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TEMPERIRTER GLETSCHER

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## HYDROLOGY OF AN ALPINE GLACIER AS INDICATED BY THE CHEMICAL COMPOSITION OF MELT WATER

By DAVID N. COLLINS, Manchester

With 8 Figures and 2 Tables

### SUMMARY

The chemical composition of water emerging from the snout and flowing across the surface of the Gornergletscher (Switzerland) was monitored during July and August in both 1974 and 1975. Electrical conductance, a measure of total ionic concentration, was continuously recorded. Samples of meltwaters were analysed for  $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  by atomic absorption spectrophotometry. The main problems encountered in analysis were the correction of conductivity to a standard temperature and interference by sedimentary particles.

Surface meltwaters are characterised by consistent low ionic concentrations, actual conductivity measurements being in the range  $0.1 - 6.4 \mu\text{S cm}^{-1}$ . There is a marked diurnal fluctuation in solute concentration in the water draining from the snout of the glacier. When discharge is low, conductivity measurements lie in the range  $25 - 44 \mu\text{S cm}^{-1}$  and decrease to a daily minimum of about  $8 \mu\text{S cm}^{-1}$  with increasing flow. Observations of discharge and meltwater chemistry together allow the identification of internal hydrological networks of the glacier. There is evidence of two routes of water transmission within the Gornergletscher. Concurrent with ablation during the day, waters low in ionic content rapidly appear at the snout. Other meltwaters drain through the glacier at lower rates, maintaining flow at night, and undergoing chemical enrichment during their passage. The source of solute is considered to be subglacial morainic sediments and glacial erosion of the bed rather than suspended sediment in meltwaters. This points to a basal hydrological system existing alongside a more important englacial clean ice network, both transmitting water at different rates and mixing close to the snout. Some water is forced into subglacial storage in morainic sediments or cavities during increased water pressure in basal conduits concurrent with daily ablation. A simple two-component mass-balance equation using discharge and chemical composition parameters provides a useful approach to quantitative investigation of the internal drainage of the Gornergletscher.

### DIE CHEMISCHE ZUSAMMENSETZUNG DES SCHMELZWASSERS ALS INDIKATOR DER HYDROLOGIE EINES ALPINEN GLETSCHERS ZUSAMMENFASSUNG

Die chemische Zusammensetzung des Wassers, das aus der Zunge und über die Oberfläche des Gornergletschers fließt, wurde in den Jahren 1974 und 1975 im Juli und August bestimmt. Die elektrische Leitfähigkeit als ein Maß der gesamten Ionenkonzentration wurde laufend registriert. Schmelzwasserproben wurden auf  $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{Ca}^{++}$  und  $\text{Mg}^{++}$  mit Absorptionsspektrometrie untersucht. Die Hauptprobleme der Analyse war die Korrektur der Leitfähigkeit auf eine Standardtemperatur und die Störung durch Sedimentteilchen.

Für Oberflächenschmelzwasser sind durchwegs niedrige Ionenkonzentrationen typisch, gemessene Leitfähigkeiten lagen im Bereich von  $0,1 - 6,4 \mu\text{S cm}^{-1}$ . Im Wasserabfluß aus der Gletscherzunge gibt es eine deutliche Tagesschwankung der Lösungskonzentration. Bei niedrigem Abfluß liegen Leitfähigkeitswerte zwischen  $25$  und  $44 \mu\text{S cm}^{-1}$  und nehmen mit stärker werdendem Abfluß auf ein Tagesminimum von etwa  $8 \mu\text{S cm}^{-1}$  ab. Die Beobachtung des Abflusses und der Schmelzwasserzusammensetzung zeigen innere Abflußsysteme des Gletschers, wobei im Gornergletscher Evidenz für zwei Durchflußrouten gefunden wurde. Während der täglichen Ablationszeit erscheint an der Zunge Wasser mit niedrigem Ionengehalt. Langsames Durchfließen von Schmelzwasser durch den Gletscher speist den nächtlichen Abfluß und ist in der Lage, ihn dabei chemisch anzureichern. Als Quelle der Lösungen kann subglaziales Moränensediment und Erosion



vom Felsuntergrund eher angesehen werden als im Schmelzwasser suspendiertes Material. Das deutet auf die Koexistenz eines basalen Abflußsystems neben einem wichtigeren, sauberen System im Inneren des Gletschers, die beide das Wasser mit verschiedenen Geschwindigkeiten transferieren und sich in der Nähe des Gletscherendes mischen. Ein Teil des Wassers wird in subglazialen Höhlungen oder Moränensediment gespeichert, wenn während der täglichen Ablation der Druck im basalen Abfluß steigt. Eine einfache Massenbilanz, die durch Abfluß und chemische Zusammensetzung parametrisiert ist, schafft eine brauchbare Annäherung zur quantitativen Erfassung des Inneren Abflusses im Gornergletscher.

## 1. INTRODUCTION

As there are few direct observations at depth, studies of the internal drainage of glaciers have relied on indirect observations and theoretical considerations in attempts to answer the question 'What happens to meltwater between where it disappears into surface moulins and where it emerges from the portal at the glacier snout?'. The structure and behaviour of the internal hydrological systems of glaciers remain subjects of discussion, but it is generally accepted that water flows through glaciers in a network of englacial and subglacial conduits (Krimmel et al., 1972; Röthlisberger 1972; Shreve 1972; Behrens et al. 1975). Such tunnels in ice close under the ice overburden pressure, but are kept open or widened by melting of the walls by frictional heat produced in flowing water. In a hydraulic treatment, Röthlisberger (1972) considers that flow is in discrete conduits which join to form major arterial pipes, and that channels can exist both in sub- and englacial locations, the latter at the level of the hydraulic grade line.

Surface meltwaters from the ablation area pass rapidly through the conduit system to the snout without retention, as indicated by dye and salt tracer experiments at small glaciers (Ambach et al. 1972; Krimmel et al. 1972; Stenborg 1969, 1970), and by determinations of diurnal variations of the tritium content of meltwater streams (Behrens et al. 1971). For larger glaciers, the rhythmic daily peak of discharge in the late afternoon following ablation contributes only a fraction of the total daily runoff, being superimposed on a steady background flow maintained throughout the day and maintaining flow as they drain at night (Elliston 1973). The purpose of this study is to evaluate the use of water quality characteristics of meltwaters as a means of determining the structure, location and functioning of the internal drainage network of a glacier. 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. The portal meltstream showed diurnal variations in chemical composition reflecting changing proportions in the total discharge of waters from different englacial hydrochemical environments. This paper describes chemical characteristics of glacial meltwaters during the ablation season. In particular, the observations are intended to permit separation of components of total discharge taking different routes with varying transit times through the glacier, rather than separation of waters from different sources (snowmelt water, icemelt water, groundwater) which may be determined using naturally-occurring isotopes (Behrens et al. 1971).

In non-glacierised areas, the determination of runoff components of total discharge in streams by chemical characteristics has provided satisfactory separation of the direct runoff proportion from groundwater contributions. 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 1965; Pinder and Jones 1969; Nakamura 1971). A composite concentration curve of  $\text{HCO}_3^-$ ,  $\text{SO}_4^{2-}$ ,  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  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).

The observations were made in the catchment of the Gornergletscher, canton Wallis, Switzerland (45° 47' N, 07° 46' E) as part of an intensive series of investigations of the total environment of glacial meltwater streams. An area of 82 km<sup>2</sup> is drained by one proglacial stream, the Gornera, on which Grande Dixence, S. A. maintain a well developed gauging station, recording discharge hydrographs between June and September. Currently 83.7 per cent of the catchment is glaciated. The basin has a vertical extent of 2619 m from the gauging station (2005 m a. s. l.) to the highest point, Dufourspitz, at 4634 m. The trunk Gornergletscher receives several tributaries from the southern watershed (e. g., the Theodul, Zwillingen, Schwärze and Grenzletschers; see Fig. 1). Approximately 50 per cent of the glacier surface

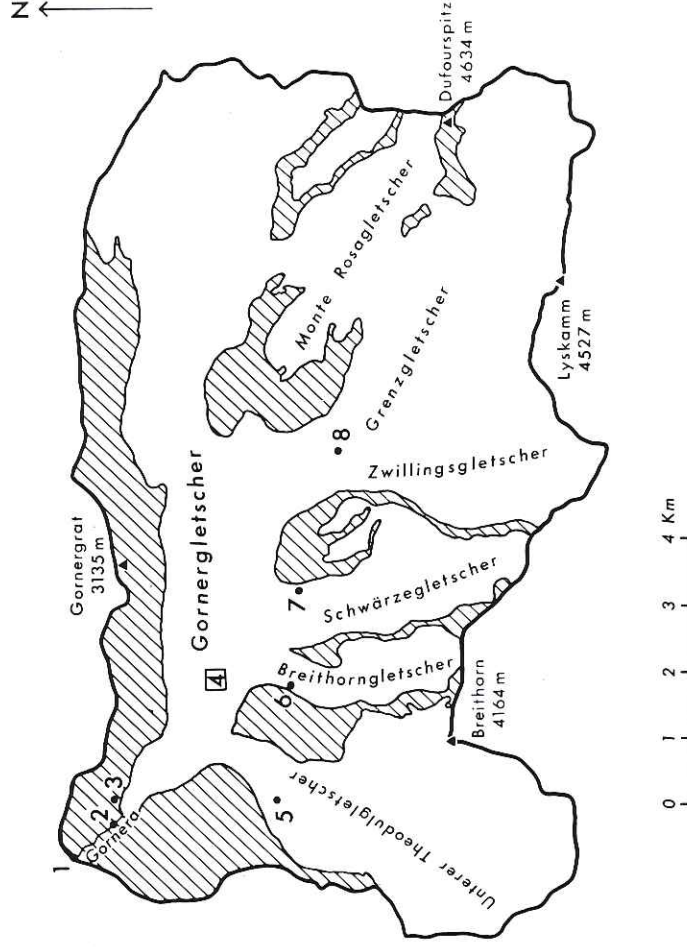


Fig. 1: Map of the Gornergletscher catchment area:

1. Prise d'eau gauging station (2005 m a. s. l.)
2. Measurement site on Gornera
3. Seepage in lateral moraine
4. Surface ice melt streams on Gornergletscher
- 5-8. Supra-glacial snowmelt stream sampling sites.



area lies in the ablation zone in summer (Miller et al. 1976). The glacier descends to 2120 m, with a mean altitude of 3220 m. The bedrock underlying the catchment is of igneous and metamorphic origins, granite, gneiss and schists, all of which are impermeable, with a very small area of calcareous rocks (Beaerth 1953). The bedrock topography is known in detail, both by seismic and drilling techniques. A basal morainic layer exists between the ice and bedrock, over the width of the glacier. Near the ice margin it is several metres thick, shown by drilling, but it may extend to be 50 m thick, the discrepancy between drilling and sounding depths at the centre of the glacier (Bézinge et al. 1973).

## 2. COMPONENTS OF RUNOFF IN GLACIER CATCHMENTS

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

$$Q_t = Q_g + Q_r \quad (1)$$

where  $Q$  represents runoff proportions and the subscripts refer to the glacierised area ( $g$ ), the area not covered by ice ( $r$ ) and total discharge from the catchment ( $t$ ). The water in an Alpine glacier itself comes from a variety of sources:

$$Q_g = Q_s + Q_i + Q_q + Q_p + Q_n + Q_m \quad (2)$$

where the subscripts refer to snowmelt on the glacier surface ( $s$ ), surface ice ablation ( $i$ ), subglacial melting ( $q$ ), precipitation on the surface of the glacier ( $p$ ), subglacial springwater or groundwater ( $n$ ) and internally produced meltwater resulting from ice deformation, pressure melting and frictional melting by flowing water ( $m$ ). On ice-free slopes surrounding the glacier, water is derived from two sources:

$$Q_r = Q_k + Q_l \quad (3)$$

where ( $k$ ) is snowmelt and ( $l$ ) precipitation, both on the non-glacierised part of the catchment. There is probably little delay of runoff on steep slopes bearing a thin debris mantle on impermeable rocks.

The proportions of the runoff components contributing to  $Q_t$  are variable both at seasonal and diurnal timescales. Here, only the summer ablation period (July to September) is considered. Meltwater produced at the glacier surface is by far the most important source, being orders of magnitude greater than the others. Calculations from measurements of tritium and deuterium contents indicate that up to 40 per cent of surface runoff is contributed by snowmelt (Behrens et al. 1971). Subglacial and internal melting together produce a negligible amount of water, of the order of 10 mm per unit area of bed year (Shreve 1972). From determinations of deuterium content, 40 per cent of the summer runoff of Hintereisferner (Ötztal Alps, Austria), appears to originate from subglacial springs (Ambach et al. 1976). However, the question of the existence of groundwater systems beneath Alpine glaciers remains unsettled (Lütschg et al. 1950; Stenborg 1965). In the Gornergletscher catchment, streams on the ice-free slopes are maintained only during snowmelt, and flow effectively ceases early in the summer ablation period. However, the streams flow immediately following heavy precipitation. At times with no precipitation, the nonglacierised areas do not contribute significantly to the catchment runoff,  $Q_i = Q_p = 0$ , and therefore total runoff  $Q_t$  is given by:

$$Q_t = Q_g = Q_s + Q_i + Q_n \quad (4)$$

The drainage system of an Alpine glacier consists of three distinct but connected networks: supraglacial, englacial and subglacial. There are diurnal and seasonal variations of inputs to the supraglacial streams due to changing surface ablation conditions. Total channel length decreases during the ablation season as the englacial system adjusts to take increasing quantities of meltwaters. The englacial system leads meltwater through conduits which join to form increasingly large pipes leading to the subglacial network. Englacial channels are cut in predominantly clean ice, have no sediment load, and the chemical composition of meltwaters remains unchanged. A maximum of about 1 m of meltwater per unit area of bed per year can pass slowly through the englacial vein network (Nye and Frank 1973). The subglacial system receives large increments of discharge where the arterial conduits of the englacial system reach the bed, and downglacier provides a route for an increasing proportion of the total meltwater. Suspended sediment derived from basal debris-laden ice and glacial erosion is entrained at the bed, and probably contributes solutes to the meltwater. The subglacial system will also carry springwater, and subglacial meltwater, both of which are likely to be solute-rich. It is possible then to separate the proportions of water routed through the englacial and subglacial networks by their chemical characteristics. The concentration of solutes in the total runoff will be made up of proportional contributions from the two components:

$$Q_t C_t = Q_b C_b + Q_e C_e \quad (5)$$

where

$$Q_t = Q_b + Q_e$$

and

$$Q_b = Q_n + (Q_s + Q_i - Q_e)$$

where  $C$  is the total dissolved solids content or the concentration of an individual ion in runoff components and subscripts refer to routes taken by meltwaters within the glacier, subglacial (b) and englacial (e). Temporal variations in the quality of the total discharge reflect varying proportions of meltwaters routed through the two conduit networks.

### 3.1. STRATEGY

## 3. METHODS AND EVALUATION OF TECHNIQUES

A preliminary investigation in the summer of 1974 permitted evaluation of measurement techniques. A comprehensive field programme was undertaken in the summer ablation season of 1975, with some subsequent observations. Electrical conductivity was continuously monitored on the Gornera 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 major cations. The role of suspended sediment in meltwater chemistry was investigated, on account of its interest as a source of solute and its citation as a cause of interference in atomic absorption spectrophotometry (Reynolds 1971).

### 3.2. MEASUREMENT PROCEDURES

#### 3.2.1. ELECTRICAL CONDUCTIVITY

Electrical conductivity was used as a measure of the total dissolved load of meltwaters since it can be determined with portable field instruments and is suited to continuous monitoring. Preliminary tests at Hintereisferner, proved that conductivity was a useful indicator of runoff components in glacier hydrology (Behrens et al. 1971). Field conductivity of samples was determined with a Walden Precision



Apparatus CM 25 conductivity meter, equipped with a range of accurately calibrated platinum-electrode dip cells. In 1975, conductivity of meltwaters in the Gornera glacier portal (see Fig. 1). A Sproule electrolytic dip cell (cell constant = 1.0) of carbon electrodes in a resin probe was positioned to remain always in the turbulent main flowline of the stream. 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. The cell was attached to a WPA CM 25 conductivity meter, with Rustrak 6v chart recorder. Chart time-keeping and levels of battery charge were checked daily. A shielded thermistor was located on the streambed, and temperatures recorded at 3 h intervals. A similar system was used at the supraglacial stream on the Gornergletscher.

### 3.2.2. CHEMICAL ANALYSES

Samples of meltwaters were collected from the fastest flowing streamline at all sites, to ensure complete turbulent mixing. Samples were collected and stored in polyethylene bottles, which were pre-washed with double-distilled deionised water, and immediately before collection washed with water from that about to be sampled. In order to evaluate the effects of suspended sediments, many samples were collected in duplicate. One sample of each pair was immediately filtered following collection through an Oxoid 0.45  $\mu$  membrane, previously rinsed in deionised water, in a washed perspex cylinder under pressure from a hand pump. For some samples, conductivity was measured before and after filtration. All samples were refrigerated between the times of collection and analysis. Samples were analysed between two days and two months after collection. The unfiltered samples were vacuum-filtered as above immediately prior to analysis.

Concentrations of sodium, potassium, calcium and magnesium in filtered meltwaters were determined with a Perkin-Elmer 403 atomic absorption spectrophotometer, under standard conditions. Reynolds (1971) used atomic absorption methods to determine cations in samples in which suspended sediments had settled out between the times of collection and analysis, and considered that sediments caused interferences producing enhanced concentrations. Replicate determinations from each of several samples (n) showed the following reproducibility of results:  $\text{Na}^+ = 2.8$  per cent (n = 11),  $\text{K}^+ = 7.0$  per cent (n = 9),  $\text{Ca}^{2+} = 3.2$  per cent (n = 5),  $\text{Mg}^{2+} = 1.6$  per cent (n = 13). Determinations of each of the four cations were made for about 300 samples.

### 3.2.3. DISCHARGE MEASUREMENTS

Shifting beds, standing waves and excessive turbulence prevent calibration of reliable rating curves at gauging stations close to glacier snouts. The Gornera is gauged 1 km from the glacier snout, at the intake to a hydro-electric adduction gallery. Subsequently, both the extracted water and that remaining in the river bed are gauged again, and these measures provide a useful check on the performance of the limnigraph station. Hourly mean discharges have been used in this study to remove short term fluctuations.

## 3.3. EVALUATION OF ANALYSIS TECHNIQUES

### 3.3.1. CONDUCTIVITY MEASUREMENTS

The comparison of conductivities of samples determined before and after filtration in the field shows that most values determined after filtration were greater than



those of the unfiltered samples. 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 below are determinations of unfiltered waters.

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 before measurement in laboratory determinations (Mackereth 1963). For measurements made at field temperatures, it is usual to use tables of correction factors (Golterman 1969), or a conductivity meter which automatically compensates for temperature. Both methods assume increases in conductivity of about 2 per cent per degree Celsius. The rate of increase is greater than 2 per cent 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 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. 2). 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 paper at the measured temperature, in most cases between 0.1 and 1.2°C. The maximum error due to temperature variation within this range is about 8 per cent of the determined conductivity. The

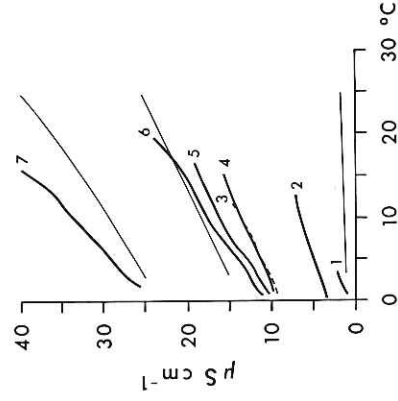


Fig. 2: Curves showing the increase of conductivity on warming meltwater samples from the Gornergletscher catchment: 1, 2: unfiltered supraglacial stream waters; 3, 4: simultaneous samples from the Gornera, unfiltered (3), filtered (4); 5-7: unfiltered meltwaters from the Gornera. The other curves give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

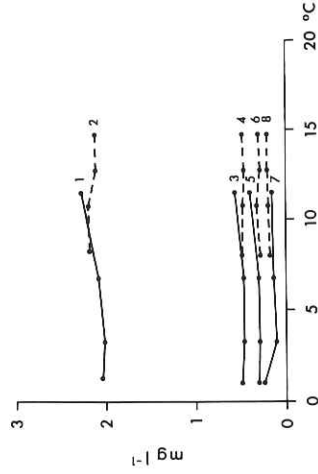


Fig. 3: Changes in ionic composition of meltwaters from the Gornera on warming filtered and unfiltered samples:  $\text{Ca}^{2+}$  (unfiltered/filtered) — 1/2;  $\text{Mg}^{2+}$  — 3/4;  $\text{K}^+$  — 5/6;  $\text{Na}^+$  — 7/8.

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.

During the warming up of the filtered sample, no change occurred in the concentration of the ions  $\text{Mg}^{2+}$ ,  $\text{K}^+$  and  $\text{Na}^+$ , but a slight reduction of  $\text{Ca}^{2+}$ . In contrast,  $\text{Mg}^{2+}$  and  $\text{Ca}^{2+}$  increased in concentration by 10 and 16 per cent respectively, and  $\text{Na}^+$  decreased 40 per cent in an unfiltered sample (Fig. 3). 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  $0.45 \mu$  are probably present in the filtered sample.

### 3.3.2. 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  $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  of the pair of samples show that for all pairs of samples, the concentrations of  $\text{Mg}^{2+}$  and  $\text{K}^+$  were considerably higher in the sample stored unfiltered. In the majority of pairs, the concentration of  $\text{Na}^+$  was higher in the unfiltered sample, but in some cases it was higher in the sample stored filtered. The concentration of  $\text{Ca}^{2+}$  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  $\text{Mg}^{2+}$  and  $\text{K}^+$  accompanied by some relative decreases of  $\text{Na}^+$  and  $\text{Ca}^{2+}$ . Lorrain and Souchez (1972) determined that significant quantities of the major cations were sorbed on suspended sediment particles in meltwater, and greater amounts on moraine sediments at the Moiry glacier, Switzerland. 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,  $\text{Ca}^{2+}$  is the most important cation. During storage it is probable that both limited solution of particles and some desorption have occurred. In addition,  $\text{Ca}^{2+}$  and  $\text{Na}^+$  ions have either displaced  $\text{Mg}^{2+}$  and  $\text{K}^+$  by cation exchange reactions, or become selectively re-adsorbed on particle surfaces.

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 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 paper, the results of chemical analyses are those performed on samples filtered immediately after collection. Further sampling is 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) or field analytical techniques requiring no separation such as portable ion selective electrodes may provide more accurate data.

#### 4. MEASUREMENT RESULTS

Chemical composition and electrical conductivity of waters representative of the major hydrochemical environments within the Gornergletscher catchment are shown in Table 1. All supraglacial meltwater streams show very low electrical conductivities ( $0.1$  to  $2.7 \mu\text{S cm}^{-1}$ ), 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  $2.7 \mu\text{S cm}^{-1}$  at  $0.1^\circ\text{C}$ , periodically interrupted by impulses of waters showing conductivities rising to a maximum of  $5.4 \mu\text{S cm}^{-1}$  at  $0.1^\circ\text{C}$  (Fig. 4). The impulses occurred between 08.00—10.00 h and 19.00—21.00 h, when the smaller tributary streams

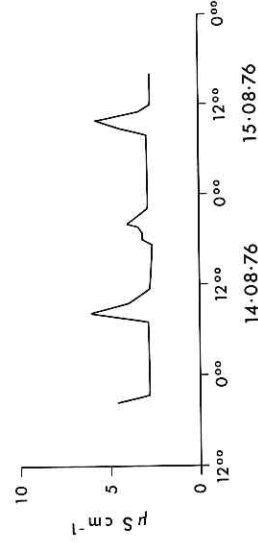


Fig. 4: Daily variations of measured electrical conductivity of a major supraglacial meltwater stream, Gornergletscher.

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. Results of sample determinations (1974) and continuous measurement (1975) of the conductivity of the runoff in the Gornera are shown in Fig. 5 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 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 1–2 h and the maximum conductivity occurs 2–3 h 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 is lower than  $10 \mu\text{S cm}^{-1}$ . This implies that a large proportion of the discharge is surface meltwater which has passed through the glacier relatively unchanged in solute content. Although most of the solute-rich meltwaters originate from surface melting, they do not reach the portal in increased quantities until about 12 h 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.

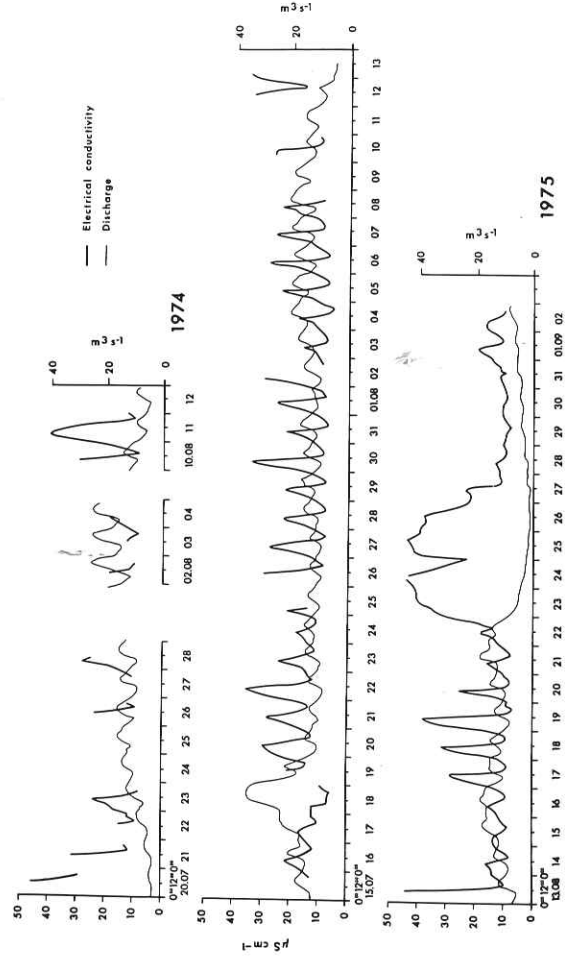


Fig. 5: Discharge hydrographs and measured electrical conductivity of meltwaters in the Gornera, 20 July–12 August 1974 and 15 July–2 September 1975.



Hydrological environment		Date	Temperature °C	Observed electrical conductivity $\mu\text{S cm}^{-1}$	$\text{Na}^+$ $\text{mg l}^{-1}$	$\text{K}^+$ $\text{mg l}^{-1}$	$\text{Ca}^{2+}$ $\text{mg l}^{-1}$	$\text{Mg}^{2+}$ $\text{mg l}^{-1}$
Small supra-glacial ice melt streams Gornergletscher		22. 7. 1974	0.1	0.2	0.0	0.4	0.1	0.0
		24. 7. 1974	0.1	0.1				
		24. 7. 1974	0.1	0.2				
		18. 8. 1975	—	—				
		28. 7. 1977	0.1	0.8				
		29. 7. 1977	0.1	1.6				
Large supra-glacial ice melt streams Gornergletscher		27. 7. 1977	—	—	0.1	0.2	0.7	0.1
		13. 8. 1976	—	2.7	0.3	0.2	0.6	0.1
		14. 8. 1976	0.1	2.7	0.2	0.1	0.5	0.1
		15. 8. 1976	—	2.7	0.4	0.3	0.4	0.1
Glacier Surface snow-melt streams Theodulgletscher		26. 7. 1974	0.1	1.3	0.0	0.6	—	0.5
		11. 8. 1975	—	—	0.0	0.1	0.3	0.1
		11. 8. 1975	—	—	0.0	0.1	0.1	0.0
		11. 8. 1975	—	—	0.0	0.1	0.1	0.0
Seepage in lateral moraine, 150 m above snout of Gornergletscher		22. 7. 1974	5.2	22.7				
Non-glacial snow melt stream Gakihaupt		3. 8. 1977	0.8	28.0				

Table 1: Chemical characteristics of water from major hydrological environments, Gornergletscher catchment

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, a glacially-dammed lake 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 Grenzletscher and trunk Gornergletscher. The minimum conductivity measured in the Gornera ( $6.0 \mu\text{S cm}^{-1}$ ) was recorded during the lakeburst flood. This value is very close to that of surface snow and ice melt 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 by an englacial conduit although field observations are in favour of a subglacial outlet (Röthlisberger 1972). 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 the diurnal rhythm of discharge was subject to modifications for which no meteorological explanations exist. On 15–16 August, 20–21 August and 22–23 August, discharge remained at the early evening level throughout the night on each occasion. Conductivity remained low, reaching maxima of about  $16.0 \mu\text{S cm}^{-1}$ , rather than the usual  $25–35 \mu\text{S cm}^{-1}$ . These anomalies are probably the result of either the drainage of entomnoirs (Renaud 1936) or englacial water pockets. The low conductivities associated with these waters suggest a source remote from solute-rich 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  $44.0 \mu\text{S cm}^{-1}$ , though the minimum was about the usual  $10 \mu\text{S cm}^{-1}$ . 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 subglacially routed 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 melt-water supply reduced the conductivity of water in the Gornera from  $44.0$  to  $9.5 \mu\text{S cm}^{-1}$  in 6 h.

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  $44.0 \mu\text{S cm}^{-1}$ , 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 continued 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  $24.0 \mu\text{S cm}^{-1}$  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  $44.0 \mu\text{S cm}^{-1}$  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  $10.0 \mu\text{S cm}^{-1}$ . Rain over the catchment on 28–31 August did not increase the solute load by runoff from the extra-glacial areas.

Temporal variations in concentration of individual cations in meltwaters of the Gornera were measured during several 24 hour periods. Because electrical conductivity is the sum of conductances due to individual ions, changes in the concentrations of the most important cations,  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  are closely paralleled by fluctuations of conductivity.  $\text{Na}^+$  and  $\text{K}^+$  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 individual ions in the Gornera. However, calcium and magnesium ion concentrations would also provide useful indicators of runoff portions in glacier hydrology.

## 5. GLACIO-HYDROLOGICAL CONSIDERATIONS

### 5.1. 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 occurs where dilute meltwaters first encounter sedimentary materials. Water circulating through pores and capillaries in moraine also become enriched with solute.

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. Where englacially routed meltwaters reach the trunk subglacial passages, they do not become enriched, but dilute the solute-rich waters draining from the upglacier segments of the subglacial conduit network. 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.

### 5.2. QUANTITATIVE DEVELOPMENT

Assuming the validity of the two-component system of proportions and concentrations of meltwaters within the Gornegletscher, equation (5) can be simplified and solved for the portion of total discharge routed through the subglacial system (following Pinder and Jones 1969):

$$Q_b = [(C_t - C_e)/(C_b - C_e)] Q_t \quad (6)$$

This mass-balance equation (6) applies when there is no further reaction from sediments when sediment-laden waters from the subglacial system come into contact with englacially routed meltwaters, and that both components of total runoff have a uniform density of  $1 \text{ Mg m}^{-3}$ .

$C_b$ ,  $C_e$  and  $C_t$  were taken as values of electrical conductivity. The quantities  $Q_t$  and  $Q_b$  were obtained from curves of daily variations.  $C_e$  was assumed to be the same as the conductivity of supraglacial ice and snowmelt waters, although there may be some increases during circulation. An average value of conductivity from determinations of surface meltwaters was used for this parameter. More problematic is the determination of  $C_b$  because it is likely that on no occasion during the study period was water in transit only through the subglacial conduits. Since a repeated maximum value of conductivity ( $44.0 \mu\text{S cm}^{-1}$ ) was recorded during three separate periods of recession, this value was used as an estimate of  $C_b$ . In reality,  $C_b$  may be a function of  $Q_b$ , depending on the amount of discharge through the conduits, length of time taken for subglacial transit and the nature of channels in relation to subglacial sediments.

The proportion of total discharge routed through the subglacial conduits ( $Q_b$ ) calculated from equation (6) is shown in Fig. 6. Although there may be error in the

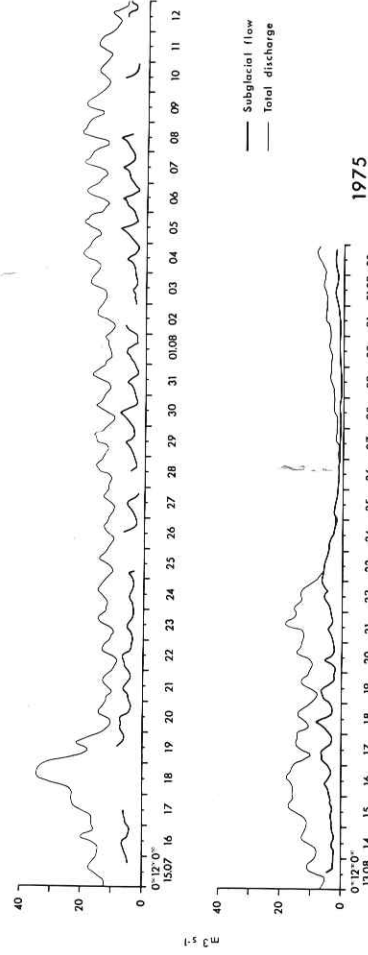


Fig. 6: Curves of the total discharge of the Gornera ( $Q_t$ ) and the portion of discharge routed through the subglacial conduits of the Gornergletscher ( $Q_b$ ), calculated from measurements of electrical conductivity and  $Q_t$  for 15 July—2 September 1975. See text for details of calculation.

values taken for numerical parameters, the simple model probably provides reasonable insight into the nature of water flow through the Gornergletscher. If the true value of  $C_b$  is higher than that estimated, the proportions of subglacial flow in the total runoff given by the present calculation will be reduced, although the overall shape of the hydrograph of the subglacial component will remain much the same.

### 5.3. DAILY VARIATIONS OF THE COMPONENTS OF DISCHARGE

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. 6). 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 dischar-



ge increases both the proportion contributed by and the actual quantity of water discharged in the basal conduits decreases sharply. The dynamics of the subglacial system contrast with results of the separation of the groundwater component of discharge at Hintereisferner by Behrens et al. (1971) which indicate a steady flow with only slight diurnal variations, fed from subglacial springs.

Daily curves of flow in the two runoff systems are shown in Fig. 7 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 moulines 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 moulines (a function of the large dimensions and the geometry of the Gornersgletscher) and the increase in transit times caused by water being prevented from draining freely through the system at times of greatest surface input to the conduits. Diurnal variations in the rate of ablation 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.

There is a steady discharge through the subglacial channels of between  $2\text{--}4\text{ m}^3\text{ s}^{-1}$  in this period, and maintained throughout the period of investigations (Fig. 6) 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 2 h after minimum discharge through the englacial system. A large proportion of total daily flow through the subglacial conduits occurs during the peak. As discharge in the englacial system increases in the morning, flow from the subglacial

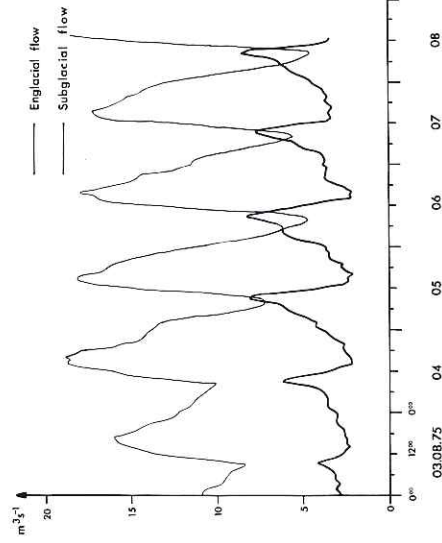


Fig. 7: Daily variations of the discharge components routed through the englacial and subglacial networks during sustained ablation 3–8 August 1975, calculated from measurements of electrical conductivity and  $Q_t$ .

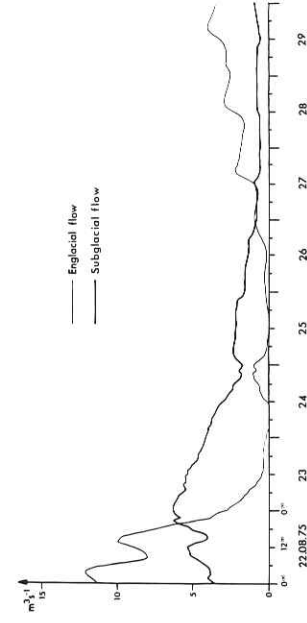


Fig. 8: Daily curves of the portions of discharge routed through the subglacial ( $Q_b$ ) and englacial ( $Q_e$ ) networks of the Gornergletscher during a period of recession following snowfall 22–29 August 1975, calculated from measurements of electrical conductivity and  $Q_t$ .

conduits is very suddenly cut off, reducing outflow by about 70 per cent in 5 h, to a minimum within 3 h of the englacial system maximum. This behaviour implies direct hydraulic interconnection of the two systems, probably over a large area. Such a sub-vertical pipe system or a network of veins does not appear to enlarge during the season, as the flow from the subglacial system does not noticeably increase through time. There may be little flow through such a network, but it provides a hydraulic continuity to transmit water pressure fluctuations through the glacier. When inputs of meltwater to the glacier were severely curtailed during the period of snowfall, 23–27 August 1975, almost all the discharge remaining in the Gornera was from the subglacial network (Fig. 8). In the absence of significant inputs, this flow must be maintained by water stored under the glacier before the start of depletion. Integration beneath the curve of subglacial discharge depletion over 5 d indicates that  $9.3 \times 10^5 \text{ m}^3$  of water was stored beneath the glacier before the reduction of input. On 23 and 24 August, 85 and 89 per cent respectively of the total daily runoff of the Gornera had been routed through subglacial channels. The englacial system ceased flow after 24 h, representing depletion of the limited volume of water remaining in transit at the start of this period. A smaller quantity of meltwater can be stored in transit in the subglacial conduits because of their lower capacity. This suggests the existence of off-conduit subglacial reservoirs.

Table 2 shows the proportions of the daily total of discharge in the Gornera routed through the englacial and subglacial systems, calculated from measurements of

Table 2: Proportions of daily total discharge routed through the subglacial and englacial networks of the Gornergletscher, calculated from measurements of conductivity and  $Q_t$

Date	Total discharge ( $\times 10^5 \text{ m}^3 \text{ d}^{-1}$ )	Subglacial network (%)	Englacial network (%)
3. 8. 75	13.1	19.6	80.4
4. 8. 75	15.1	19.8	80.2
5. 8. 75	15.2	24.9	75.1
6. 8. 75	13.7	28.8	71.2
7. 8. 75	14.4	27.8	72.2
18. 8. 75	10.9	34.1	65.9
19. 8. 75	9.1	39.9	60.1
20. 8. 75	10.3	24.0	76.0
22. 8. 75	11.7	35.0	65.0
23. 8. 75	5.4	85.0	15.0
24. 8. 75	3.0	89.1	10.9



conductivity and discharge. The proportions indicate the flow capacities of the two networks. During intermediate discharges,  $(9.0-12.0 \times 10^5 \text{ m}^3 \text{ d}^{-1})$  about 40 per cent of the total drainage passes through the subglacial system (18, 19, 22 August 1975). At low discharges, the subglacial system carries a higher proportion of the total discharge because englacial flow is rapidly depleted and subglacial flow is augmented by drainage of reservoirs. During periods of high discharge less than 30 per cent of the total flow passes subglacially. At such times (e. g. 3-7 August 1975) subglacial flow through the system during the day is much lower than at night, and it is suggested that at such times water leaves the subglacial channels and becomes retained under the glacier. The absolute quantity of water flowing through the basal conduits is increased during higher total discharges even if the proportion of the total drainage through the glacier is lowered. Actual flow through is reduced, however, because water is retained in storage. An anomalous situation on 20 August may be related to the draining of englacial or supraglacial reservoirs (see section 4). The importance of englacial conduits in the drainage of the Gornergletscher is indicated by the routing of between 60 and 80 per cent of the total discharge through this network on all days with favourable ablation conditions.

#### 5.4. A MODEL OF HYDROLOGICAL BEHAVIOUR OF THE GORNERGLETSCHER

The supply of surface meltwaters to the internal drainage system varies in phase with the diurnal ablation cycle. 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, but only the englacial conduits show increased discharges during the day.

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 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 water from the conduits. Such cavities have been envisaged by Liboutry (1968). 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. As a result of cavity formation and channel margin storage in sedimentary materials actual flow through the subglacial channels decreases with increasing water pressure. The thickness of morainic sediments under the Gornergletscher suggests that large quantities of water can 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 of water stored in transit in the englacial system. Discharge from the subglacial conduits decreases rapidly when the water pressure builds up to the critical level to produce outflow to cavities and moraine storage.

Since the chemically unaltered water from the englacial conduits reaches the snout relatively soon after surface melting, the master englacial conduits cannot join flow

in the basal conduits until downstream of the area where water pressure exceeds ice pressure. They probably do not join except within 1–2 km of the snout, downstream of a deep depression in the long profile of the glacier bed.

## 6. CONCLUSION

The separation of total discharge into the two components of a simple mixing model by the use of chemical characteristics provides a useful impression of the nature and functioning of the internal drainage system of the Gornergletscher. It points to two connected networks of major conduits, one within the glacier and the other at the bed. Pressure fluctuations in the conduits encourage temporary storage of some subglacial water in basal morainic layers and cavities at the bed. Diurnal changes in basal water storage may be of importance in studies of short term variations of glacier motion. Englacial conduits, probably located at the hydraulic grade line, transmit about 75 per cent of the total internal drainage of the Gornergletscher during the ablation season. Meltwaters from the englacial system do not join the subglacial system in large quantities until close to the glacier snout.

Further investigation remains necessary in order to improve methods of processing and analysing glacial meltwaters. Observations over a period of several years are required for accurate calibration of the mass-balance equation. Determination of electrical conductivity together with measurements of total discharge can provide a method of runoff analysis appropriate for glaciers too large for meaningful salt and dye tracer studies. Analysis of routing by chemical characteristics gives an overall indicator of glacial hydrology for the entire ablation area of the glacier, whereas tracer studies provide detailed information about transit times to the portal from a few selected moulins. That these studies are complementary suggests a possibility for comprehensive study combining measurements of discharge, isotope contents, determinations of chemical composition and dyetracing to separate origins and routing and to calculate residence times of water within glaciers.

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Author's address: D. N. Collins  
Department of Geography  
University of Manchester  
Manchester  
M13 9PL.