Annals of Glaciology 2 1981

SEASONAL VARIATION OF SOLUTE CONCENTRATION IN MELT WATERS DRAINING FROM AN ALPINE GLACIER

by

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ABSTRACT

Electrical conductivity of melt waters draining from the portal of Gornergletscher, Switzerland, was recorded continuously for extended periods during the 1978-79 hydrological year. Conductivity was used as a surrogate measure of the total dissolved solids concentration in melt water to describe the seasonal variation of solute, and its relation to discharge, in an attempt to use melt-water hydrochemistry as an indicator of the nature of subglacial processes within an alpine glacier. In winter, conductivity was 2 to 10 times higher than during the summer ablation season, and also showed considerable diurnal and annual variations independent of discharge. The transition from winter to summer discharge regime was preceded by falling solute concentration. A distribution shaped as a "triangle-with-spike" describes the complex relationship between discharge and electrical conductivity for the annual cycle of run-off. Almost all the solute load from beneath Gornergletscher is evacuated during summer. Melt-water hydrochemistry provides some insight into the nature of subglacial chemical processes, but, since melt waters do not appear to have access to all areas of the glacier bed, it probably underestimates total chemical activity.

INTRODUCTION

Subglacial chemical activity is important in both glaciological and geomorphological processes. The dynamics of glacier motion may be affected where concentrations of solutes in ice and water at the bed significantly reduce ice-melting temperatures and therefore heat flow critical for regelation, hence reducing the velocity of sliding (Lliboutry 1971). Chemical weathering and erosion processes at the beds of Alpine glaciers have been inferred from the chemical composition of melt waters in subglacial torrents (Vivian and Zumstein 1973), and the nature of sub- and englacial hydrochemical environments indicated by the chemical composition of melt waters draining from glacier portals (Collins 1979[a]). Considerable subglacial chemical activity is suggested by the presence of discontinuous precipitates of both calcite and silicate on glacier beds from which ice has recently retreated (Ford and others 1970, Hallet 1975).

Studies of subglacial chemical processes have depended on such indirect observations, together with laboratory experiments and theoretical considerations, because of the difficulty of gaining direct access to areas of intimate ice-bedrock contact beneath glaciers, without disturbing basal hydrological, hydraulic, and thermal conditions. Pro-glacial melt-water characteristics provide a useful indirect means of sampling basal attributes, since melt waters pass through various hydrochemical environments as they flow across the bed in rock channels (Nye 1973), conduits incised in ice (Röthlisberger 1972), thin basal films (Weertman 1964), and interlocking cavities (Lliboutry 1976). The dissolved load of a portal melt stream reflects the mixing in varying proportions through time of waters with different chemical characteristics from different environments (Collins 1979[b]). Using discharge and hydrochemical data for the melt stream leaving the catchment of South Cascade Glacier, U.S.A., Reynolds and Johnson (1972) estimated the annual basin cationic denudation rate, which suggests an intensity of chemical weathering in alpine glacial environments considerably higher than continental averages. The annual cycle of chemical variation in the drainage from South Cascade Glacier was assumed to be sinusoidal, of the form

$$y = a \sin (2 \pi x/366) + c ,$$

where y is solute concentration,
a is the amplitude of variation,
x is number of days, consecutively from 1 December, and
c is mean solute concentration.

The parameters of the curve were estimated from cationic analyses ($\Sigma Mg^{2+} + Ca^{2+} + Na^{+} + K^{+}$) of 12 samples of melt water, only one of which was collected outside the months of June to August. Almost all published chemical data for all melt streams are of determinations made on samples collected during ablation seasons (Collins 1979[a], Table IV).

Theoretically, assuming that subglacial waters are locally saturated with respect to precipitates on the bed wherever they form, eutectic concentrations of basal solutions can be calculated from phase relationships (Hallet 1976). Artificial weathering experiments show that silicates interact rapidly with water at near-freezing temperatures (Tamm 1924, Reynolds and Johnson 1972) but after the initial rapid reaction, subsequent chemical change is extremely slow (Lemmens and Roger 1978). The possible formation of a protective layer on the surface of minerals after the first stage of decomposition may prevent further reaction, as suggested by Wollast (1967). Since the presence of liquid water is required for reactions to occur and for translocation of solutes, subglacial chemical and hydrological conditions must essentially be considered together.

The purpose of this study is to describe in detail variations in the solute content of melt waters draining from an alpine glacier throughout an annual discharge cycle including semi-continuous observations during the winter period. The relationships between solute concentration and discharge are investigated with the intention of assessing sources of dissolved load beneath an alpine glacier, and providing a temporal sampling framework for estimating rates of chemical denudation within an alpine drainage basin. Additionally, the use of water-quality characteristics of melt waters draining from an alpine glacier is evaluated as an indicator of the interaction of subglacial chemical and hydrological processes.

MELT-WATER AND SOLUTE SUPPLY TO RUN-OFF

Sources of run-off

The total discharge of a melt stream draining from the portal of an alpine glacier is composed of waters derived from several sources:

$$Q_t = Q_s + Q_i + Q_q + Q_p + Q_m \pm Q_z + Q_n , \quad (1)$$

where Q represents run-off proportions, and subscripts refer to total discharge (t), snow-melt on the glacier surface (s), ice ablation (i), basal sources, including ice melted by the geothermal heat flux, pressure-melting at the ice-bedrock interface, and water produced by pressure-melting within the basal ice mass and squeezed out from the ice (Robin 1976) (q), rain and condensation on the surface of the glacier (p), internal melting in the body of the glacier, resulting from ice deformation, pressure-melting and frictional melting by flowing water (m), and run-off from snow-melt and precipitation on ice-free areas (n). Some water may enter or leave a groundwater system beneath the glacier (Q_z).

Routing of run-off and sources of solutes

The extent to which initially-dilute components of glacier melt-water discharge are chemically modified depends on their routing through the glacier. A proportion of the water derived from snow and ice melt on and in the glacier and rain on the glacier (Q_s, Q_i, Q_p, Q_m) in summer, at least, reaches the portal through conduits without undergoing chemical enrichment. The remainder and that from basal sources (Q_q) come into contact with lithospheric materials, and acquire solutes during transit in tunnels, film, and groundwater (Collins 1977). Solutes may be added to subglacially-routed melt waters from bedrock, basal moraine, and sediment-rich basal ice. Most effective enrichment occurs where dilute melt waters first encounter sedimentary environments, and little further reaction occurs when morainic particles enter transit as suspended sediment. The total solute load at any time in the melt stream depends on the fractions of the total discharge which have become enriched, and the amount of solute acquired by each portion. In addition to seasonal changes in the absolute quantities and relative proportions of individual sources of melt water, temporal variations occur in the proportions of water flowing through the identified routes within the glacier.

FIELD MEASUREMENTS

Approach

Continuous measurements of both discharge and solute concentration throughout a hydrological year are required to investigate seasonal variations of melt-stream hydrochemistry. Electrical conductivity has proved useful as an indicator of the total dissolved solids content of melt water (Collins 1977), and is suited to continuous monitoring at a remote site. For logistical reasons, continuous measurements proved impossible but recording during reasonable time periods was achieved.

Field area

The field measurements were undertaken on the Gornera, the only melt stream draining from the snout of Gornergletscher, Alpi Pennine, Switzerland. The catchment, which drains to a gauging station about 1 km from the glacier portal, has an area of 82 km^2, of which 83.7% is covered by perennial ice and snow. Underlying the glacier, igneous and metamorphic rocks include gneisses, micaschist, gabbro, dolomitic marble, and serpentine (Lütschg and others 1950) which should limit leakage, and restrict groundwater flow to morainic layers.

Measurement records

The measurements reported here were largely undertaken during the 1978-79 hydrological year, and are presented with comparative results from 1975 and 1980. Techniques for measuring electrical conductivity in glacial melt waters have been described elsewhere (Collins 1977, 1979[a]). Electrical conductivity was recorded continuously throughout the following periods (in 1979 except for the first): 28 December 1978-29 January 1979, 17 February-4 April, 5-14 May, 26 May-4 June, 26 June-6 September and 16 September-17 October, and an instantaneous measurement on 27 October. Discharge was recorded from 14 May-30 September, at other times the flow being beneath the operational minimum for the gauge (*c*. 0.2 m^{3}s^{-1}).

MEASUREMENT RESULTS AND DISCUSSION

Discharge

Mean daily discharge of the Gornera during late spring and the summer ablation season of 1979 is shown in Figure 1. From the late winter flow of < 0.2 m^{3}s^{-1}, discharge increased slowly to a maximum of 6.3 m^{3}s^{-1} on 20 May, after which the flow (snow-melt, $Q_s + Q_n$) oscillated towards the appearance of the normal diurnal cycle of glacial run-off, which was established by 1 June. During the ablation season the Gornera usually exhibits a marked repeating diurnal rhythm of discharge ($Q_i + Q_s$) (Collins 1977). The regular diurnal regime is interrupted by occasional unusual hydro-glaciological events. A sudden increase to peak (16 m^{3}s^{-1}) on 2 June probably reflects the draining of an englacial or ice-marginal reservoir. From 26 June-1 July, the diurnal rhythm was subsumed by the high flow associated with the drainage of the ice-dammed marginal lake, Gornersee, which produced the maximum instantaneous flow of the year of 34.9 m^{3}s^{-1}, on 29 June. Periods of decreased flow and recession respond to meteorological conditions unfavourable for ablation, particularly summer snow-fall (e.g. 14-18 June, 17-21 August, 21-30 September). By 30 September, discharge had fallen to 0.8 m^{3}s^{-1} and was subject to only minor fluctuations in decline

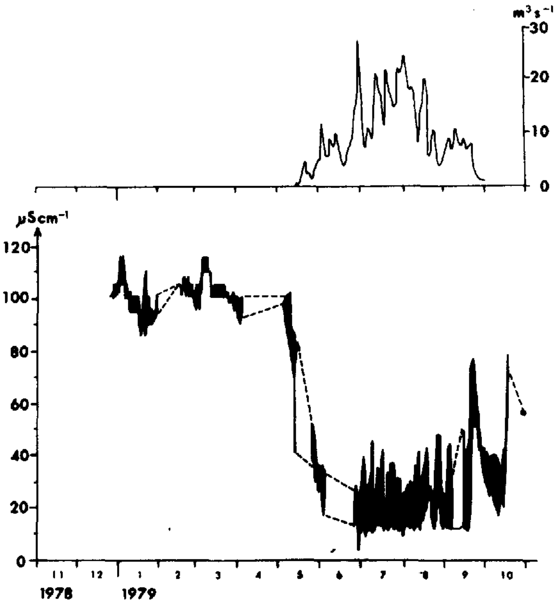

Fig.1. Seasonal variations of discharge and electrical conductivity of melt waters in the Gornera for the hydrological year 1978-79. Mean daily discharges recorded 1 km from the glacier snout are shown for the period 14 May-30 September 1979. Maximum and minimum daily values of electrical conductivity form the upper and lower limits of the distribution which are continued by pecked lines between observation periods.

towards the winter minimum ($Q_z + Q_q + Q_m$ and any water remaining stored in firn and ice).

Electrical conductivity

Results of continuous monitoring of electrical conductivity are also presented in Figure 1. Summary daily data are shown in the form of maximum and minimum values of electrical conductivity which form the upper and lower limits of the distribution recorded each day. From the onset of the repeating diurnal rhythm of discharge in early summer, electrical conductivity has been shown to exhibit similar daily periodic variations out of phase with those of discharge (Collins 1979[a]) giving an inverse relationship between temporal fluctuation of conductivity and discharge. The daily ranges of electrical conductivity of the Gornera in 1979 are represented by the vertical width of the shaded block in Figure 1, and for the period 1 June - mid-September these widths indicate the variation in conductivity associated with the diurnal rhythm. There is no simple relationship between discharge and conductivity in this period. The overall range of conductivity during summer was 8.0 to 58.5 µS cm^{-1}, and the minimum summer daily span 22-28 µS cm^{-1} on 21 August, and the maximum 14-50 µS cm^{-1} on 9 July. The minimum daily value of conductivity in the ablation season usually lies in the range 10 to 14 µS cm^{-1}. The daily maximum varies considerably from day to day. The lowest value, 8.0 µS cm^{-1}, was recorded on 29 June, during the draining of the Gornersee.

In winter, with minimal steady discharge between November and April, some diurnal variation of electrical conductivity was recorded. The overall range of conductivity in winter was 85 to 115 µS cm^{-1}, with maximum daily range 90 to 110 µS cm^{-1} on 21 January, though conductivity was constant on several days. Winter fluctuations may be explained by occasional snow-melt during periods with warmer temperatures, or by slow drainage of dilute water from englacial storage. Otherwise high winter solute content indicated by these results suggests intimate association between melt waters and lithospheric solute sources.

The transition between winter and summer regime is marked, occurring in about 20 days. Although discharge measurements had not commenced when conductivity first decreased about 6-7 May, discharge is unlikely to have increased simultaneously. Slowly-increasing flows accompanied the fall in solute content of melt-waters towards 30 May. The daily ranges of conductivity increased considerably, with reducing minima, while the maxima declined more slowly, suggesting that before the increase in melt-water discharge, selective routes become available within the glacier which permit some water to reach the portal of Gornergletscher without undergoing chemical enrichment.

At the end of the ablation season, diurnal range of electrical conductivity is reduced and almost eliminated by late October. The general level of conductivity increases as a discharge is diminished following persistent snow-falls. Some residual leakage of summer melt water which remains stored in temperate glaciers may continue into winter (Tangborn 1965).

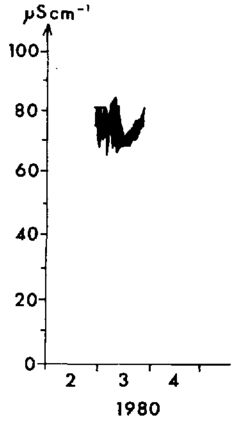

Fig.2. Maximum and minimum daily values of electrical conductivity of melt waters in the Gornera from 28 February-28 March 1980.

Electrical conductivity of melt waters in the Gornera was also recorded during February and March 1980. During the equivalent period in 1979, solute content was at its highest concentration, 95-115 µS cm^{-1}, but in 1980, conductivity ranged between 66-84 µS cm^{-1} (Figure 2). Stenborg (1965) and Lütschg and others (1950) considered that high solute concentrations in portal melt streams in late winter indicated subglacial groundwater contributing to flow. The hydrochemical data presented in this paper suggest that, while such a component may exist beneath Gornergletscher, melt water draining from a groundwater system, even after considerable storage time in lithospheric contact, does not reach an equilibrium solute content. Alternatively, other dilute water drains through the glacier in varying quantities throughout winter. Consequently, electrical conductivity, while remaining high in winter, is also variable throughout an individual winter season, and between years.

Winter solute concentration in the Gornera was between 2 and 10 times greater than in summer. At South Cascade Glacier, the sinusoidal annual variation in melt-water hydrochemistry predicted a winter maximum concentration double that of the summer minimum (Reynolds and Johnson 1972). For the conductivity data of the Gornera, the sinusoidal curve is not an appropriate model.

SOLUTE CONCENTRATION-DISCHARGE RELATIONSHIPS

The relationship between solute concentration and discharge in glacial melt-water rivers has been described by a model using a trapezoidal framework (Collins 1979[a]). The trapezium enclosing all the distribution of electrical conductivity plotted against discharge for the Gornera, based on hourly averages of conductivity and discharge from July to September 1975, is shown in Figure 3 (ABCD).

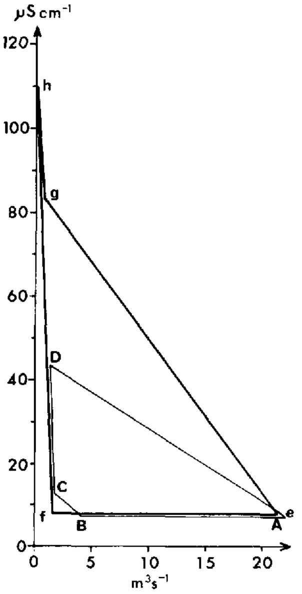

Fig.3. Solute concentration and discharge relationships for the Gornera. The figures ABCD and efhg enclose the distributions of plotted points of hourly mean electrical conductivity against hourly mean discharge from near-continuous data for the period 15 July-2 September 1975 and the hydrological year 1978-79 respectively.

Using data from throughout the 1978-79 hydrological year, the trapezium is modified to the figure efhg, a triangle efg and spike gh. The discharge and conductivity recorded during the draining of the Gornersee are not plotted, and lie outside the figure. Including these data would have the effect of extending the line fe beyond e. Line ef represents the lowest conductivity which recurs, independent of discharge, and is effectively determined by the concentration of atmospherically-derived solutes in precipitation. Point h is located by the maximum observed solute concentration in winter, which is considerably greater than that observed in the ablation season D, and is associated with a lower discharge. Line fh is located by the variability of conductivity at very low flows during winter and early spring. Line egh is positioned by the high conductivities associated with periods of recession flow in spring and summer.

The relative importance of each season in the annual evacuation of solute from beneath Gornergletscher can be obtained by the use of an index of instantaneous dissolved load transport, S, in the Gornera, where $S = QC$ and Q is discharge ($m^3 s^{-1}$) and C electrical conductivity ($\mu S\ cm^{-1}$). Minimum and maximum values of Q and C for each of the four seasons were used to calculate seasonal ranges of values of S (Table I). Most of the annual solute load is removed during summer, when high discharges flush solute from subglacial environments. In winter, although conductivity of the Gornera is high, low discharge results in limited solute yield. The data of Figure 1 provide no evidence of exhaustion of solute supply during summer, suggesting that summer melt waters are chemically reactive and are not simply removing solutes stored under the glacier during reduced drainage in winter.

MELT-WATER HYDROCHEMISTRY AS AN INDICATOR OF SUBGLACIAL CHEMICAL PROCESSES

Since melt waters flow across considerable areas of an alpine glacier bed, their quality characteristics might be expected to result from sampling chemical environments throughout. However, although melt waters will penetrate zones of the bed whence conduit access exists, some basal areas may not be hydraulically integrated. Souchez and others (1978) have shown that the ratio $(Na^+ + K^+)/(Ca^{2+} + Mg^{2+})$ in melt waters from the Glacier de Tsidjiore Nouve, Swiss Alps, was lower than that of regelation

TABLE I. SEASONAL VARIATIONS OF SOLUTE LOAD TRANSPORTED BY THE GORNERA

1978-79	Discharge $m^3 s^{-1}$	Principal components of discharge	Electrical conductivity $\mu S\ cm^{-1}$	Index of instantaneous solute transport S arbitrary units
Winter (December-April)	0.1-0.2	Q_z	90-115	9.0-23.0
Spring (May)	0.2-5.7	Q_s, Q_n	30-89	17.8-171.0
Summer (June-September)	8.3-20.2	Q_i, Q_s	10-41	202.0-340.3
Autumn (October-November)	0.2-0.8	Q_i (delayed), Q_z	40-51	20.0-40.8

ice. It is suggested here that regelation ice therefore develops separately from those basal melt waters integrated with conduit flow. Hallet (1976) has postulated that subglacial precipitates form by enrichment of water as solutes are selectively rejected into freezing water by the growth of ice during the regelation process. At Blackfoot Glacier, Montana, the Ca^{2+} content of a sample of pro-glacial water was 1.5×10^{-4} eq ℓ^{-1}, in comparison with a calculated 10^{-2} - 10^{-3} eq ℓ^{-1} necessary to permit $CaCO_3$ precipitation, assuming that subglacial waters must be saturated with respect to the precipitate (Hallet 1979). This is suggestive of water flowing through a conduit hydrological system isolated from the subglacial film in which spatially-restricted precipitates form. This view would find some corroboration in the results of bore-hole testing to the bed of Blue Glacier, Washington (Engelhardt and others 1978). A layer of gravel about 0.1 m thick was found between the bedrock and glacier sole, which was actively involved in the sliding process. It only partially enclosed interstitial ice, but was saturated elsewhere with water at a pressure near to that due to the overlying ice. This layer is impermeable probably because of barriers to flow between subglacial film and conduit where the active subsole drift is absent and the glacier sole is in intimate bedrock contact. Solution, reaction, and precipitation may occur within these areas with no hydraulic connection to conduit flow, so that total subglacial chemical activity will be underestimated by studies of melt-water hydrochemistry.

Some interaction of melt waters with areas of bed away from conduits is probable, however. Sediments must be derived from zones adjacent to conduit walls to maintain observed sediment concentrations in portal melt streams. Channels in ice migrate, and the locations of areas of subsole drift, which are hydraulically isolated from conduit flow, will alter through time because of glacier motion over an irregular bed. Weertman (1972) has shown the existence of pressure barriers adjacent to conduits which prevent movement of water and hence solute between film and conduit. Interconnection may occur, however, through moraine, striae, and rock joints, since barriers are unlikely to be intimate ice-smooth bedrock seals. Such a system of hydrochemical interaction can remain independent of local movements of pressure-melt water and solute to areas of reduced pressure in the lee of bedrock bumps. Lliboutry (1976) has suggested a cyclic evolution from lee cavities which are autonomous (isolated) to those which interconnect with conduits. This mechanism would allow melt waters periodic access to areas of possible solute concentration.

Some of the solute in melt water will be derived from sources other than the glacier bed, by subglacial groundwater Q_z and by run-off from the non-glacierized portion of the catchment Q_n. The amount of dissolved load transported by Q_n will be at a maximum in spring during snow-melt. The groundwater contribution is probably low, although apparently significant in winter. More detailed sampling of morainic seepage and snow-melt waters would be required to determine the relative solute yields of non-glacial sources.

CONCLUSION

Annual temporal variations of electrical conductivity of melt waters in the Gornera describe three main periods distinguished by hydrochemical characteristics. During winter, solute load is high, with limited diurnal variation, whereas in summer, high fluctuations are superimposed on a generally lower level. A short transition period precedes the spring increase in discharge, when electrical conductivity reduces rapidly. Most chemical activity occurs in summer, because of the increased water availability. Lithological influences characterize the composition of melt waters at lower discharges, and particularly in winter.

The marked seasonal and diurnal variations of hydrochemistry of glacial run-off result from variable contributions through time of waters from different sources following varying routes in changing proportions. Variable routing is associated with the passage of water through different hydrochemical environments, and provides a control on melt-water solute content. Periodic interaction of hydrologically-isolated and probably solute-rich waters within zones of subsole drift with water transferred rapidly through conduits, undergoing little chemical enrichment after initial contact with morainic particles, may account for some of the temporal variation of melt-water chemistry. The relationship between solute concentration and discharge is complex, as evidenced by the "triangle-with-spike" distribution.

The approach described in this paper is of limited use for the separation of water and solute contributions, which requires more detailed investigation of individual ionic compositions and isotope contents of melt waters to disentangle the various components of discharge, and their routing and residence in basal film, subsole drift, and subglacial conduit system.

However, the temporal variations of solute concentration identified in this study establish a useful design for a sampling strategy for a chemical and isotope programme. The estimation of rates of chemical weathering and erosion beneath alpine glaciers requires analyses of individual ionic concentrations in melt water, within this sampling framework, together with continuous recording of discharge throughout an annual cycle.

ACKNOWLEDGEMENTS

This study was supported by a grant from the Natural Environment Research Council (Grant GR3/3831). The author gratefully acknowledges the assistance of A. Bezinge, J.-P. Perreten, and Grande Dixence, S.A., who have generously provided field support and made available discharge measurements of the Gornera. P.G. Cleves and J.-P. Perreten made vital contributions to the fieldwork, and their help is greatly appreciated.

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