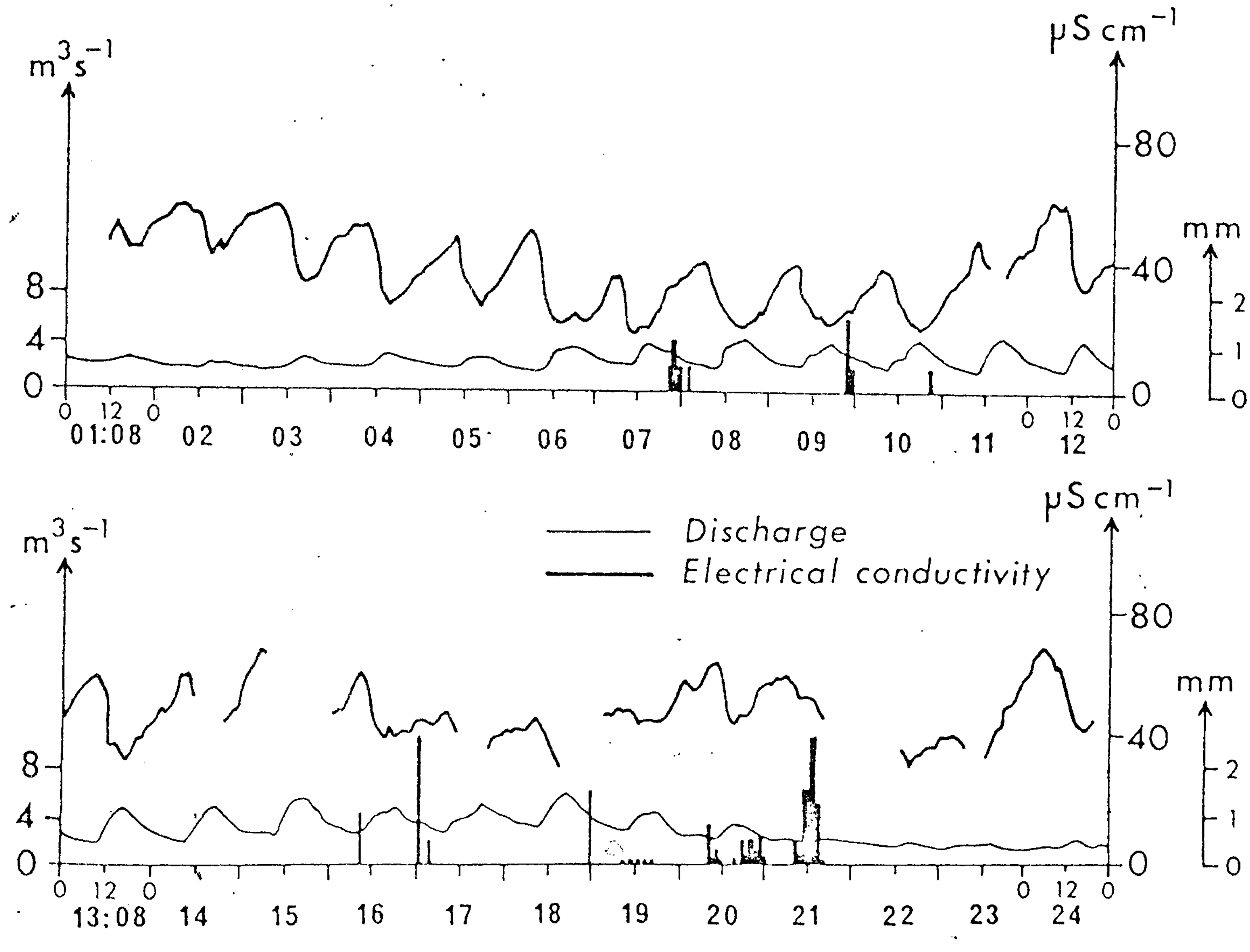


Figure 7.13 Discharge hydrographs and chemographs of recorded electrical conductivity of meltwater in the Findelenbach, draining from Findelengletscher from 1 - 24 August 1977, and precipitation at a gauge close to the glacier snout.

debris, and resulting from braiding probably downstream of the glacier snout. Ranges of all ionic concentrations determined for waters from the Feevispa were greater than those from the Gornera (Table 7.8). It is suggested that the concentrations of ions were enhanced by dissolution of particles included in the samples during storage. Neither membrane filtration nor refrigerated storage was available for use.

7.4.2 Ionic concentration-discharge relationships

Individual ionic concentration-discharge relationships were calculated for the two simple concentration models $c = a - bQ$ and $c = a\,Q^{-b}$. The results show that the usual inverse solute-discharge relationship was not present in these waters (Table 7.9). It appears that the concentrations of all ions increased to a relatively uniform level during storage. An excess of solute in the form of suspended sediment contained in the sample provided ions into the solution, possibly up to equilibrium levels for the particular mineral assemblage at the storage temperature.

7.5 Comparison of meltwater analyses with those from other glaciers

The few studies of electrical conductivity of glacial meltwaters include only limited data of temporal variations. Some comparative results from other glaciers, all in catchments underlain by igneous and metamorphic rocks, are given in Table 7.10, but direct comparison is difficult because of variations in sample treatment, length of sampling record and sampling intervals. Excluding the Alaskan glaciers, the ranges of conductivity of all meltstreams fall between 6.0 and 60.00 $\mu S\ cm^{-1}$, though individual streams differ considerably reflecting the percentage glacierisation of catchments, nature of bedrock and sediments, variations in the chemical composition of precipitation and the internal hydrology of glaciers. The ratio of maximum to minimum observed conductivity provides a useful dimensionless indication of the ranges of diurnal and seasonal variations of solute content in meltwaters. On a daily basis, this ratio for the Gornera shows a wide range (1.22-4.40) between which limits lie all observations for individual days at the other glaciers. The magnitude of the ratio depends on the timing of sample collection, which should include sampling throughout 24h periods because of diurnal variations of conductivity.

Comparison of ratios of maximum to minimum conductivity for long observation periods requires knowledge of hydrological conditions such

TABLE 7.8 SUMMARY OF RANGES OF IONIC CONCENTRATIONS IN MELTWATERS FROM THE FEEVISPA, 1972

Cation	No. of samples	Range of concentration	
		Minimum	Maximum
		mg $^{-1}$	mg $^{-1}$
Na^+	36	0.4	3.8
K^+	38	0.4	7.4
Ca^{2+}	30	0.3	9.8
Mg^{2+}	-	-	-

TABLE 7.9 PARAMETERS OF SIMPLE CONCENTRATION-DISCHARGE MODELS FOR INDIVIDUAL IONIC CONCENTRATIONS IN THE FEEVISPA

Ion	Number of samples	$c = a - bQ$	r^2	$c = a\ Q^{-b}$	r^2
Na^+	40	$c = 1.76 + 0.01Q$	0.01	$c = 1.74Q^{0.01}$	0.02
K^+	39	$c = 3.97 - 0.05Q$	0.01	$c = 4.79Q^{-0.21}$	0.03
Ca^{2+}	40	$c = 6.80 - 0.07Q$	0.02	$c = 3.92Q^{-0.04}$	0.01

TABLE 7.10 DIURNAL VARIATIONS AND SEASONAL RANGES OF ELECTRICAL CONDUCTIVITY MEASUREMENTS IN THE GORNERA, FINDELENBACH AND OTHER GLACIAL MELTWATERS

Meltwater stream	Date	Sampling design	Electrical conductivity $\mu S\ cm^{-1}$ Minimum	Maximum	Ratio Max:Min	Nature of measurements	Source
Gornera	15 July-2 September 1975	Continuous record	6.5	44.0	(6.77)	Field observations, unfiltered, 0.1-1.0°C temperature range	
	30 August 1975	Continuous record	9.5	11.0	1.22	250m from glacier portal	
	13 August 1975	Continuous record	10.0	44.0	4.40		
Surface stream, Gornergletscher	July/August 1974/1976	Continuous record	2.7	5.4	2.00	Field observation, unfiltered 0.1°C	
Findelenbach, Findelengletscher	1-24 August 1977	Continuous record	18.6	68.2	3.66	Field observations, unfiltered, 0.1-0.4°C temperature range 10m from glacier margin	
Lewis River, Baffin Island	27 July 1963 16 August 1963	4 times per hour for 24 hours	110 μS 95 μS	140 μS 205 μS	1.27 2.16	Arbitrary undetermined electrode geometry. Field observations, corrected to 1°C. 1.5km from glacier snout	Church (1974)
Chamberlin Glacier, Alaska	5-6 August 1958	Every 2 hours for 24 hours	9.0	16.0	1.78	Laboratory determinations after storage standardised at 25°C. 244m from glacier portal	Rainwater and Guy (1961)
	7 July-28 August 1958	1 observation on each of 9 days	9.0	60.0	(6.67)		
Hintereisbach, Hintereisfirner Ötztal Alps	22-3 July 1970	Every 3 hours for 24 hours	30.0	45.0	1.50	Standardised at 20°C	Behrens and others (1971)

/Continued

TABLE 7.10 (Continued)

Meltwater stream	Date	Sampling design	Electrical conductivity $\mu S\ cm^{-1}$ Minimum	Maximum	Ratio Max:Min	Nature of measurements	Source
Ekalugad Fjord, Baffin Island							
North River	10 July-	Every 4 days	6.8	12.4	(1.82)	Laboratory determinations	Church
Middle River	19 August 1967	Sample collected in	7.0	15.3	(2.19)	after storage unfiltered	(1974)
South River		late afternoon	12.8	49.1	(3.84)	for over 1 month. Standardised at 20°C	
Alaskan glaciers							
Castner	August 1968	13 samples	144.0	316.0	(2.19)	Laboratory determinations	
Norris	July 1969	7 samples	48.0	86.0	(2.26)	Filtered after storage. 25°C	Slatt (1970)
South Cascade Glacier Northern Cascade Mountains	11 August 1970	5 samples	6.3	12.9	2.05	Laboratory determinations. Storage at 24-25°C.	Reynolds and Johnson (1972)

Brackets indicate seasonal range ratios of maximum:minimum conductances.

as recession flows throughout the duration of observations. Effects of different lithological environments on meltwater conductivity can be discriminated only in terms of maximum values determined when flow is exclusively routed subglacially during recession. The wide spreads of both maximum conductivities and maximum-minimum ratios for observations throughout ablation seasons (Table 7.10) result as much from varied hydrological conditions at the glaciers during the observations as from their different environments.

Ca^{2+} is the dominant ion in meltwaters from all the glaciers listed in Table 7.11, except those on Baffin Island, where Na^{+} is probably preferentially supplied from the underlying bedrock (Church, 1972), and in Miller Creek, British Columbia, where K^{+} is dominant. All the glaciers are based on igneous or metamorphic bedrocks, but there is considerable variation in size and percentage glacierisation of catchments. Slatt (1972) showed that Ca^{2+} was the most readily mobilised ion at Matanuska, Castner and Norris glaciers in Alaska, followed by Mg^{2+} or Na^{+}. At Gornergletscher (Table 7.5), the order of rate of release of solutes is Ca^{2+} and Mg^{2+} or K^{+}. Despite the different environmental conditions experienced at the glaciers in Table 7.11, ions occur in similar relative proportions, but the ranges of ionic concentrations at each glacier probably reflect varying local hydrological conditions.

7.6 Sources of solutes

Solutes may be contributed to meltwaters from bedrock, subglacial morainic sediments, sediment-laden basal ice and suspended sediments in transit in streams. A large contribution by solute-rich groundwater flow from subglacial springs seems improbable in a catchment of predominantly impermeable rocks. The supply of readily mobilised ions is maintained by fracture of mineral crystal lattices by glacial erosion of the bed, and by crushing and frictional wear of the surfaces of particles within morainic sediment layers undergoing continuous subglacial deformation. The melting of basal ice releases particles into water courses, and sediments become entrained in waters in conduits flowing partially or totally in moraine. The most effective cation exchange and desorption probably occur where dilute meltwaters first encounter sedimentary materials. Water circulating through pores and capillaries in moraine also becomes enriched with solute.

TABLE 7.11 SUMMARY OF CATIONIC COMPOSITION OF MELTWATERS FROM GLACIER CATCHMENTS OTHER THAN THOSE IN THIS STUDY

Glacier	Date	No. of determinations	Ranges of % as %($Na^+ + K^+ + Ca^{2+} + Mg^{2+}$) Na^+ %	K^+ %	Ca^{2+} %	Mg^{2+} %	Source
Lewis Glacier, Baffin Island Lewis River	June-August 1964	14	44.6-47.0	4.7-12.4	38.1-39.7	7.5-11.0	Church (1974)
Maktak River, Baffin Island	July-August 1972	9	44.5	31.0	19.9	4.5	Church (1974)
Miller Creek, British Columbia	13 July 1973	1	14.8	42.6	39.3	3.3	Zeman and Slaymaker (1975)
Castner Glacier, Alaska	July-August 1968	11	10.9	4.2	67.2	17.6	Slatt (1970)
Norris Glacier, Alaska	July 1969	3	12.4	6.1	63.3	6.1	Slatt (1970)
Moiry Glacier, Switzerland	Summer 1971	9	-	-	68.8-90.1	-	Lorrain and Souchez (1972)

It is unlikely that suspended sediment in transit is a major source contributing solutes to the originally dilute meltwaters. Wide fluctuations in concentration of sediments occur in phase with discharge variations (Østrem, 1975) and hence out of phase with changes in conductivity. Desorption and ion-exchange initially occur rapidly to the equilibrium solute concentration in meltwater, but then, although further ions may remain surf-adsorbed to particles (Lorrain and Souchez, 1972), they are not released further during transport as suspended load. Sources of solutes restricted to the subglacial environment allow the separation of the component of total flow following subglacial passages from the portion transmitted through the englacial system.

7.7 Conclusion

Marked temporal variation in the chemical composition of glacial runoff results from the variable mixing of components of discharge which drain in changing proportions through englacial and subglacial routes within an Alpine glacier. At low flows, lithological influences characterise the composition of meltwaters, which become enriched in solute at the ice-sediment-bedrock interface of the glacier bed. Solutes are probably derived from interaction of water with freshly abraded rock flow, and eroding areas of the bed. Higher discharges are associated with dilute meltwaters, often approaching the atmospheric controlled solute content of precipitation. Ca^{2+} is the dominant ion in glacial meltwater streams draining igneous and metamorphic terrain. Glacial meltwaters should always be treated as variable in chemical composition.

Clockwise hysteretic loops occur on a diurnal time basis. Variations of electrical conductivity through time provide an indication of changing total dissolved load rather than fluctuations of individual ionic species concentrations. The presence of hysteresis loops and the variable discharge-conductivity relationship in meltwaters prevents the derivation of accurate solute transport rating curves of the usual form $S = pQ^r$ (Church, 1972), where $S = Qc$, and S is instantaneous solute transport, and c either total or individual ionic concentration, and points to the necessary use of continuous monitoring or close interval sampling over an entire season to determine solutional transport from an Alpine catchment. Ionic loads should be used, rather than loads derived from electrical conductivity since the proportions of individual ions do not remain constant.

The results from Findelengletscher and Gornergletscher provide detailed hydrochemical data for ablation seasons for two particular glacierised catchments. There remains an important need for observations in winter and during the snowmelt season in these catchments. Further intensive observations are required from other glacierised basins to determine the effects of different hydrological, glaciological and geological conditions on Alpine water quality. The data suggest that hydrochemical analysis provides a method for the separation of components of discharge within Alpine glaciers.

8. QUANTITATIVE SEPARATION OF COMPONENTS OF FLOW THROUGH INTERNAL HYDROLOGICAL SYSTEMS OF ALPINE GLACIERS

8.1 Introduction

This chapter describes a hydrochemical method for the determination of components of flow through the internal hydrological system of an Alpine glacier. The method is applied to the separation of flow-component hydrographs for the englacial and subglacial conduits of Gornergletscher and Findelengletscher. Water quality characteristics are used as a means of characterising the components of flow at the beds of the glaciers and in their englacial passages. Temporal observations of meltwater quality (Chapter 7) and discharge (Chapter 4) were used in order to evaluate changing englacial and subglacial flow capacities, and any interaction between conduit flow and temporary storage of water which may occur in cavities existing at the ice-rock interface or in pockets in the body of the glacier.

In non-glacierised catchments, portions of total discharge from delayed flow through the groundwater system and quickflow arising from precipitation have been determined from measurements of temporal changes of stream hydrochemistry (Pinder and Jones, 1969). Water percolating slowly through pores in soil and rock becomes solute-rich, and at low discharges, during baseflow recession, streams have high solute contents. During precipitation events, rapid surface and subsurface runoff allows only limited chemical enrichment of waters in transit and such waters increase discharge and dilute the solute content of the baseflow component (Toler, 1965b; Pinder and Jones, 1969; Nakamura, 1971). A composite concentration curve of HCO_3^-, SO_4^{2-}, Ca^{2+} and Mg^{2+} ions was successfully used to perform this separation (Pinder and Jones, 1969) but electrical conductivity provides a useful measure of total solute content for runoff analyses (Nakamura, 1971).

In glacierised catchments, this problem is complex because of the interaction in runoff of ice and snowmelt, precipitation on the glacier surface and over the non-glacierised area and a possible groundwater component. To overcome these problems, only the summer ablation season is considered here, when meltwater produced at the glacier surface is the most important source of water, since internal and subglacial melting together contribute negligible quantities of runoff.

In the Gornergletscher and Findelengletscher catchments, streams on the ice-free slopes are maintained only during snowmelt, and flow has effectively ceased by July ($Q_k \rightarrow 0$). However, the streams flow immediately following heavy precipitation. At times with no precipitation, the non-glacierised areas do not contribute significantly to the catchment runoff, $Q_l = Q_p = 0$. Equation (2.3) can therefore be simplified so that total runoff Q_t is given by:

$$Q_t = Q_g = Q_s + Q_i + Q_n \tag{8.1}$$

Since it is unlikely for subglacial springs to occur in these catchments, with impermeable bedrock, $Q_n \rightarrow 0$. At times with no precipitation in July and August, variations in the chemical quality of meltwaters leaving the glacier portal reflect the interaction of water with sources of solutes within or beneath the ice.

8.2 Hydrochemical separation of components of flow within glaciers

8.2.1 Routing of water determined by chemical characteristics

Diurnal inverse variations of solute concentration of portal meltstreams with discharge, during summer, result from dilution of solute-rich meltwaters by relatively pure waters flowing rapidly through the glacier from the surface (see Chapter 7). At least two chemically-distinct routes for water flow through a glacier are suggested. Water derived from the surface can flow through the glacier without delay and without chemical enrichment. Since ice away from glacier soles is relatively solute-free (Renaud, 1952a; Hallet and others, 1978), flow through an englacial, sediment-free, ice-walled conduit system would provide a route in which enrichment was minimised. Water routed through the subglacial zone, probably at overall slower rates, would become increasingly concentrated with ions on account of contact with the solute-rich basal hydrochemical environment (Souchez and others, 1973; Souchez and Lorrain, 1975). Determinations of chemical composition have shown that subglacial waters in cavities beneath Alpine glaciers are relatively solute-rich (Vivian and Zumstein, 1973).

The subglacial hydrological system has channels which may be moraine-walled, or cut in bedrock and in which sediment transport occurs. Solutes may be added to subglacial meltwaters from bedrock, subglacial morainic sediments, sediment-laden basal ice and from suspended sediments in transit in streams. Rapid desorption, ion-exchange and solution within the subglacial hydrochemical environment is assumed to bring subglacial waters to a uniform equilibrium concentration. The supply of ionic material is always maintained by fracture of mineral lattices of basal particles and the bed by glacial erosion. Crushing and frictional wear of subglacial morainic layers mobilise ionic particles as the sediments are continually deformed. Most effective enrichment probably occurs where slowly-moving dilute meltwaters first enter sedimentary environments, especially in circulation through pores and capillaries in basal moraine. Any subglacial springwater, considerably enriched chemically during slow seepage through bedrock cracks and pores, may add to the solute load of water at the bed.

Large quantities of englacially-routed waters flowing from moulins and in arterial conduits located at the bed, under the ablation area, dilute waters circulating from the subglacial system. No enrichment occurs in arterial conduits because of large volumes and high rates of flow and limited areas of contact with materials supplying ions. In this chapter, 'englacial' is used to describe the conduit system in which chemical enrichment does not occur. Englacial does not necessarily define conduit location, since arterial tunnels located at the bed form part of this system. The 'subglacial' hydrological system is that in which enrichment takes place, and of necessity is located at the ice-bedrock interface but excludes basal arterial conduits.

8.2.2 Quantitative model

Concentration of solutes in total runoff results from the contributions of water and dissolved material from the two components of flow:

$$Q_t \ C_t = Q_b \ C_b + Q_e \ C_e \tag{8.2}$$

where Q represents the runoff proportions, C the total dissolved solids content or the concentration of an individual ion in solution, in a runoff component, the subscripts refer to the total discharge from the glacier (t), flow routed through the subglacial system (b), and flow through the englacial system (e), and $Q_t = Q_b + Q_e$. Also,

$$Q_i + Q_s = Q_b + Q_e \tag{8.3}$$

Temporal variations in the quality of the total discharge reflect varying proportions of meltwaters routed through the two conduit networks.

Equation (8.2) can be solved for the portion of total discharge routed through the subglacial system:

$$Q_b = (C_t - C_e)/(C_b - C_e) \quad Q_t \qquad (8.4)$$

Mass balance equation (8.4) can be used to determine subglacial flow provided that both components of total runoff have a uniform density of 1 Mg m^{-3}, no chemical reaction occurs when the components mix, and there is no reaction between suspended sediments from the subglacial system with englacially-routed water when they meet. Sedimentary particles in suspension retain significant quantities of ions adsorbed to their surfaces, even in transit away from the portal (Lorrain and Souchez, 1972), suggesting that solution of particles (Slatt, 1972) and cation-exchange between suspended load and meltwaters (Lemmens and Roger, 1978) play only a minor role modifying the chemical composition of meltwaters once flow is in arterial canals.

8.2.3 Parameter measurement

In order to determine temporal variations of the flow-components, continuous records of both discharge and solute concentrations were required. Electrical conductivity was adopted as a measure of the total dissolved load (C) of meltwaters, since continuous records were available for C_t. Although conductivity can be used only as a measure of overall chemical composition because the proportions of individual ions are not constant through time (see Chapter 7), inaccuracy resulting from this variability is considered to be negligible in the operation of this model. The conductivity (C_e) of englacially-routed water was taken as an average value of measurements of the input, ice and snowmelt waters on the glacier surface. Measurement of the electrical conductivity characterising the hydrochemical environment beneath the glacier (C_b) was not possible, and this parameter was obtained indirectly. During recession flow, when surface ablation ceases or is greatly reduced (for example, during the lying of snow from summer precipitation), the reduction of dilute meltwater input and the steady draining of englacially and subglacially stored water allows the solute concentration of total discharge from the portal to increase towards that pertaining in the subglacial system. The maximum conductivity repeatedly recorded during recession flows provides a minimum estimate of the true subglacial value, though some dilution probably occurs at all times during the ablation season.

Hourly mean flows from the gauging stations were used for the discharge parameter Q_t. The quantities Q_t and C_t were obtained from curves of daily variations.

8.2.4 Estimates of conductivity of subglacial waters

The conductivities of subglacial water (C_b) were taken as the highest observed conductivities during recession flows of the meltstreams draining from the snouts. Records for the Gornera show that 44.0 $\mu S\ cm^{-1}$ was a repeated maximum value of conductivity during several periods of snowfall-induced recession in 1974 and 1975 (Table 7.2). During observations at Findelengletscher, such recession occurred for only one period (21-24 August 1977). The maximum observed conductivity was 68.2 $\mu S\ cm^{-1}$ (Table 7.7). A longer period of observation, extending into the winter recession flow, is needed to check the accuracy of these estimates as indicators of chemical conditions beneath the two glaciers.

8.3 Flow-component hydrographs

8.3.1 Hydrographs of the components of discharge through Findelengletscher

The proportions of total discharge flowing through the englacial and subglacial hydrological networks, calculated from equation (8.4) are shown in Figure 8.1. During the build-up of flow from 1-5 August 1977, the subglacial component of flow remained constant with a discharge of about 1.0 $m^3 s^{-1}$. The englacial conduits enabled rapid transport of ablation meltwaters to the snout during the day, and the hydrographs of the flow through the englacial system were perfectly in phase with those of total flow, and were asymmetrical with steeper rising limbs. Discharge from the englacial system continues throughout the night, suggesting that some water is delayed in flow, probably water arising from melting in the lower parts of the accumulation zone. Increased total discharge from 6-13 August was accompanied by a slight increase of mean daily flow in the subglacial conduits to 1.4 $m^3 s^{-1}$, with low amplitude diurnal variation of subglacial flow, having maxima and minima in phase with those of the total discharge. A high subglacial flow on 11 August, not caused by precipitation, either initiated or resulted from a sudden altering of the subglacial conduit capacity. Subsequent incomplete data, while not showing evidence of diurnal rhythm, illustrate the increase of capacity of flow of subglacial conduits to about 2.2 $m^3 s^{-1}$ as ablation was maintained. Reduction of energy supply during overcast days at the end of the observation

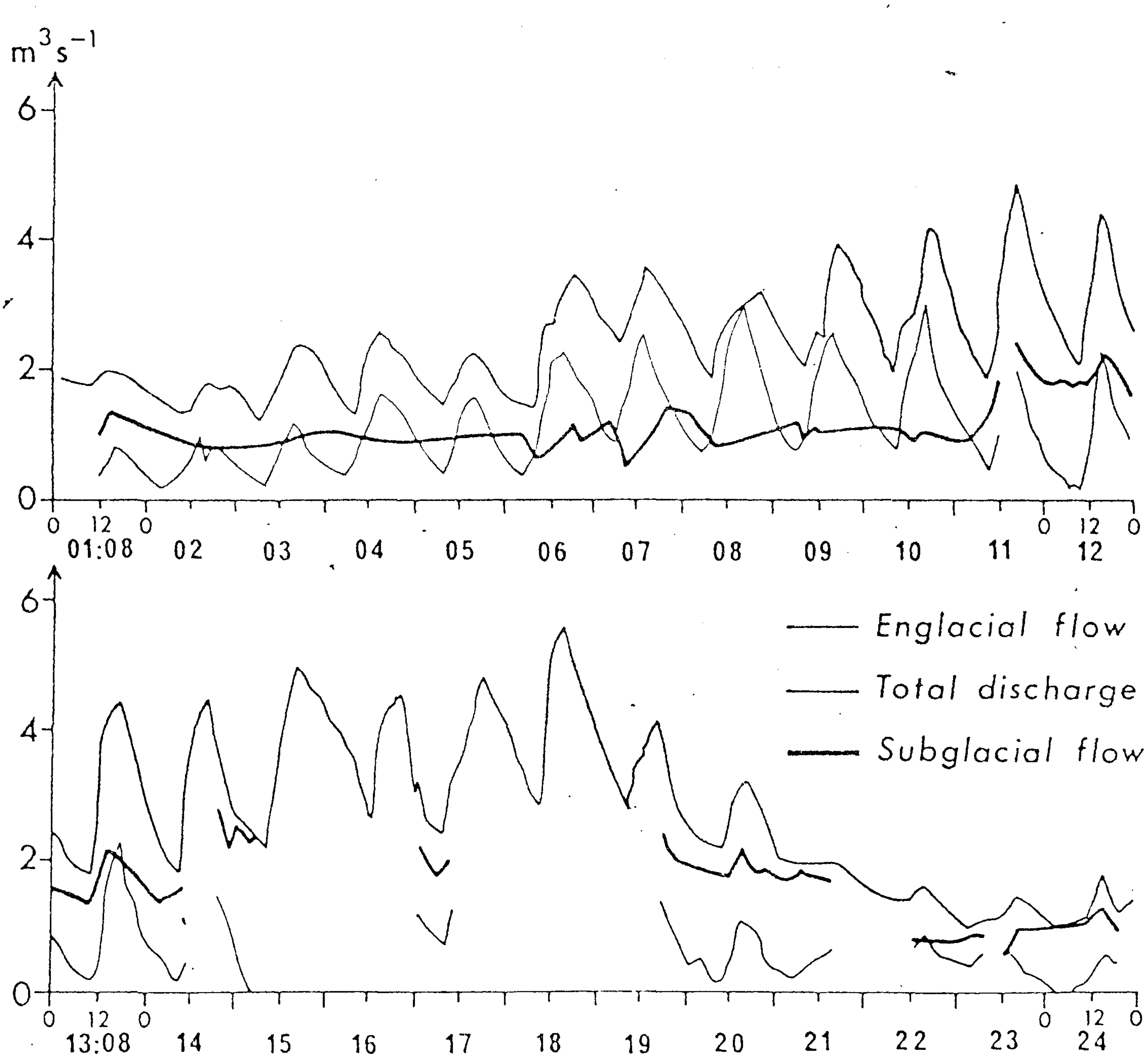


Figure 8.1 Proportions of the total discharge of the Findelenbach routed through englacial and subglacial conduits of Findelengletscher calculated from measurements of electrical conductivity of meltwaters, and discharge.

period was marked by reduction of the flow through the subglacial system. The englacial system produced hydrographs of increased peak flows with considerable temporal variation, some flow at night and maintaining asymmetry. The asymmetry of flow probably results from the time-concentration curve resulting from the shape and extent of the glacier.

In early August, the proportion of total daily flow routed through englacial conduits increased steadily to a maximum of about 60 per cent of the total discharge (Table 8.1). The subglacial system became increasingly important as the season progressed, and also carried most of the discharge when surface inputs were low. Following the high subglacial flow on 11 August, the proportion of water routed subglacially increased from 40 to 60 per cent. Diurnal variations of proportions of total discharge routed through the subglacial system are great, reflecting the importance of englacial conduits as routes for the transmission of much of the diurnal melt component through the ablation area.

8.3.2 Hydrographs of the components of discharge through Gornergletscher

Discharge through the subglacial system has a characteristic diurnal rhythm which is out of phase with that of the total discharge in the Gornera (Fig. 8.2). During the periods of background flow in the Gornera at night, the subglacial network supplies a proportion of total discharge often in excess of 50 per cent. As overall glacier discharge increases in the morning, both the proportion contributed by and the actual quantity of water discharged in the basal conduits decreases sharply. There is a steady discharge through the subglacial channels of between 2-4 $m^3 s^{-1}$ in this period, and maintained throughout the period of investigations except at times of recession produced by reduced surface ablation. There is a repeating diurnal pattern of increasing flow in the evening followed by a sudden decrease of discharge with the onset of increased flow in the englacial network. The asymmetry of the hydrograph is a mirror image of that of the englacial system and Gornera. Flow rises slowly and irregularly to a maximum which coincides with or follows up to 2h after minimum discharge through the englacial system. A large proportion of total daily flow through the subglacial conduits occurs during the peak. Maximum daily discharge in basal conduits varied from 3.2 - 8.3 $m^3 s^{-1}$ during sustained ablation. As discharge in the englacial system increases in the morning, flow from the subglacial conduits is very suddenly cut off, reducing outflow by about 70 per cent in 5h, to a minimum within 3h of the

TABLE 8.1. PROPORTIONS OF TOTAL DAILY DISCHARGE ROUTED THROUGH SUBGLACIAL AND ENGLACIAL HYDROLOGICAL SYSTEMS OF FINDELENGLETSCHER

Date	Findelenbach Mean discharge $m^3 s^{-1}$	Total discharge $x10^5 m^3 d^{-1}$	Total subglacial discharge $x10^4 m^3 d^{-1}$	Subglacial network %	Englacial network %
2.8.77	1.50	1.291	9.256	71.7	28.3
3.8.77	1.60	1.381	8.723	63.2	36.8
4.8.77	1.84	1.588	8.453	53.2	46.8
5.8.77	1.92	1.662	8.341	50.2	49.8
6.8.77	2.30	1.987	8.032	40.4	59.6
7.8.77	2.73	2.359	9.018	38.2	61.8
8.8.77	2.92	2.524	9.972	39.5	60.5
9.8.77	2.86	2.468	9.842	39.9	60.1
10.8.77	2.94	2.541	10.001	39.4	60.6
12.8.77	2.93	2.528	16.693	66.0	34.0
13.8.77	2.80	2.416	15.533	64.3	35.7
17.8.77	3.56	3.078	19.386	63.0	37.0
20.8.77	2.54	2.199	17.255	78.5	21.5

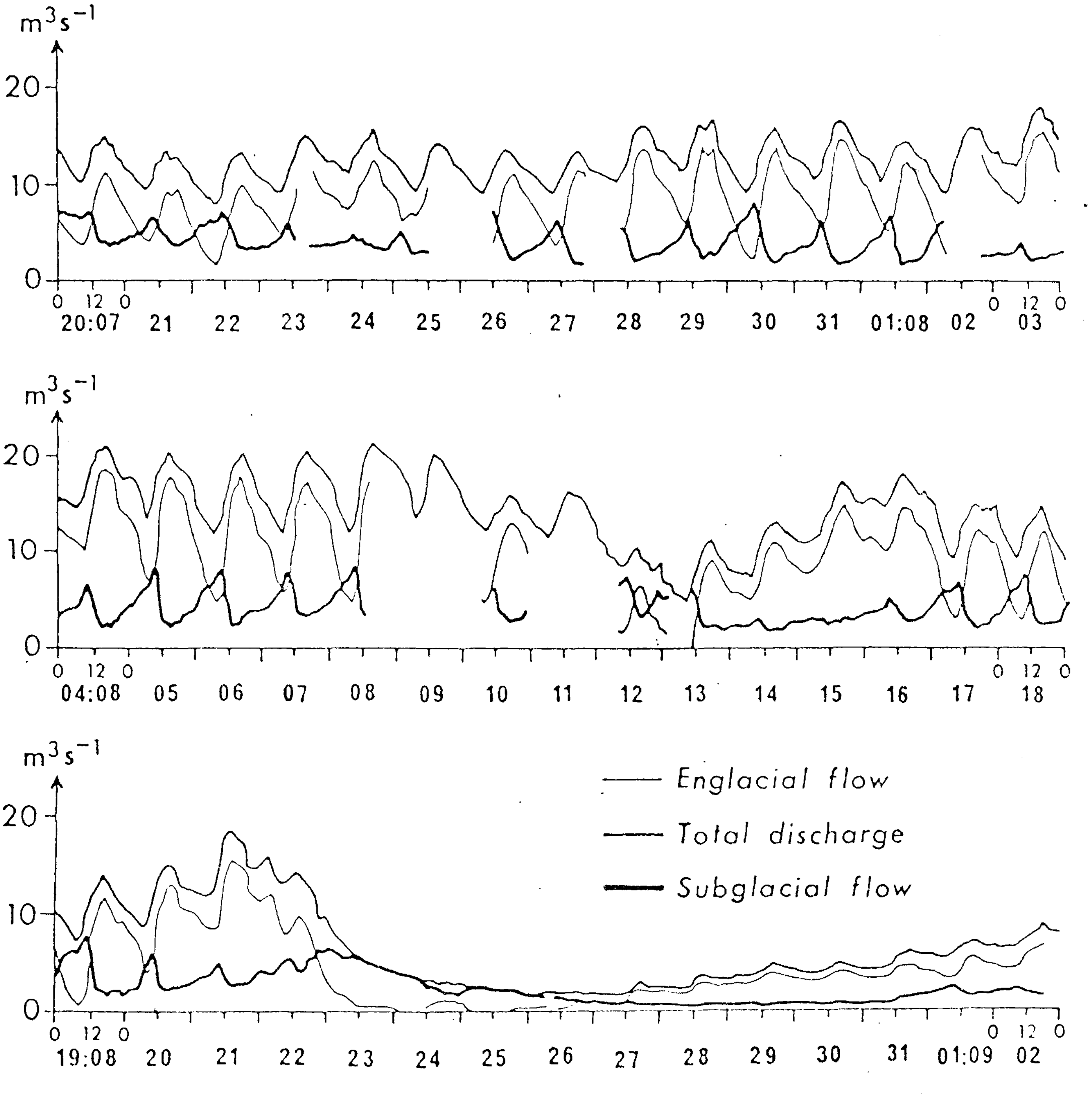


Figure 8.2 Components of flow in englacial and subglacial conduits of Gornergletscher derived from measurements of discharge and electrical conductivity in the Gornera.

englacial system maximum. The diurnal rhythmic component of discharge of the Gornera occurs in phase with variations of flow through the englacial conduits of Gornergletscher as at Findelengletscher (Fig. 8.2). Both total flow and the englacial component have asymmetrical hydrographs, with steep rising limbs concurrent with increasing melt at the surface in the morning. Rising limb gradients are steeper for the hydrographs of the englacial component and recession of peak flow decreases more rapidly than the curve of total discharge of the Gornera. The proportion of flow in the englacial system occurring during diurnal peaks is greater than for total discharge. Some flow continues through the englacial system after ablation has ceased, probably supplied by ablation in the higher remote parts of the tributary glaciers, traversing long distances to the portal. During times of sustained ablation, 60-80 per cent of the total daily flow was routed through the englacial conduits (Table 8.2).

Daily curves of flow in the two conduit systems are shown in detail in Fig. 8.3 for a period of sustained ablation (3-8 August 1975). The discharge hydrograph of waters flowing through the englacial conduits is characterised by asymmetrical peaks superimposed on a background flow which shows some limited fluctuation. Following the onset of increased surface ablation, flow rises rapidly starting between 07.00 and 09.00h to reach a peak between 15.00 - 18.00h. Discharge through the englacial system allows dilute meltwaters to reach the snout in large quantities very soon after the increase of ablation. However, it is probably only those waters descending large moulins within 1-2 km of the snout which have short transit times to the portal. The englacial system discharge hydrograph is asymmetrical with a gentle slope to its recession limb because of the time taken for water to flow to the portal from distant moulins (a function of the large dimensions and the geometry of Gornergletscher) and the increase in transit times caused by water probably being prevented from draining freely through the system at times of greatest surface input to the conduits. Diurnal variations in the rate of ablation must produce variations in transit times. The distinctive daily pattern of englacial flow is similar to the shape of the hydrograph of the total discharge of the Gornera.

The minimum percentage of total flow passing subglacially occurred at the same time as both minimum subglacial discharge and maximum total discharge, and _vice versa_, suggesting a delicate interdependence between englacial and subglacial components. The daily ranges of proportions

TABLE 8.2 PROPORTIONS OF TOTAL DAILY DISCHARGE ROUTED THROUGH SUBGLACIAL AND ENGLACIAL HYDROLOGICAL SYSTEMS OF GORNERGLETSCHER FROM 3-7 AND 14-25 AUGUST 1975

Date	Gornera Mean discharge $m^2 s^{-1}$	Total discharge $x10^5 m^3 d^{-1}$	Total subglacial drainage $x10^5 m^3 d^{-1}$	Subglacial network %	Englacial network %
3.8.75	15.19	13.123	2.571	19.6	80.4
4.8.75	17.58	15.191	3.008	19.8	80.2
5.8.75	17.64	15.245	3.794	24.9	75.1
6.8.75	15.89	13.729	3.995	28.8	71.2
7.8.75	16.71	14.437	4.013	27.8	72.2
14.8.75	10.56	9.122	2.136	23.4	76.6
15.8.75	14.30	12.356	2.686	21.7	78.3
16.8.75	16.54	14.288	3.354	23.4	76.6
17.8.75	13.47	11.639	3.870	33.3	66.7
18.8.75	12.63	10.909	3.717	34.1	65.9
19.8.75	10.45	9.026	3.536	39.9	60.1
20.8.75	12.01	10.373	2.481	24.0	76.0
21.8.75	14.96	12.922	2.769	21.4	78.6
22.8.75	13.59	11.740	4.100	34.9	65.1
23.8.75	6.28	5.430	4.603	84.7	15.3
24.8.75	3.38	2.924	2.605	89.1	10.9
25.8.75	2.32	2.000	1.851	92.6	7.4

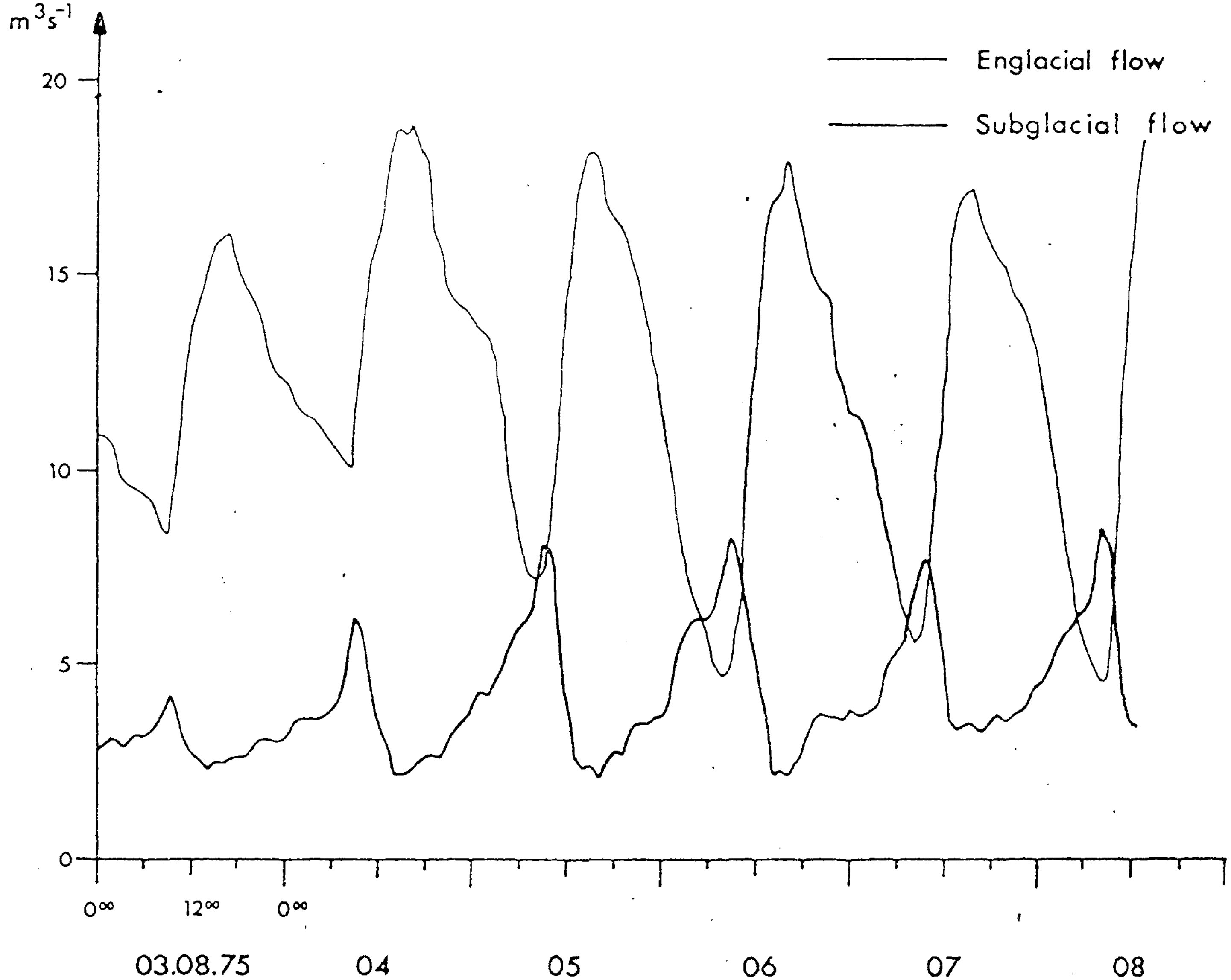


Figure 8.3 Daily variations of the discharge components routed through the englacial and subglacial networks of Gornergletscher during sustained ablation 3 - 8 August 1975, calculated from measurements of electrical conductivity and Q_t.

of flow routed subglacially were greater than for Findelengletscher. During continuing ablation, between 10-25 per cent of total flow always flows subglacially, but for a few hours each day 30-70 per cent may be so routed. Total subglacial flow is variable from day to day, and this variability overrides any trend which might result from the evolution of subglacial conduits during the ablation season.

This hydrological behaviour implies direct hydraulic interconnection of the two conduit systems, probably over a large area. A sub-vertical pipe system or a network of veins which appears not to enlarge during the season, and through which there may be little flow, probably provides a hydraulic continuity to transmit water pressure fluctuations through the glacier.

The usual diurnal rhythm of flow of the Gornera was curtailed for two separate periods (Fig. 8.2). On 15-16 August 1975, when discharge remained at the early evening level throughout the night, the usual peak flow of the subglacial system was suppressed. Increased flow through the englacial system produced a subsidiary peak between 0.00h and 3.00h, maintaining high flow until the onset of ablation in the morning. This event shows the control of subglacial flow by englacial flow within the Gornergletscher. The increased englacial discharge probably resulted from the sudden release of water held up by a blockage of major englacial conduits.

During the period 22-27 August, marked depletion occurred because of raised albedo and delayed runoff resulting from summer snowfall. Elliston (1973) attributed the continuation of depletion flow for several days after snowfall to the draining of englacial reservoirs. The flow of the englacial system effectively ceased after one day on 23 August, showing that water passes readily without storage through the conduit network. When some snowmelt occurred on 24 August, the englacial conduits allowed a small volume of meltwater quick access to the glacier portal. As englacial flow decreased, flow from the subglacial network increased for 16h to a maximum of 6.4 $m^3 s^{-1}$ before subglacial storage became subject to depletion. During recession flow from 22-27 August, the subglacial component increased to 90 per cent of the total. Integration beneath the curve of subglacial discharge depletion over 5d indicates that $9.3 \times 10^5 m^3$ of water was stored beneath the glacier before the reduction of input.

From 28 August to the end of the observation period, slow recovery of flow through the englacial system resulted in low amplitude daily peaks with an increasing background flow, suggesting flow retention in englacial conduits, either resulting from decreased capacity due to closure by ice overburden pressure, or because low flows are associated with low velocities in open channel flow. Diurnal fluctuation of subglacial system discharge only recommenced on 1 September, probably after depleted subglacial reservoirs had refilled.

8.4 Discussion

The simple two-component mixing model appears to give a useful impression of the contrasting behaviour of water beneath two Alpine glaciers, on the basis of measurements of chemical composition of meltwaters. The method has the advantage of integrating the effects of water flow throughout the bed area, and provides an indication of average conditions at the bed, in contrast to isolated measurements of pressure in boreholes or moulins or dye-tracing from individual moulins. Further, temporal variations of subglacial hydrological conditions can be determined, although no secular trend in flow was found at the Gornergletscher. The separation of subglacial flow does not distinguish between groundwater and other components of basal discharge. Unfortunately, the model does not allow the estimation of total water storage at the base of a glacier, but enables determination of rates of addition to and depletion from reservoirs.

Some inaccuracy in the calculated proportion of total flow routed through the subglacial system of a glacier will follow from errors resulting from the choice of conductivity values to represent subglacial hydrochemical environment conditions (C_b) and englacial or surface meltwater characteristics (C_e). If different estimates were used for these parameters, the percentage of total flow routed subglacially would be changed, with consequent effects on the actual quantities of meltwaters calculated as passing through both the subglacial and englacial systems. In the calculations, the value of C_b was taken as the maximum conductivity determined in the meltstream draining from each glacier during summer, and is a minimum estimate of C_b. In reality, C_b may be a function of Q_b. For Gornergletscher, should for example 88.0 $\mu S\ cm^{-1}$ be the true value of conductivity associated with the subglacial environment (rather than 44.0 $\mu S\ cm^{-1}$ used in the calculations), both the proportion of total flow routed subglacially (Q_b/Q_t) and the actual quantity Q_b

would be reduced by about 51 per cent throughout the range of total discharges in comparison with the results presented here. The choice of value of C_e also has an effect on the proportion of discharge passing subglacially and on Q_b, reduction of which varies directly with Q_t and inversely with C_t. Taking C_e as 4.0 $\mu S\ cm^{-1}$, instead of 2.0, with $C_b = 44.0$, the values of Q_b given in this chapter would be reduced by approximately 21 per cent at highest total discharges, the percentage reduction in Q_b declining towards zero as discharge decreases. Q_e would be subject to corresponding numerical increases in respect of both parameter estimation errors since $Q_e = Q_t - Q_b$. Although there may be errors in estimation of parameters, the true shapes of the hydrographs of subglacial flow will be similar to those presented here (albeit for reduced absolute discharges and with reduced or accentuated amplitudes).

8.5 Conclusion

The results of separation of the subglacial component of flow at Findelengletscher provide evidence of seasonal changes in the nature of the internal drainage system of the glacier. The calculated subglacial discharges for the beginning of the observation period support the observations by Behrens and others (1971) that a steady basal component of flow is maintained beneath Alpine glaciers, with only slight diurnal variations. However, when total discharge from the glacier is high, the subglacial system acquires an in phase diurnal rhythm of flow, alongside that of the englacial system, which responds rapidly to changes of input caused by surface hydrometeorological conditions. Interconnection between subglacial and englacial systems is probably widespread, allowing increased water pressures in the englacial hydrological system occurring at the times of highest discharges to cause in phase variation of subglacial discharge. During the observation period, the subglacial drainage network was well developed, and water was able to pass through without storage in either cavities or subglacial moraine. Some cavities may occur at the bed but they are integrated with conduit water flow. Similar conditions were inferred from dye-tracing experiments at Hintereisferner (11.2 km^2, length 6.9 km) (Ambach and others, 1972; Behrens and others, 1975).

The functioning of the internal hydrological system of the Gornergletscher appears to depend on variations of total water supply from the surface. As water supply increases with ablation in the morning, flow through the englacial system rises rapidly. Not all supplied meltwater can run off through the englacial conduits, which are probably adjusted to a mean discharge over several days (Röthlisberger, 1972). Consequently, water pressure builds up in the conduits, when rates of channel widening fail to keep pace with increasing supply. Some increase in flow will occur on account of the pressure head. Subglacial water pressure also rises, assuming a network interconnecting englacial and subglacial systems.

Subglacial water pressure will be relatively high at all times, but becomes increased at times of high water supply. Hydraulic pressure in the basal conduits may exceed the hydrostatic pressure of ice around the channel margins. The ice pressure distribution over an irregular bed will not be uniform, and areas of reduced overburden pressure may occur downstream of upstanding protuberances. Ice can separate from the bed downstream of irregularities to form cavities (Lliboutry, 1968).

It is suggested that water is diverted under pressure into cavities, which continue to expand provided water supply is maintained. Channel margin storage in cavities can account for decreased conduit flow when water pressure is relatively high. The thick morainic layers beneath the Gornergletsher may also store water which is forced at high pressure into intergranular spaces. Although flow is reduced in the subglacial network, the actual quantity of water held at the bed is greatest during higher water pressures. Evidence for such diurnal fluctuations of water pressures at the bed has been obtained at Gornergletscher (Bezinge and others, 1973). When ablation decreases in late afternoon, the supply of surface meltwaters is reduced, and falling subglacial water pressure is exceeded by the ice overburden pressure. Water from the cavities and moraine, now chemically enriched, is returned slowly to the conduits.

The daily fluctuation of water storage beneath the Gornergletscher suggests that about 30 per cent of the total water flowing within the glacier spends at least 12h in traversing through the basal conduits. The development of water-filled cavities at the bed may be related to high rates of glacier sliding (Lliboutry, 1968), and the difference between water pressure in conduits and ice overburden pressure, which also determines the closure rate of conduits (Röthlisberger, 1972). High water pressures may result from the head of water within the thick glacier, or relate to the closed depressions found in the long profile of the glacier. Water pressure appears to be transmitted from the englacial conduits to the glacier bed.

Separation of components of meltwater flow through Alpine glaciers on the basis of chemical composition has allowed some insight into the possible functioning of their internal hydrological systems. Although the parameters of the simple mass-balance equation may not be accurate, the two-component model of flow has enabled the identification of two contrasting basal hydrological regimes within Alpine valley glaciers. The model provides an overall approach to integrating the hydrological characteristics over wide areas of the glacier beds.

9. CONCLUSION

9.1 Meltwater characteristics as indicators of the internal hydrology of alpine glaciers

Temporal variations of discharge for an alpine glacier provide only limited information about the structure and functioning of the internal hydrological system. Annual, seasonal and diurnal variations of flow, although distinctive, are strongly dependent on variations in meteorological conditions. Hydrograph studies would be more useful, however, if detailed hydrometeorological data were also available.

Annual and seasonal regimes of discharge, integrated into the catchment water balance can provide a better understanding of factors controlling inputs to the glacier hydrological system. The importance of winter snow cover in preventing spring and early summer melting of ice and of snowfall terminating the ablation season are indicated. At other times, ice and firn provide reservoirs of frozen water, the release of which is limited only by energy supply, resulting in rapid variations of discharge. Variability of discharge from year to year points to the existence of differing states of development of internal drainage systems, although at Hintereisferner, the conduit network appeared not to change from one summer to the next (Behrens and others, 1975).

Assessment of the water balance of a glacierised catchment provides a useful method for investigating the impact of glacierisation on temporal variations of runoff, the mass balance of the glacier and variations in proportions of runoff derived from icemelt, or changes in glacier mass.

Diurnal hydrographs provide inconclusive evidence of the nature and behaviour of internal drainage. At best, a two-component division of runoff is suggested, a rapid flow-component concurrent with daily ablation and one which is delayed. Hydrograph studies do not permit the separation of sources or routing of the two components. As with flood hydrographs from non-glacierised rivers, hydrograph analysis leaves open the question of how much water from different sources in what proportions accounts for the peak discharge.

Hydrograph studies also provide little information about the evolution of the internal drainage networks of alpine glaciers. Of the criteria previously suggested as diagnostic of evolutionary development (Elliston, 1973), earlier timing of the peak daily discharge throughout the ablation season was not found useful. The actual timing probably depends on antecedent flows and on meteorological conditions, in addition to any evolution effect. Diurnal hydrograph shapes were so variable that monthly mean diurnal hydrographs provide inaccurate characterisation of seasonal changes.

The study of hydrographs becomes more useful during periods of anomalous discharges, permitting calculation of the total amount of water stored within an alpine glacier. However, only that storage available for runoff during depletion is included, and more liquid water probably remains stored in the glacier. Information about temporary conduit blockages, their location in the drainage network, effect and duration, can also be obtained during flow anomalies.

Much more important for the understanding of internal hydrology than measurements of quantity of flow are determinations of meltwater quality. The interaction of water with sediment at the bed results from basal hydrological and erosional processes. The study of temporal variations of suspended sediment concentration provides an indication of the sediment delivery and transport processes at the bed. The variations of discharge-suspended sediment concentration between rising and falling limbs of diurnal hydrographs and from day to day, suggests that continuous monitoring of sediment concentration throughout the period April to November is necessary for accurate estimation of rates of subglacial sedimentation. Even then, such data provide a measure only of the rate of evacuation of stored material rather than rates of actual glacial erosion as contended by Østrem (1975).

It is the hour by hour variations and sudden increases and decreases of suspended sediment concentration which provide most information about hydrological and erosional conditions at the ice-bedrock interface. Other aspects of sediment content in meltwaters may provide more information about subglacial conditions. Particle size, shape, minerology, clay minerology, and surface texture and chemistry would probably also be useful indicators of conditions at the glacier sole.

Hydrochemical analysis of meltwater allows much insight into the englacial and subglacial behaviour of water within alpine glaciers. The separation of components of flow by routing within the glacier in either subglacial (solute-rich) zones or in englacial (solute-free) zones is permitted. Temporal variations of the chemical composition of meltwaters suggests diurnal changes of flow routing and rates of transit of waters through different zones of the glacier. Based on the variable proportions of waters of atmospheric chemical origins and of lithospheric enrichment contributing to discharge, the solute-discharge relationship in meltwaters was described as a trapezium, which although non-predictive, is a better description of reality than either rating curves or hysteresis loops.

The major use of hydrochemical separation is the possibility of the use of a mass-balance mixing model based on the albeit simple two-component flow model to allow a quantitative investigation of the internal hydrology of alpine glaciers. Actual quantities of water, variable through time, in transit in different conduits, entering and leaving different storage locations and mixing together in changing proportions can be calculated. Such a quantitative separation provides a powerful method of obtaining actual values for potential use in testing theoretical models of internal drainage and of the role of water in glacier sliding. Electrical conductivity was shown to be a useful indicator of runoff components in glacio-hydrological studies.

Analysis of meltwater quality characteristics has several advantages over other field methods for the determination of internal hydrology. Direct observations can be made only in limited, small, and probably unrepresentative basal sites, where either artificial galleries penetrate subglacial cavities or where marginal caves provide access to the bed. Remote measurements of water pressure through boreholes are difficult to interpret and boreholes may change hydrological conditions locally. Also many boreholes are required to monitor undoubted spatial variations over the glacier bed. Meltwater quality studies permit interpretation of internal hydrological characteristics throughout the glacier, over the entire basal area, and may be easily subjected to continuous monitoring to allow investigation of diurnal and seasonal variations in behaviour.

Studies of isotope content of meltwaters form a complementary approach. The content of tritium, deuterium and oxygen-18 in meltwaters enables separation of flow components by source as either snowmelt or icemelt, and from long-term groundwater storage if present. Continuous monitoring for isotope content is not yet possible. However, simultaneous frequent sampling for isotope determinations, continuous monitoring of suspended sediment concentration and electrical conductivity, and recording of discharge of meltwaters would provide considerably more information about the internal hydrological systems of alpine glaciers than measurements of any of the parameters alone.

9.2 Internal hydrology of the Alpine glaciers studied, as indicated by chemical composition and suspended sediment concentration of meltwaters.

Two distinctive and contrasting subglacial hydrological regimes have been inferred from the results of quantitative separations of runoff components by the hydrochemical method. Both identified regimes, from Findelengletscher and Gornergletscher, provide information against which theories of water flow in glaciers and of the effect of water on glacier sliding may be tested. For both glaciers, diurnal supply of meltwaters occurs in phase with melting during the diurnal ablation cycle. Large quantities of dilute meltwaters rapidly reach the snout as flow increases concurrent with the onset of ablation. The dilute englacial components of flow were important at both Findelengletscher and Gornergletscher and support Röthlisberger's (1972) hypothesis of the existence of major arterial conduits beneath glaciers. While many of the major conduits are located at the bed, some may be in englacial locations, and the existence of conduits in englacial locations even beneath ablation zones of Alpine glaciers, may explain the frequent failure of subglacial hydroelectric schemes to capture meltwater streams (for example, at Glacier d'Argentière and at Bondhusbreen).

Beneath Findelengletscher, subglacial flow was at first a small and constant component of total discharge, as predicted by Behrens and others (1971), who calculated a steady groundwater flow from isotopic measurements on meltwaters from Hintereisferner. Subsequently, flow through Findelengletscher developed so that the subglacial enriched component, routed in small conduits or through basal moraine, exhibited repeated asymmetrical discharge hydrographs in phase with those of englacial and total flows. At this stage, the two internal systems are limited in their response to diurnal inputs from the surface. The change from constant to diurnal rhythmic subglacial flow was sudden, suggesting network reorganisation rather than steady widening of the subglacial system.

In contrast, Gornergletscher exhibited a subglacial flow behaviour where diurnal variations occurred inversely with those of the major internal flows and total discharge, and with reverse asymmetry. A probable interpretation is that water flows in reduced quantities through subglacial conduits other than arterial canals, (and through basal moraine at times of high flows) because high water pressures divert flow from channels into basal storage. Since conduit diameters will correspond to adjustment to a mean discharge (Röthlisberger, 1972) there are increased water pressures in the conduits approximately in phase with the availability of meltwater input. Increased water pressure can be expected to increase the flow of water through all conduits within the glacier, as shown by the englacial components of discharge at Gornergletscher, and both englacial and subglacial components at Findelengletscher.

The ice pressure distribution around subglacial channels is not uniform, and there will be areas of reduced ice pressure, especially downstream of upstanding irregularities in the bed. Water pressures at the base of the glacier will be relatively high at all times, and particularly high during the daytime. It is probable that during the day water pressure in the subglacial conduits beneath Gornergletscher exceeds the ice pressure in the zones where it is reduced by basal sliding of the ice, and ice is forced to separate from the bed to form subglacial cavities which fill with watter from the conduits. The existence of such cavities downstream of bedrock protuberances has been envisaged by Lliboutry (1968) in a theoretical treatment. Water may also be forced into the pores between sedimentary particles in morainic layers at the bed, when the pressure in the conduits is sufficiently high. Water pressures beneath the much thinner Findelengletscher are probably insufficient to initiate this interaction of conduits with cavities.

As a result of cavity formation and channel margin storage in sedimentary materials actual flow through the subglacial channels of Gornergletscher decreases with increasing water pressure. The thickness of morainic sediments under the Gornergletscher also suggests that large quantities of water may be stored in that location. When water pressure in the conduits is reduced as meltwater supply decreases, water is returned to channels under the influence of ice overburden pressure. Irregularities in the increase of flow may reflect the release of water from separate groups of storage reservoirs. The rise in flow is slow because water pressure will be maintained high for some time after maximum input from the surface to conduits because of water stored in transit in the englacial system. Discharge from the subglacial conduits decreases rapidly when the water pressure builds up again to the critical level to reverse flow back into cavities and moraine storage.

Lliboutry-cavities which continue to expand while water pressure is high probably interact with conduit flows beneath large thick Alpine glaciers. While the arterial conduits are of most importance in allowing large quantities of meltwater preferentially quick transit to the glacier portal, most of the stored water is in cavities at the glacier bed, where its potential to affect glacier sliding is greatest. Further, the proportion of water at the bed either in transit at Findelengletscher or in storage at Gornergletscher is greatest at times of highest discharges.

Elliston (1973) has proposed that Gornergletscher acts as a storage reservoir for meltwaters, from which outflow is simply regulated by reservoir water pressure. In the two-component model suggested here, increased water pressure prevents outflow of subglacial chemically-enriched water. Flow through the arterial conduit system independently responds in phase with pressure changes due to daily inputs. Effectively, during high discharges, some water is locked off in subglacial cavities, where considerable storage occurs, rather than in cracks, crevasses and moulins alone, as suggested by Elliston.

Variations of suspended sediment concentration in meltwaters from the Gornera suggest that much of the channel network within Gornergletscher occurs at the bed. This network is divided into two contrasting parts. Most of the flow appears to pass through arterial conduits in which discharge increases each day at a greater rate than sediment supply. These conduits are probably incised in the bed as suggested by both Nye (1973) and Röthlisberger (1972). Smaller tributary unstable pipes, which form a dense network over the glacier bed at the ice-rock interface, contribute most of the sediment load to the main conduits. It is probably from these smaller pipes that water is interchanged with cavities. Strong evidence for the diurnal filling and draining of cavities is provided by the morning increases of suspended sediment concentration in the Gornera concurrent with maximum flow through the subglacial drainage system as cavities drain. As water is returned to the pipes, sediment becomes entrained and enters the pipe network. Then, as flow through the small subglacial pipes is reduced, or more accurately net outflow reduced, sediment contributions are reduced. Suspended sediment concentration in the Gornera decreases both as a result of decreasing sediment supply and increasing water discharge. The network of smaller pipes at the ice-bedrock interface is unstable, providing sudden increases of sediment supply to the Gornera as pipes migrate across the bed to impinge on unworked subglacial sediment pockets.

The behaviour of the internal drainage system of Gornergletscher shows both rhythmic self-regulation of flow in response to diurnal variations of input and occasional instability during the summer ablation season. No evidence of progressive enlarging of the system was found.

Large volumes of water were also found to be stored within Feegletscher as at Gornergletscher. It would be interesting to know the extent of storage within Findelengletscher in view of its contrasting subglacial hydrological regime. Unfortunately also, there is no information about the subglacial hydrological regime of Feegletscher. Some subglacial build-up of water in cavities occurs beneath some glaciers, but this phenomenon may not be general. Englacial and arterial conduits transmit significant proportions of total discharge irrespective of subglacial hydrological conditions. A better knowledge of subglacial and englacial hydrology may result from measurements of basal water pressures alongside observations of chemical composition and discharge of meltwaters of several glaciers with differing sizes, thicknesses, and bedrock characteristics in order to determine the relationships between conduit flow and cavity storage.

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APPENDIX 1. Chemical composition of water samples collected in the Gornera close to the snout of Gornergletscher in 1974-5

All samples filtered in field immediately on collection. Electrical conductivity measured on unfiltered sample at field water temperature. (9.99 = not determined; 0.0 = determined, no trace; electrical conductivity, 0.0 = not measured)

Sample no.	Electrical conductivity $\mu S\ cm^{-1}$	Na^+ $mg\ l^{-1}$	Na^+% (%/Na^++K^++Mg^{2+}+Ca^{2+})	Na^+ $\mu Eq\ l^{-1}$	K^+ $mg\ l^{-1}$	K^+% (%/Na^++K^++Mg^{2+}+Ca^{2+})	K^+ $\mu Eq\ l^{-1}$	Mg^{2+} $mg\ l^{-1}$	Mg^{2+} (%/Na^++K^++Mg^{2+}+Ca^{2+})
Mg^{2+} $\mu Eq\ l^{-1}$	Ca^{2+} $mg\ l^{-1}$	Ca^{2+} (%/Na^++K^++Mg^{2+}+Ca^{2+})	Ca^{2+} $\mu Eq\ l^{-1}$	Na^++K^++Ca^{2+}+Mg^{2+} $mg\ l^{-1}$	(Na^++K^+)% (%/Na^++K^++Ca^{2+}+Mg^{2+})	Fe $mg\ l^{-1}$	SiO_2 $mg\ l^{-1}$	Discharge $m^3\ s^{-1}$	
74002	45.70	.55	5.47	23.93	.70	6.97	17.90	2.10	20.90
172.75	6.70	66.67	334.33	10.05	12.44	0.00	9.99	3.25	
74003	34.30	.45	5.26	19.58	.50	5.85	12.79	1.70	19.83
1[illegible]9.[illegible]4	5.90	69.01	294.41	8.55	11.11	.10	.50	3.60	
74004	33.30	.40	4.82	17.40	.50	6.02	12.79	1.60	19.28
131.62	5.80	69.88	289.42	8.30	10.84	0.00	.50	3.80	
74005	32.70	.25	3.18	10.88	.40	5.10	10.23	1.50	19.11
123.39	5.70	72.61	284.43	7.55	8.26	.10	.50	3.80	
74006	30.70	.30	3.85	13.05	.40	5.13	10.23	1.40	17.95
115.16	5.70	73.08	284.43	7.80	8.97	0.00	9.99	3.80	
74007	29.30	.50	6.33	21.75	.50	5.33	12.79	1.40	17.72
115.16	5.50	69.62	274.45	7.90	12.66	.10	9.99	3.80	
74008	28.70	.30	4.17	13.05	.30	4.17	7.67	1.30	18.06
106.94	5.30	73.61	264.47	7.20	8.33	0.00	.50	3.80	
74010	33.30	1.00	11.11	43.50	.60	6.67	15.34	1.60	17.78
131.62	5.80	64.44	289.42	9.00	17.76	0.00	.60	3.30	

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Sample no.	Electrical conductivity µS cm^{-1}	Na^{+} mg l^{-1}	Na^{+}% (%/Na^{+}+K^{+}+Mg^{2+}+Ca^{2+})	Na^{+} µEq l^{-1}	K^{+} mg l^{-1}	K^{+}% (%/Na^{+}+K^{+}+Mg^{2+}+Ca^{2+})	K^{+} µEq l^{-1}	Mg^{2+} mg l^{-1}	Mg^{2+} (%/Na^{+}+K^{+}+Mg^{2+}+Ca^{2+})	Mg^{2+} µEq l^{-1}	Ca^{2+} mg l^{-1}	Ca^{2+} (%/Na^{+}+K^{+}+Mg^{2+}+Ca^{2+})	Ca^{2+} µEq l^{-1}	Na^{+}+K^{+}+Ca^{2+}+Mg^{2+} mg l^{-1}	(Na^{+}+K^{+})% (%/Na^{+}+K^{+}+Ca^{2+}+Mg^{2+})	Fe mg l^{-1}	SiO_2 mg l^{-1}	Discharge m^3 s^{-1}
74012	22.70	1.00	11.11	43.50	.60	6.67	15.34	1.60	17.78	131.62	5.80	64.44	289.42	9.00	17.78	0.00	9.99	4.20
74013	14.70	.25	4.50	10.88	.30	5.41	7.67	.70	12.61	57.58	4.30	77.48	214.57	5.55	9.91	0.00	.30	4.95
74016	13.00	.25	4.59	10.88	.20	3.67	5.11	.50	9.17	41.13	4.50	82.57	224.55	5.45	8.26	.10	9.99	5.68
74019	13.00	.20	4.44	8.70	.20	4.44	5.11	.60	13.33	49.36	3.50	77.78	174.65	4.50	8.89	.20	.30	6.0
74021	11.70	.70	12.50	30.45	.40	7.14	10.23	.60	10.71	49.36	3.90	69.64	194.61	5.60	19.64	.10	.30	6.0
74022	13.00	.30	5.66	13.05	.20	3.77	5.11	.70	13.21	57.58	4.10	77.36	204.59	5.30	9.43	.20	.30	6.0
74023	11.70	.30	5.26	13.05	.30	5.26	7.67	.70	12.28	57.58	4.40	77.19	219.56	5.70	10.53	.10	.30	8.43
74024	16.00	.80	11.43	34.80	.60	8.57	15.34	.90	12.86	74.03	4.70	67.14	234.53	7.00	20.00	.20	.50	7.90
74025	17.30	.45	6.77	19.58	.70	10.53	17.90	.90	13.53	74.03	4.60	69.17	229.54	6.65	17.29	.20	.50	7.60
74026	16.70	.45	6.98	19.58	.60	9.30	15.34	.90	13.95	74.03	4.50	69.77	224.55	6.45	16.28	.40	.50	7.45
74027	15.00	.45	6.67	19.58	.70	10.37	17.90	1.10	16.30	90.49	4.50	66.67	224.55	6.75	17.04	.50	.60	7.25
74028	20.70	.35	4.52	15.23	.90	11.61	23.01	1.40	18.06	115.16	5.10	65.81	254.49	7.75	16.13	.40	.80	5.75

Sample no.	Electrical conductivity $\mu S\ cm^{-1}$	Na^+ $mg\ l^{-1}$	Na^+% (%/Na^++K^++Mg^{2+}+Ca^{2+})	Na^+ $\mu Eq\ l^{-1}$	K^+ $mg\ l^{-1}$	K^+% (%/Na^++K^++Mg^{2+}+Ca^{2+})	K^+ $\mu Eq\ l^{-1}$	Mg^{2+} $mg\ l^{-1}$	Mg^{2+} (%/Na^++K^++Mg^{2+}+Ca^{2+})
Mg^{2+} $\mu Eq\ l^{-1}$	Ca^{2+} $mg\ l^{-1}$	Ca^{2+} (%/Na^++K^++Mg^{2+}+Ca^{2+})	Ca^{2+} $\mu Eq\ l^{-1}$	Na^++K^+ / Ca^{2+}+Mg^{2+} $mg\ l^{-1}$	(Na^++K^+)% (%/Na^++K^++Ca^{2+}+Mg^{2+})	Fe $mg\ l^{-1}$	SiO_4 $mg\ l^{-1}$	Discharge $m^3\ s^{-1}$	
74030	21.70	.45	6.12	19.58	.70	9.52	17.90	1.30	17.69
106.94	4.9[illegible]	66.67	244.51	7.35	15.65	.40	9.99	6.10	
74031	21.00	.25	3.94	10.88	.50	7.87	12.79	.90	14.17
74.04	4.7	74.[illegible]	234.54	6.35	11.81	.20	.50	6.60	
74032	24.00	.70	[illegible]	26.10	.70	9.72	17.90	1.00	13.69
62.26	4.9[illegible]	66.6[illegible]	244.51	7.26	18.06	.10	.50	31.9	
7403[illegible]	17.10	.40	6.67	17.40	.40	5.67	10.23	.70	11.67
57.5[illegible]	4.50	75.[illegible]	224.55	6.00	13.33	0.00	9.99	13.0	
74039	11.70	.50	6.47	21.75	.50	8.47	12.79	.80	15.56
65.51	4.10	69.47	204.59	9.90	16.95	.20	9.99	14.00	
74040	9.30	.20	4.88	8.70	.20	4.88	5.11	.30	7.32
24.65	3.40	[illegible]	169.56	4.10	9.76	0.00	9.99	15.0	
74041	10.70	.20	4.33	8.70	.20	4.88	5.11	.30	7.32
24.67	3.40	82.9	169.56	4.10	9.76	.20	9.99	15.3	
74042	9.30	.25	6.02	10.88	.20	4.82	5.11	.30	7.25
24.66	3.40	81.9	169.66	4.15	10.64	.00	9.99	15.0	
74043	10.70	.05	1.30	2.18	.10	2.60	2.56	.20	5.19
16.45	3.50	90.91	174.65	3.85	3.90	.10	9.99	14.5	
74044	12.00	.40	7.69	17.40	.50	9.62	12.79	.50	9.62
41.15	3.00	73.0	149.62	5.26	17.31	.30	.50	13.8	
74045	10.70	.15	3.90	6.55	.20	5.19	5.11	.30	7.79
24.00	3.2[illegible]	[illegible].1	159.85	[illegible]	9.09	.5[illegible]	9.99	14.7	
74046	10.70	.10	41.19	154.23	.50	4.76	12.79	.20	4.05
24.63	3.5[illegible]	47.7	174.65	7.40	48.65	.4[illegible]	9.99	13.5	

Sample no.	Electrical conductivity $\mu S\ cm^{-1}$	Na^+ mg l^{-1}	Na^+% (%/Na^++K^++Mg^{2+}+Ca^{2+})	Na^+ $\mu Eq\ l^{-1}$	K^+ mg l^{-1}	K^+% (%/Na^++K^++Mg^{2+}+Ca^{2+})	K^+ $\mu Eq\ l^{-1}$	Mg^{2+} mg l^{-1}	Mg^{2+} (%/Na^++K^++Mg^{2+}+Ca^{2+})
Mg^{2+} $\mu Eq\ l^{-1}$	Ca^{2+} mg l^{-1}	Ca^{2+} (%/Na^++K^++Mg^{2+}+Ca^{2+})	Ca^{2+} $\mu Eq\ l^{-1}$	Na^++K^++Ca^{2+}+Mg^{2+} mg l^{-1}	(Na^++K^+)% (%/Na^++K^++Ca^{2+}+Mg^{2+})	Fe mg l^{-1}	SiO_4 mg l^{-1}	Discharge $m^3\ s^{-1}$	
74047	13.30	.25	4.50	10.86	.50	9.01	12.79	.70	12.61
57.56	4.10	73.87	204.59	5.55	13.51	.40	9.99	12.4	
74048	14.00	.50	8.20	21.75	.70	11.48	17.90	.70	11.48
57.5	4.20	68.85	209.57	6.10	19.67	.20	.40	11.6	
74049	22.30	.55	8.20	15.25	9.99	11.48	255.44	1.10	11.48
90.49	5.10	68.85	254.49	6.60	0.00	.10	9.99	8.9	
74050	25.00	.40	5.48	17.40	.60	8.22	15.34	1.20	16.44
98.71	5.10	69.88	254.49	7.30	13.70	.20	9.99	8.8	
74051	24.70	.55	6.36	23.93	.60	6.94	15.34	2.30	26.59
109.20	5.20	60.12	259.48	8.65	13.29	.30	9.99	8.7	
74056	8.70	.35	8.05	15.23	.50	11.49	12.79	.50	11.49
41.13	3.00	65.97	149.70	4.35	19.54	.50	9.99	9.99	
74057	9.30	.35	7.53	15.23	.70	15.05	17.90	.60	12.95
49.36	3.00	64.52	149.70	4.65	22.56	.60	.70	9.99	
74058	9.30	.30	6.62	13.05	.60	13.54	15.34	.30	11.36
41.13	3.00	66.16	149.70	4.46	20.45	.50	9.99	9.99	
74059	11.40	.60	10.17	29.10	1.30	22.05	33.24	1.00	16.95
82.26	3.00	50.85	149.75	5.90	37.20	2.70	9.99	9.99	
74060	10.30	.75	12.82	32.65	1.20	20.51	30.68	.90	15.35
74.03	3.00	51.27	149.70	5.85	33.33	1.10	9.99	9.99	
74061	9.30	.40	7.41	17.40	1.00	16.52	25.57	.90	16.67
74.03	3.10	57.41	154.69	5.40	29.93	1.00	9.99	9.99	
74062	8.70	.60	10.00	26.10	1.30	21.67	33.24	1.40	23.45
115.16	2.70	45.00	134.75	[illegible]	31.67	2.00	.90	9.99	

Sample no.	Electrical conductivity $\mu S\ cm^{-1}$	Na^+ $mg\ l^{-1}$	$Na^+\%$ ($\%/Na^++K^++Mg^{2+}+Ca^{2+}$)	Na^+ $\mu Eq\ l^{-1}$	K^+ $mg\ l^{-1}$	$K^+\%$ ($\%/Na^++K^++Mg^{2+}+Ca^{2+}$)	K^+ $\mu Eq\ l^{-1}$	Mg^{2+} $mg\ l^{-1}$	Mg^{2+} ($\%/Na^++K^++Mg^{2+}+Ca^{2+}$)
Mg^{2+} $\mu Eq\ l^{-1}$	Ca^{2+} $mg\ l^{-1}$	Ca^{2+} ($\%/Na^++K^++Mg^{2+}+Ca^{2+}$)	Ca^{2+} $\mu Eq\ l^{-1}$	Na^++K^+ / $Ca^{2+}+Mg^{2+}$ $mg\ l^{-1}$	$(Na^++K^+)\%$ ($\%/Na^++K^++Ca^{2+}+Mg^{2+}$)	Fe $mg\ l^{-1}$	SiO_4 $mg\ l^{-1}$	Discharge $m^3\ s^{-1}$	
74067	17.30	.35	12.41	30.96	.90	13.14	23.01	.90	13.14
74.05	4.20	61.31	209.58	6.85	25.55	.60	9.99	9.99	
74068	13.70	.40	6.72	17.40	.90	15.25	23.01	1.10	15.64
90.49	3.50	59.32	174.[illegible]	5.90	22.03	1.30	9.99	9.99	
74069	15.[illegible]0	.25	5.15	1[illegible].86	.30	6.19	7.67	.40	8.25
32.90	3.90	30.41	194.81	64.85	11.34	0.00	9.99	9.99	
74070	15.30	.65	7.44	19.58	.70	11.57	17.90	.90	14.66
74.05	4.00	60.12	199.60	6.05	19.01	9.99	9.99	9.99	
74075	29.30	.45	8.98	19.58	.30	4.26	7.67	1.20	17.02
98.71	5.10	72.34	254.49	7.05	10.64	9.99	9.99	9.10	
74076	28.30	.70	9.21	30.45	.70	9.21	17.90	1.30	17.11
106.94	4.90	64.47	244.51	7.60	15.42	9.99	9.99	10.00	
74077	21.00	.60	8.96	26.10	.50	7.46	12.79	1.00	14.93
32.26	4.60	[illegible].56	229.54	7.70	16.42	9.99	9.99	11.00	
74078	16.70	.45	7.96	19.[illegible]	.30	5.31	7.67	.70	12.5[illegible]
57.58	4.20	74.34	2[illegible]7.58	5.[illegible]5	13.27	9.99	9.99	12.5	
74079	13.00	.15	[illegible].33	6.55	.20	4.71	5.11	.50	11.76
41.13	3.40	80.00	169.66	4.25	6.24	9.99	9.99	13.5	
74080	9.00	.45	13.43	1[illegible].55	.20	5.97	5.11	.20	5.97
16.45	2.50	74.63	124.75	[illegible]	19.40	9.99	9.99	14.6	
74081	6.30	.35	10.45	15.23	.20	5.97	5.11	.30	[illegible].96
24.63	2.50	74.[illegible]	124.75	[illegible].35	16.42	9.99	9.99	14.5	
74082	9.00	.55	13.92	[illegible]	.30	7.59	7.67	.30	7.59
24.68	2.90	70.59	139.76	[illegible].95	21.52	9.99	.30	13.6	

Sample no. / Mg^{2+} µEq l^{-1}	Electrical conductivity µS cm^{-1} / Ca^{2+} mg l^{-1}	Na^+ mg l^{-1} / Ca^{2+} (%/Na^++K^++Mg^{2+}+Ca^{2+})	Na^+% (%/Na^++K^++Mg^{2+}+Ca^{2+}) / Ca^{2+} µEq l^{-1}	Na^+ µEq l^{-1} / Na^++K^+ / Ca^{2+}+Mg^{2+} mg l^{-1}	K^+ mg l^{-1} / (Na^++K^+)% (%/Na^++K^++Ca^{2+}+Mg^{2+})	K^+% (%/Na^++K^++Mg^{2+}+Ca^{2+}) / Fe mg l^{-1}	K^+ µEq l^{-1} / SiO_4 mg l^{-1}	Mg^{2+} mg l^{-1} / Discharge m^3 s^{-1}	Mg^{2+} (%/Na^++K^++Mg^{2+}+Ca^{2+})
74083	9.30	.35	9.53	15.23	.30	8.00	7.67	.30	8.00
24.66	2.80	74.67	139.72	.75	17.33	9.99	9.99	13.5	
74084	12.30	.[illegible]	17.39	34.80	.50	10.67	12.79	.30	6.52
24.66	3.00	65.22	149.70	4.60	28.26	9.99	9.99	13.2	
74085	40.00	.70	7.41	30.45	.90	5.43	12.79	1.80	19.57
148.07	6.20	67.39	309.36	9.20	15.04	9.99	9.99	6.2	
74087	40.00	.85	8.61	36.96	.60	3.29	20.46	1.90	19.69
156.29	6.10	63.21	304.39	9.65	17.10	9.99	9.99	6.0	
74089	3[illegible].70	.80	8.79	34.80	.60	6.59	15.34	1.80	19.78
148.07	5.90	64.14	294.61	9.10	15.38	9.99	9.90	6.0	
74091	31.00	.55	6.01	23.93	.90	9.84	23.01	1.80	19.67
148.07	5.90	64.45	294.41	9.15	15.85	9.99	.67	6.5	
74093	33.70	.75	9.94	31.98	.60	7.02	15.34	1.60	18.71
131.62	5.50	64.33	274.45	7.55	16.96	9.99	9.99	7.2	
74095	29.70	.55	7.36	23.93	.50	5.71	12.79	1.50	17.45
106.94	5.10	68.44	254.49	7.45	14.09	9.99	9.99	8.00	
74097	20.30	.25	4.25	10.86	.30	5.04	7.67	.90	15.13
74.03	4.50	75.61	224.55	7.99	9.24	9.99	9.99	8.3	
74099	12.00	.15	3.37	6.53	.20	4.49	5.11	.50	11.24
41.13	3.60	80.[illegible]	179.64	[illegible].45	7.87	9.99	9.99	9.1	
74100	34.30	.40	5.[illegible]	17.40	.50	5.53	12.79	1.50	1[illegible].99
123.39	5.50	59.[illegible]	274.45	[illegible]	11.39	[illegible]	[illegible]	9.0	
74101	9.70	.10	1.82	4.35	.10	1.80	2.56	.20	[illegible].45
24.[illegible]	5.00	90.91	249.5[illegible]	5.[illegible]	5.84	9.99	9.99	9.2	

Sample no.	Electrical conductivity $\mu S\ cm^{-1}$	Na^+ $mg\ l^{-1}$	Na^+% (%/Na^++K^++Mg^{2+}+Ca^{2+})	Na^+ $\mu Eq\ l^{-1}$	K^+ $mg\ l^{-1}$	K^+% (%/Na^++K^++Mg^{2+}+Ca^{2+})	K^+ $\mu Eq\ l^{-1}$	Mg^{2+} $mg\ l^{-1}$	Mg^{2+} (%/Na^++K^++Mg^{2+}+Ca^{2+})
Mg^{2+} $\mu Eq\ l^{-1}$	Ca^{2+} $mg\ l^{-1}$	Ca^{2+} (%/Na^++K^++Mg^{2+}+Ca^{2+})	Ca^{2+} $\mu Eq\ l^{-1}$	Na^++K^+ / Ca^{2+}+Mg^{2+} $mg\ l^{-1}$	(Na^++K^+)% (%/Na^++K^++Ca^{2+}+Mg^{2+})	Fe $mg\ l^{-1}$	SiO_2 $mg\ l^{-1}$	Discharge $m^3\ s^{-1}$	
74102	0.00	.40	18.55	17.40	.10	7.89	7.67	.20	5.26
16.45	2.90	76.32	144.71	5.80	18.42	9.99	9.99	10.0	
74103	10.70	.10	2.94	4.35	.10	2.94	2.56	.30	8.82
24.6[illegible]	2.90	65.29	144.71	3.40	5.86	9.99	9.99	9.5	
75100	22.00	.50	7.70	21.75	.69	10.63	17.64	1.00	15.41
62.20	4.30	66.20	214.57	6.49	16.34	9.99	9.99	11.49	
75103	13.00	.26	5.09	11.31	.57	11.15	14.57	.80	15.66
65.61	3.48	68.10	173.65	5.11	16.24	9.99	9.99	12.62	
75105	14.50	.23	5.25	10.01	.50	11.42	12.79	.70	15.98
57.5[illegible]	2.75	67.35	147.21	4.3[illegible]	16.67	9.99	9.99	13.20	
75107	0.00	.16	2.3[illegible]	6.96	.58	10.26	14.8[illegible]	.85	17.97
59.92	3.14	66.35	156.69	4.7[illegible]	15.64	9.99	9.99	14.92	
75108	0.00	.14	4.14	6.09	.33	9.76	8.44	.51	15.09
41.75	2.40	71.01	119.76	7.33	13.91	9.99	9.99	14.38	
75111	11.50	.15	4.23	6.33	.41	11.55	10.48	.57	16.06
46.89	2.42	66.17	120.76	5.55	15.77	9.99	9.99	14.75	
75112	14.00	.20	3.99	8.70	.54	10.78	13.81	.77	15.37
63.34	3.50	69.66	174.65	5.01	14.77	9.99	9.99	13.26	
75115	29.50	.77	6.60	33.50	.97	11.09	24.80	1.36	15.54
111.[illegible]7	5.65	64.57	261.94	8.75	19.89	9.99	9.99	11.14	
75119	24.50	.36	5.11	15.[illegible]	.74	10.56	16.92	1.15	16.31
94.[illegible]	4.80	58.07	259.52	7.65	15.80	9.99	9.99	11.91	
75123	16.50	.25	4.31	16.01	.56	10.4[illegible]	14.32	.[illegible]5	15.92
69.92	3.70	59.29	164.65	5.34	14.74	9.99	9.99	12.57	

Sample no.	Electrical conductivity µS cm^{-1}	Na^+ mg l^{-1}	Na^+% (%/Na^++K^++Mg^{2+}+Ca^{2+})	Na^+ µEq l^{-1}	K^+ mg l^{-1}	K^+% (%/Na^++K^++Mg^{2+}+Ca^{2+})	K^+ µEq l^{-1}	Mg^{2+} mg l^{-1}	Mg^{2+} (%/Na^++K^++Mg^{2+}+Ca^{2+})
Mg^{2+} µEq l^{-1}	Ca^{2+} mg l^{-1}	Ca^{2+} (%/Na^++K^++Mg^{2+}+Ca^{2+})	Ca^{2+} µEq l^{-1}	Na^++K^++Ca^{2+}+Mg^{2+} mg l^{-1}	(Na^++K^+)% (%/Na^++K^++Ca^{2+}+Mg^{2+})	Fe mg l^{-1}	SiO_2 mg l^{-1}	Discharge m^3 s^{-1}	
75127	14.50	.18	4.47	7.83	.47	11.66	12.02	.04	15.88
52.65	2.74	67.97	[illegible]	4.05	16.13	9.99	9.99	13.04	
75131	12.50	[illegible]	[illegible]	11.21	.65	16.28	16.62	.55	14.29
45.24	[illegible]	[illegible]	119.26	[illegible]	23.64	9.99	9.99	13.47	
75133	11.30	.15	4.25	[illegible]	.54	15.30	13.81	.54	15.30
44.42	[illegible]	[illegible]	114.77	[illegible]	19.55	9.99	9.99	13.60	
75135	[illegible]	.11	3.57	4.79	.35	11.36	8.95	.50	16.23
41.13	2.12	[illegible]	105.79	[illegible]	14.94	9.99	9.99	13.15	
75137	21.00	.26	3.64	11.31	.76	10.65	19.43	1.04	14.55
65.55	5.09	71.1[illegible]	[illegible]	7.15	14.27	9.99	9.99	9.62	
75139	22.00	.49	6.46	21.32	[illegible]	13.70	26.59	1.17	15.42
96.24	[illegible]	[illegible]	244.01	7.59	[illegible]	9.99	9.99	9.19	
75143	[illegible]	.28	4.97	12.13	.29	12.26	17.64	.90	15.99
78.97	4.05	[illegible]	202.16	[illegible]	17.35	9.99	9.99	1 .48	
75147	23.00	.34	4.77	14.79	.26	12.57	21.99	1.36	[illegible]
67.20	4.57	[illegible]	228.54	8.24	17.54	9.99	9.99	11.10	
75149	25.00	.49	6.27	21.32	1.11	14.19	28.38	1.09	13.94
89.66	5.13	[illegible]	[illegible]	[illegible]	[illegible]	9.99	9.99	11.12	
75154	21.00	.56	[illegible]	25.23	2.29	26.57	51.56	1.43	16.59
117.53	4.32	[illegible]	215.57	[illegible]	53.29	9.99	9.99	[illegible]	
75156	22.50	.75	3.54	[illegible]	.34	11.28	21.48	1.18	[illegible]
97.07	4.80	[illegible]	[illegible]	[illegible]	15.42	9.99	9.99	14.31	
[illegible]	24.00	[illegible]	3.54	[illegible]	.62	11.82	20.67	1.25	[illegible]
102.65	9.99	[illegible]	[illegible]	[illegible]	[illegible]	9.99	9.99	15.51	

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Sample no.	Electrical conductivity µS cm^{-1}	Na^+ mg l^{-1}	Na^+% (%/Na^++K^++Mg^{2+}+Ca^{2+})	Na^+ µEq l^{-1}	K^+ mg l^{-1}	K^+% (%/Na^++K^++Mg^{2+}+Ca^{2+})	K^+ µEq l^{-1}	Mg^{2+} mg l^{-1}	Mg^{2+} (%/Na^++K^++Mg^{2+}+Ca^{2+})
Mg^{2+} µEq l^{-1}	Ca^{2+} mg l^{-1}	Ca^{2+} (%/Na^++K^++Mg^{2+}+Ca^{2+})	Ca^{2+} µEq l^{-1}	Na^++K^+/Ca^{2+}+Mg^{2+} mg l^{-1}	(Na^++K^+)% (%/Na^++K^++Ca^{2+}+Mg^{2+})	Fe mg l^{-1}	SiO_4 mg l^{-1}	Discharge m^3 s^{-1}	
75166	21.50	.28	4.38	12.18	.68	10.63	17.39	1.04	16.25
65.55	4.40	67.75	219.56	6.40	15.00	9.99	9.99	17.25	
75172	14.00	.38	6.82	16.53	.68	12.21	17.39	.91	16.34
74.86	3.60	64.[illegible]	179.64	5.57	19.05	9.99	9.99	15.75	
75207	25.00	.35	8.57	10.98	.66	9.43	16.88	1.23	17.37
101.16	4.98	[illegible].42	242.51	7.00	13.00	9.99	9.99	8.58	
75201	16.00	.17	3.94	7.40	.50	11.57	12.79	.71	16.44
58.40	2.94	68.08	146.71	4.32	15.51	9.99	9.99	9.43	
75214	1[illegible].00	.13	3.79	5.06	.41	11.95	10.45	.57	16.62
46.[illegible]9	2.37	[illegible]7.54	115.77	5.43	15.74	9.99	9.99	10.18	
75204	10.00	.19	2.75	3.92	.37	11.31	9.46	.52	15.90
42.76	2.29	70.05	114.27	.27	14.07	9.99	9.99	10.9	
75219	10.00	[illegible]	1.9[illegible]	2.61	.33	10.78	8.44	.50	16.34
41.1	2.17	70.97	10[illegible].2[illegible]	.06	12.75	9.99	9.99	11.54	
75211	10.00	0.00	0.00	.00	.40	12.23	10.23	.54	16.51
44.42	2.35	71.25	116.27	5.27	12.23	9.99	9.99	11.52	
75209	12.00	9.99	0.00	454.57	9.99	12.23	255.44	.62	16.51
51.00	2.[illegible]	71.25	116.27	0.00	0.00	9.99	9.99	9.95	
75228	12.00	.12	3.02	5.22	.45	12.09	12.27	.62	15.62
51.00	2.75	69.27	137.23	2.97	15.11	9.99	9.99	9.60	
75229	12.50	.14	3.37	6.09	.50	12.05	12.79	.64	15.42
52.55	2.[illegible]7	[illegible].1[illegible]	145.21	4.15	15.42	9.99	9.99	9.03	
75217	12.50	.15	3.77	6.03	.47	11.81	12.02	.44	16.08
52.55	2.72	69.34	155.73	5.98	15.56	9.99	9.99	6.5	

Sample no. / Mg^{2+} µEq l^{-1}	Electrical conductivity µS cm^{-1} / Ca^{2+} mg l^{-1}	Na^{+} mg l^{-1} / Ca^{2+}% (%/Na^{+}+K^{+}+Mg^{2+}+Ca^{2+})	Na^{+}% (%/Na^{+}+K^{+}+Mg^{2+}+Ca^{2+}) / Ca^{2+} µEq l^{-1}	Na^{+} µEq l^{-1} / Na^{+}+K^{+}/Ca^{2+}+Mg^{2+} mg l^{-1}	K^{+} mg l^{-1} / (Na^{+}+K^{+})% (%/Na^{+}+K^{+}+Ca^{2+}+Mg^{2+})	K^{+}% (%/Na^{+}+K^{+}+Mg^{2+}+Ca^{2+}) / Fe mg l^{-1}	K^{+} µEq l^{-1} / SiO_2 mg l^{-1}	Mg^{2+} mg l^{-1} / Discharge m^3 s^{-1}	Mg^{2+} (%/Na^{+}+K^{+}+Mg^{2+}+Ca^{2+})
75234	14.00	.19	4.30	8.27	.62	14.03	15.85	.73	16.52
60.05	2.84	65.1[illegible]	143.71	4.42	18.33	9.99	9.99	8.5	
75241	14.50	.18	3.62	6.96	.60	13.57	13.34	.65	14.71
53.47	3.01	68.1[illegible]	150.20	4.42	17.19	9.99	9.99	8.26	
75227	14.00	.14	3.28	6.09	.52	12.18	13.30	.66	15.46
54.27	2.95	59.09	147.21	4.27	15.46	9.99	9.99	8.3	
75230	14.00	.15	3.40	6.53	.60	13.61	15.34	.66	15.42
55.94	2.98	57.57	148.70	4.41	17.01	9.99	9.99	8.1	
75235	14.50	.21	4.60	9.14	.48	10.50	12.27	.74	16.19
60.57	3.14	66.71	156.69	4.57	15.10	9.99	9.99	7.75	
75237	14.50	.27	5.74	11.75	.59	12.55	15.09	.70	14.69
57.58	3.14	66.81	156.69	4.76	18.30	9.99	9.99	[illegible]	
75240	15.00	.25	5.29	10.88	.65	14.74	16.62	.74	15.64
60.57	3.09	65.55	154.19	4.73	19.03	9.99	9.99	7.72	
75249	16.00	.23	4.97	10.01	.45	9.72	11.51	.75	16.20
61.70	3.20	65.11	159.68	4.65	14.69	9.99	9.99	8.04	
75245	16.00	.22	4.25	9.57	.70	13.51	17.90	.83	16.02
68.23	3.4[illegible]	66.22	171.16	5.16	17.76	9.99	9.99	.96	
75242	15.50	.19	3.92	8.27	.60	12.37	15.34	.77	15.86
63.34	3.29	67.84	164.17	[illegible]	16.29	9.99	9.99	9.56	
75247	13.00	.14	3.44	6.19	.50	12.29	12.79	.66	16.22
54.29	2.77	[illegible]	138.22	4.07	15.72	9.99	9.99	[illegible]	
75276	29.00	.33	5.60	14.36	.95	[illegible]	24.29	1.50	17.26
123.37	5.9	[illegible]	294.41	[illegible]	14.75	9.99	9.99	12.25	

Sample no.	Electrical conductivity $\mu S\ cm^{-1}$	Na^+ $mg\ l^{-1}$	Na^+% (%/Na^++K^++Mg^{2+}+Ca^{2+})	Na^+ $\mu Eq\ l^{-1}$	K^+ $mg\ l^{-1}$	K^+% (%/Na^++K^++Mg^{2+}+Ca^{2+})	K^+ $\mu Eq\ l^{-1}$	Mg^{2+} $mg\ l^{-1}$	Mg^{2+} (%/Na^++K^++Mg^{2+}+Ca^{2+})
Mg^{2+} $\mu Eq\ l^{-1}$	Ca^{2+} $mg\ l^{-1}$	Ca^{2+} (%/Na^++K^++Mg^{2+}+Ca^{2+})	Ca^{2+} $\mu Eq\ l^{-1}$	Na^++K^++Ca^{2+}+Mg^{2+} $mg\ l^{-1}$	(Na^++K^+)% (%/Na^++K^++Ca^{2+}+Mg^{2+})	Fe $mg\ l^{-1}$	SiO_2 $mg\ l^{-1}$	Discharge $m^3\ s^{-1}$	
75272	23.50	.31	4.66	13.49	.76	11.43	19.43	1.11	16.69
91.51	4.47	67.22	223.05	6.65	16.09	9.99	9.99	12.83	
75274	16.00	.19	4.02	8.27	.59	12.47	15.09	.78	16.49
64.16	3.17	67.02	158.14	4.73	16.49	9.99	9.99	13.21	
75278	17.50	.24	4.02	10.44	9.99	12.47	255.44	.96	16.49
78.97	3.20	67.02	159.68	0.00	0.00	9.99	9.99	10.25	
75286	22.00	.29	4.03	12.62	1.11	15.42	28.38	1.23	17.08
101.18	4.57	63.47	228.04	7.20	19.44	9.99	9.99	9.7	
75282	26.00	.30	3.79	13.05	1.16	14.65	29.66	1.32	16.67
108.58	5.14	64.90	256.49	7.92	18.43	9.99	9.99	9.3	
75287	29.00	.38	4.24	16.53	1.45	16.16	37.08	1.58	17.61
129.97	5.56	61.98	277.44	8.97	20.40	9.99	9.99	8.74	
75285	34.00	.42	5.67	20.97	1.58	14.44	40.40	1.85	16.91
152.16	6.89	62.95	343.81	10.94	20.11	9.99	9.99	7.83	
75292	36.00	.62	4.95	26.97	2.70	21.48	69.04	2.09	15.63
171.92	7.16	56.96	357.28	12.57	26.41	9.99	9.99	7.05	
75005	37.00	.54	4.45	23.49	2.00	16.47	51.14	2.19	18.04
180.15	7.41	51.06	369.76	12.14	20.92	9.99	9.99	9.1	
75007	31.00	.40	4.29	17.40	.91	9.78	23.27	1.67	17.92
137.37	6.34	68.03	316.37	9.32	14.06	9.99	9.99	10.28	
75025	11.00	.15	4.63	6.53	.32	9.88	8.18	.53	16.36
43.60	2.24	69.14	111.78	5.24	14.51	9.99	9.99	13.28	
75026	10.00	.23	7.90	10.01	.48	16.49	12.27	.43	14.78
35.37	1.77	60.52	88.32	4.91	24.40	9.99	9.99	13.92	

APPENDIX 2. Chemical composition of water samples collected in the Feevispa, close to the snout of Nordzunge of Feegletscher in 1972

All samples filtered in field immediately on collection. Electrical conductivity measured on unfiltered sample at field water temperature. (9.99 = not determined; 0.0 = determined, no trace; electrical conductivity, 0.0 = not measured)

Sample no.	Electrical conductivity µS cm^{-1}	Na^+ mg l^{-1}	Na^+% (%/Na^++ K^++Ca^{2+})	Na^+ µEq l^{-1}	K^+ mg l^{-1}	K^+% (%/Na^++ K^+ + Ca^{2+})	K^+ µEq l^{-1}	Mg^{2+} not determined	Mg^{2+}% not determined

Mg^{2+} not determined	Ca^{2+} mg l^{-1}	Ca^{2+}% (%/Na^++K^+ + Ca^{2+})	Ca^{2+} µEq l^{-1}	Na^++K^+ + Ca^{2+} mg l^{-1}	(Na^++K^+)% (%/Na^++K^+ + Ca^{2+})	Fe mg l^{-1}	$SiO4^{2-}$ mg l^{-1}	Discharge m^3 s^{-1}

72011	[illegible]	.1	[illegible].24	134.[illegible]	4.7[illegible]	[illegible].65	120.18	9.99	99.90
821.7[illegible]	.[illegible]	4.	[illegible]9.[illegible]	17.[illegible]	45.98	9.99	9.99	4.00	
72016	.[illegible]	.6	[illegible].81	69.[illegible]	3.[illegible]	[illegible].32	92.05	9.99	99.90
821.78	[illegible].8	4.[illegible]	479.[illegible]4	14.[illegible]	35.14	9.99	9.99	[illegible]2.40	
72020	.[illegible]	.4	[illegible].29	[illegible]	3.30	[illegible].51	64.38	9.99	99.90
821.70	7.7	[illegible]	[illegible]4.23	12.40	37.99	9.99	9.99	6.5	
72030	[illegible]	.3	[illegible].3[illegible]	1[illegible]	5.[illegible]	3[illegible].30	[illegible]32.96	9.99	99.90
821.76	.3	[illegible]	[illegible]4.13	[illegible]	46.[illegible]	9.99	9.99	6.5	
72032	.[illegible]	.2	[illegible]	[illegible]	2.[illegible]	[illegible].95	71.60	9.99	99.90
821.7[illegible]	.[illegible]	[illegible]7.	[illegible]	1[illegible]	32.79	9.99	9.99	6.[illegible]	
72047	22.[illegible]	.2	[illegible].34	[illegible]	[illegible]	[illegible].95	[illegible]5.44	9.99	99.90
821.70	[illegible]	[illegible]7.[illegible]	424.15	[illegible]	[illegible]	9.99	9.99	[illegible].30	
72049	.[illegible]	[illegible]	1[illegible]	7[illegible].50	3.[illegible]	[illegible]2	[illegible]1.82	9.99	99.90
821.78	[illegible].9	[illegible]4.	[illegible]44.11	13.90	35.97	9.99	9.99	[illegible].50	
72050	[illegible]	.2	[illegible].30	9[illegible].7[illegible]	2.[illegible]	1[illegible]	71.6[illegible]	9.99	99.90
821.76	[illegible].7	5.	[illegible]4.07	[illegible]	54.97	9.99	9.99	[illegible]	
72052	[illegible]	.[illegible]	[illegible].12	11[illegible].1[illegible]	[illegible].40	37.21	[illegible].65	9.99	99.90
821.78	[illegible]	7.[illegible]	[illegible].1[illegible]	[illegible]7.2[illegible]	32.33	9.99	9.99	[illegible].50	
72054	[illegible]	.3	19.[illegible]	16[illegible]	[illegible].70	[illegible].34	171.32	9.99	99.90
733.11	[illegible].9	[illegible]	444.11	19.4[illegible]	54.12	9.99	9.99	[illegible]	
7205[illegible]	[illegible]	[illegible].4	[illegible].17	[illegible]	2.[illegible]	[illegible]	[illegible]1	9.99	99.90
821.7	[illegible]	7.	[illegible]	1[illegible]	7[illegible]	[illegible]	[illegible]	.[illegible]	

Sample no.	Electrical conductivity $\mu S\ cm^{-1}$	Na^{+} mg l^{-1}	Na^{+}% (%/Na^{+}+ K^{+}+Ca^{2+})	Na^{+} $\mu Eq\ l^{-1}$	K^{+} mg l^{-1}	K^{+}% (%/Na^{+}+ K^{+} + Ca^{2+})	K^{+} $\mu Eq\ l^{-1}$	Mg^{2+} not determined	Mg^{2+}% not determined
Mg^{2+} not determined	Ca^{2+} mg l^{-1}	Ca^{2+}% (%/Na^{+}+K^{+} + Ca^{2+})	Ca^{2+} $\mu Eq\ l^{-1}$	Na^{+}+K^{+} + Ca^{2+} mg l^{-1}	(Na^{+}+K^{+})% (%/Na^{+}+K^{+} + Ca^{2+})	Fe mg l^{-1}	$SiO4^{2-}$ mg l^{-1}	Discharge $m^3\ s^{-1}$	
72[illegible]6[illegible]	.[illegible]	.1	[illegible].67	[illegible].35	2.40	19.35	61.37	9.99	99.90
821.75	[illegible].9	71.[illegible]	444.11	12.40	28.2[illegible]	9.99	9.99	7.8	
72068	23.[illegible]	9.99	[illegible].67	474.57	9.99	19.35	255.44	9.99	99.90
821.7[illegible]	9.9	71.7[illegible]	498.52	[illegible].00	0.00	9.99	9.99	2.4	
72069	[illegible]	.2	17.15	142.35	7.40	3[illegible].34	189.22	9.99	99.90
821.78	[illegible].6	44.	429.14	19.5[illegible]	55.44	9.99	9.99	9.[illegible]	
72071	.[illegible]	.6	11.[illegible]	69.6[illegible]	[illegible].30	2[illegible].76	64.38	9.99	99.90
821.7[illegible]	.6	36.	4[illegible].04	14.5	33.79	9.99	9.99	9.1	
72072	[illegible]	.4	1[illegible].51	[illegible].9[illegible]	2.8[illegible]	21.21	71.60	9.99	99.90
821.75	9.	[illegible]2.	449.10	15.26	31.62	9.99	9.99	4.5	
72073	.[illegible]	.6	1[illegible].61	69.6[illegible]	[illegible]	21.21	99.49	9.99	99.90
821.7[illegible]	9.9[illegible]	68.	49[illegible]	[illegible]	[illegible].06	9.99	9.99	4.5	
72074	23.[illegible]	.5	12.71	63.[illegible]	2.[illegible]	19.49	5[illegible].[illegible]1	9.99	99.9[illegible]
821.7[illegible]	[illegible]	7.	[illegible].20	1[illegible]	32.2[illegible]	9.99	9.99	9.3	
72075	.0	.5	12.29	63.22	2.60	2[illegible].76	71.60	9.99	99.90
821.7[illegible]	.	5.	[illegible].20	1[illegible].3[illegible]	34.76	9.99	9.99	7.[illegible]	
72076	.[illegible]0	.7	[illegible]	7[illegible].93	[illegible]	21.21	71.60	9.99	99.9[illegible]
821.7[illegible]	.7	35.[illegible]	4[illegible]4.12	13.2[illegible]	34.[illegible]9	9.99	9.99	[illegible].1	
72080	[illegible].[illegible]0	.8	1[illegible].53	7[illegible].33	3.72	[illegible]7.32	94.61	9.99	99.90
821.72	[illegible].2	36.6	[illegible]39.22	1[illegible].3[illegible]	41.35	9.99	9.99	9.3	
72085	2[illegible].	.4	9.06	[illegible].9[illegible]	3.0[illegible]	2[illegible].14	[illegible]9.49	9.99	99.90
821.7[illegible]	9.6	[illegible]	479.[illegible]4	1[illegible].5[illegible]	33.7[illegible]	9.99	9.99	9.9	
72086	.[illegible]	.[illegible]	1[illegible].73	27.[illegible]	[illegible]	[illegible]	[illegible]4.73	9.99	99.9[illegible]
821.7[illegible]	9.3	53.	4[illegible]4.[illegible]7	[illegible]	35.3[illegible]	9.99	9.99	4.2	
72087	2[illegible].[illegible]	1.4	1[illegible].45	[illegible].9[illegible]	[illegible]	1[illegible]	66.[illegible]8	9.99	99.9[illegible]
821.78	9.4	70.1[illegible]	4[illegible]9.[illegible]	[illegible].40	29.25	9.99	9.99	4.2	

Sample no.	Electrical conductivity $\mu S\ cm^{-1}$	Na^+ $mg\ l^{-1}$	Na^+% (%/Na^+ + K^+ + Ca^{2+})	Na^+ $\mu Eq\ l^{-1}$	K^+ $mg\ l^{-1}$	K^+% (%/Na^+ + K^+ + Ca^{2+})	K^+ $\mu Eq\ l^{-1}$	Mg^{2+}	Mg^{2+}% not determined
Mg^{2+} not determined	Ca^{2+} $mg\ l^{-1}$	Ca^{2+}% (%/Na^+ + K^+ + Ca^{2+})	Ca^{2+} $\mu Eq\ l^{-1}$	Na^+ + K^+ + Ca^{2+} $mg\ l^{-1}$	(Na^+ + K^+)% (%/Na^+ + K^+ + Ca^{2+})	Fe $mg\ l^{-1}$	$SiO4^{2-}$ $mg\ l^{-1}$	Discharge $m^3\ s^{-1}$	
72089	25.[illegible]	[illegible].7[illegible]	[illegible].08	73.95	3.30	62.26	54.38	9.99	99.90
821.78	.3	5.[illegible]	14.97	5.[illegible]	94.34	9.99	9.99	8.4	
72090	24.[illegible]	1.5	11.28	65.25	3.60	27.07	92.05	9.99	99.90
821.78	[illegible].2	31.6[illegible]	4[illegible]9.18	18.30	38.35	9.99	9.99	5.2	
72223	[illegible]	.4	12.33	17.[illegible]	.40	13.33	10.23	9.99	99.90
821.76	[illegible]	75.[illegible]	1[illegible]9.78	3.[illegible]	26.67	9.99	9.99	[illegible]	
72227	22.[illegible]	[illegible].9[illegible]	13.33	434.57	9.99	1[illegible].33	255.44	9.99	99.90
821.76	[illegible].8	[illegible]	4[illegible]9.12	0.00	0.00	9.99	9.99	5.[illegible]	
72235	27.[illegible]	[illegible].2[illegible]	13.1[illegible]	[illegible]5.77	4.[illegible]0	2[illegible].57	122.74	9.99	99.90
821.79	9.[illegible]	58.[illegible]	489.02	15.[illegible]	41.67	9.99	9.99	5.[illegible]	
72238	27.[illegible]	[illegible].8[illegible]	12.33	7[illegible].30	3.20	21.92	81.82	9.99	99.90
821.78	9.6	5.7	479.[illegible]	1[illegible]	34.25	9.99	9.99	7.5	
72042	2[illegible]	.[illegible]	1[illegible]	121.5[illegible]	5.[illegible]	[illegible].26	153.42	9.99	99.90
821.77	9.8	32.[illegible]	[illegible]9.[illegible]	1[illegible].5[illegible]	47.31	9.99	9.99	5.[illegible]	
72043	[illegible]	[illegible].5[illegible]	14.3[illegible]	1[illegible].75	5.7[illegible]	[illegible].73	145.75	9.99	99.90
821.7	[illegible]	31.[illegible]	4[illegible]9.14	15.[illegible]	4[illegible].81	9.99	9.99	5.[illegible]	
72044	[illegible].00	2.5[illegible]	31.25	10[illegible].75	5.30	65.00	132.96	9.99	99.90
821.76	.3	3.7[illegible]	14.97	9.[illegible]	96.25	9.99	9.99	5.6	
72046	22.[illegible]0	1.7[illegible]	32.[illegible]	73.95	3.[illegible]	62.26	84.36	9.99	99.90
821.75	.3	5.66	14.97	5.[illegible]	94.24	9.99	9.99		
72093	[illegible]	[illegible].3[illegible]	[illegible].53	10[illegible].05	3.[illegible]	27.93	92.05	9.99	99.90
821.73	[illegible].8	62.[illegible]	489.[illegible]	15.70	37.38	9.99	9.99		
72095	25.5[illegible]	1.7	[illegible].29	50.55	2.[illegible]	[illegible]1	71.[illegible]	9.99	99.90
821.78	9.[illegible]	70.[illegible]	443.51	[illegible].79	29.31	9.99	9.99		
72096	[illegible]	[illegible].7	13.96	117.43	4.50	27.22	117.52	9.99	99.90
821.79	9.[illegible]	56.[illegible]	479.04	13.9[illegible]	43.20	9.99	9.99		

Sample no.	Electrical conductivity $\mu S\ cm^{-1}$	Na^{+} $mg\ l^{-1}$	$Na^{+}\%$ ($\%/Na^{+} + K^{+} + Ca^{2+}$)	Na^{+} $\mu Eq\ l^{-1}$	K^{+} $mg\ l^{-1}$	$K^{+}\%$ ($\%/Na^{+} + K^{+} + Ca^{2+}$)	K^{+} $\mu Eq\ l^{-1}$	Mg^{2+} not determined	$Mg^{2+}\%$ not determined
Mg^{2+} not determined	Ca^{2+} $mg\ l^{-1}$	$Ca^{2+}\%$ ($\%/Na^{+} + K^{+} + Ca^{2+}$)	Ca^{2+} $\mu Eq\ l^{-1}$	$Na^{+} + K^{+} + Ca^{2+}$ $mg\ l^{-1}$	($Na^{+} + K^{+}$)% ($\%/Na^{+} + K^{+} + Ca^{2+}$)	Fe $mg\ l^{-1}$	$SiO4^{2-}$ $mg\ l^{-1}$	Discharge $m^3\ s^{-1}$	
72[illegible]9[illegible]	.[illegible]	.2	[illegible].35	1[illegible].43	[illegible]	57.58	97.17	9.99	99.90
821.7[illegible]	.[illegible]	6.	19.96	6.65	93.94	9.99	9.99		
72099	[illegible]	[illegible].6	16.46	113.1[illegible]	4.[illegible]	25.32	102.28	9.99	99.90
821.78	[illegible]	[illegible]8.	459.08	15.60	41.77	9.99	9.99		
721[illegible]	.	.[illegible]	[illegible].59	[illegible].72	4.10	25.32	1[illegible]4.[illegible]4	9.99	99.90
821.7[illegible]	[illegible]	1.	[illegible]3.51	16.19	38.91	9.99	9.99		
7210[illegible]	.[illegible]	.7	1[illegible].[illegible]9	1[illegible]7.45	5.[illegible]	2[illegible].63	135.52	9.9[illegible]	99.9[illegible]
821.7[illegible]	.[illegible]	[illegible]5.	[illegible]93.51	17.89	44.72	9.99	9.99		
72111	.[illegible]	.1[illegible]	[illegible].27	1[illegible].[illegible]	5.[illegible]	[illegible]1.73	127.85	9.99	99.90
821.7[illegible]	.[illegible]	[illegible].	[illegible].39	[illegible].1[illegible]	100.1[illegible]	9.99	9.99		
72[illegible]1	.	.7	[illegible].99	72.[illegible]	3.7[illegible]	[illegible].73	94.61	9.9[illegible]	99.90
821.73	.[illegible]	4.	44.91	[illegible]	65.71	9.99	9.99		
722[illegible]7	.[illegible]	.4	[illegible].70	[illegible].90	5.[illegible]	31.[illegible]	13[illegible].41	9.99	99.90
821.7[illegible]	[illegible].4	[illegible].	47[illegible].[illegible]4	[illegible].1[illegible]	40.[illegible]	9.99	9.99		
72211	[illegible].	.99	[illegible].7	4[illegible].37	9.[illegible]	3[illegible].6[illegible]	255.44	9.9[illegible]	99.90
821.7[illegible]	.	9.	[illegible].10	[illegible]	[illegible].00	9.9[illegible]	9.99		
72[illegible]10	.[illegible]	.4	1[illegible].9[illegible]	6[illegible].9[illegible]	3.[illegible]	2[illegible].44	76.71	9.9[illegible]	99.9[illegible]
821.7[illegible]	[illegible].4	[illegible]5.	41[illegible].15	[illegible]	[illegible]4.38	9.99	9.99		
72064	[illegible]	.5	[illegible]1.19	6[illegible].[illegible]	3.[illegible]	[illegible].39	7[illegible].71	9.9[illegible]	99.90
821.78	[illegible].9	[illegible]	[illegible]4.11	[illegible].4[illegible]	33.[illegible]	9.99	9.99		
72065	.[illegible]	.5	1[illegible]	[illegible]	3.[illegible]	[illegible].92	7[illegible].71	[illegible].99	99.90
821.7[illegible]	[illegible].	[illegible].	4[illegible]9.[illegible]	[illegible]4.[illegible]	31.47	9.99	9.9[illegible]		
7211[illegible]	27.[illegible]	.[illegible]	[illegible]	[illegible]	[illegible]	1[illegible].72	61.37	[illegible]	99.90
821.[illegible]	[illegible].7	1.	[illegible]4.[illegible]	[illegible]	28.[illegible]	9.9[illegible]	[illegible].9[illegible]		

Sample no.	Electrical conductivity µS cm^{-1}	Na^+ mg l^{-1}	Na^+% (%/Na^++ K^++Ca^{2+})	Na^+ µEq l^{-1}	K^+ mg l^{-1}	K^+% (%/Na^++ K^+ + Ca^{2+})	K^+ µEq l^{-1}	Mg^{2+}	Mg^{2+}% not determined
Mg^{2+} not determined	Ca^{2+} mg l^{-1}	Ca^{2+}% (%/Na^++K^+ + Ca^{2+})	Ca^{2+} µEq l^{-1}	Na^++K^+ + Ca^{2+} mg l^{-1}	(Na^++K^+)% (%/Na^++K^+ + Ca^{2+})	Fe mg l^{-1}	$SiO4^{2-}$ mg l^{-1}	Discharge m^3 s^{-1}	
72224	[illegible]	[illegible]	71.47	87.0[illegible]	.90	26.57	2[illegible].46	9.99	99.90
821.78	.3	0.	[illegible]	[illegible].80	100.00	9.99	9.99		
72236	27.[illegible]	[illegible].7	24.29	77.9[illegible]	4.10	58.57	104.84	9.99	99.90
821.78	1.2	17.[illegible]	59.88	7.0[illegible]	82.86	9.99	9.99		
72241	[illegible]	[illegible]	[illegible].00	55.55	2.[illegible]	50.85	71.60	9.99	99.90
821.78	.1	21.[illegible]	54.89	[illegible]	78.85	9.99	9.99		
72243	2[illegible].	.5[illegible]	[illegible].25	10[illegible].75	[illegible]	61.64	115.07	9.99	99.90
821.78	.3[illegible]	4.[illegible]	14.97	7.3[illegible]	95.89	9.99	9.99		
72249	2[illegible]	[illegible].6[illegible]	1[illegible].82	[illegible]9.6[illegible]	4.7[illegible]	5[illegible].29	1[illegible].18	9.99	99.90
821.78	[illegible].2	[illegible]5.	1[illegible]9.72	8.5[illegible]	74.12	9.99	9.99		
72164	[illegible]	[illegible].5[illegible]	1[illegible].46	65.85	4.[illegible]	57.14	112.51	9.99	99.90
821.78	[illegible]	[illegible]3.	[illegible]9.52	[illegible].70	75.62	9.99	[illegible].99		
72202	[illegible]	[illegible].4[illegible]	18.34	[illegible].9[illegible]	[illegible].56	3[illegible].11	[illegible].49	9.99	99.90
821.78	[illegible]	[illegible]5.	[illegible]9.47	1[illegible].90	44.95	9.99	9.99		
72203	[illegible]	[illegible]	35.45	[illegible].9[illegible]	2.80	[illegible].64	69.49	9.99	99.90
821.78	.8	10.[illegible]	[illegible]9.94	5.50	89.09	9.99	9.99		
72246	2[illegible]	4.2	37.54	1[illegible].72	5.40	[illegible].65	13[illegible]	9.99	99.90
821.78	1.5	13.[illegible]	74.85	11.10	86.49	9.99	9.99		