HYDROCHEMICAL SEPARATION OF COMPONENTS OF DISCHARGE IN ALPINE CATCHMENTS 1/ 649-79

By

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Introduction

Total discharge from an alpine glacierised catchment is derived from snow- and ice-melt and precipitation which contribute to runoff in varying quantities through time, and which follow different routes from source to outlet. The investigation of alpine runoff is complex because of spatial and temporal variations in the rate of melting, variations in water content and water equivalent of snowcover, and variations in the altitude-area distributions of effective contributing snow- and ice-melt sources. Resultant difficulty in direct measurement of snowmelt and ice ablation contributions to runoff has led to use of indirect methods for prediction of discharge from snow- and ice-covered catchments (e.g. Quick and Pipes, 1973; Jensen and Lang, 1973). Further understanding of physical processes leading to alpine runoff formation is required because of their intrinsic interest and as an aid to development of distributed models for forecasting.

Winter discharge from a glacierised watershed is composed of small contributions from englacial storage and subglacial springs, although the question of the existence of subglacial groundwater systems remains unsettled (Lütschg and others, 1950; Stenborg, 1965). In spring, increasing discharge results from snowmelt over the lower basin area, but runoff is lower than predicted from quantities of snow melted, because of storage in snowpack and glacier (Stenborg, 1970). This stored water is released later in summer, adding to high discharge resulting from ablation of the increasing surface area of ice exposed as the transient snowline rises. Rapid runoff due to daily ablation produces rythmic diurnal variation in meltstream discharge during summer but peaks account for only small proportions of total daily flow. Elliston (1973) considered that some water becomes stored in the body of the glacier to drain under the variable pressure head created by the repeating pattern of diurnal inflow. Lagged drainage of snowmelt water from temporary storage in the glacier accumulation area may contribute much of the background flow (Golubev, 1973).

Because of measurement problems, the contributions of snow- and ice-melt sources in runoff have been assessed indirectly from isotopic composition of meltwaters draining from glacierised catchments (Behrens and others, 1971). Runoff from snow (accumulated post-1952 precipitation) can be effectively separated from that of ice dating from before atmospheric thermonuclear testing because of its higher tritium content. Monthly contributions of spring snowmelt and summer icemelt to runoff in the Mistaya and North Saskatchewan Rivers, Alberta, Canada, were successfully calculated from measurements of meltwater isotopic content by Prantl and Loijens (1977), and this discrimination seems to provide a good description of actual hydro-glaciological processes involved (Loijens, 1974). Environmental isotopes in catchment outflow have also permitted determination of routing of waters within alpine basins. About 40 per cent of total snow- and ice-meltwaters from Hintereisferner, Ötztal Alps, Austria, was identified as having flowed through a groundwater system, with a mean residence time of a few years (Ambach and others, 1976). In a non-glacierised basin in the Krkonose Mountains, Czechoslovakia, about 66 per cent of snow-meltwater infiltrated into a soil-groundwater system, which showed a sub-surface residence time of 2.5 ($\sigma = \pm 1.25$) years (Dinçer and others, 1970), but the remainder formed runoff within 24 h of production.

Separation of components by source and routing using isotopic content is unsuited to detailed study at the diurnal timescale, especially over extended periods, since frequent

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sampling generates much expensive laboratory analysis. This paper presents some results from attempts to separate components of alpine runoff defined by routing, using natural chemical characteristics to distinguish waters following different paths through a catchment. The studies were designed to investigate diurnal variations in discharges of different flow-components as a contribution to the understanding of the formation runoff from alpine glaciers. In a glacierised British Columbia catchment, in Canada, Zeman and Slaymaker (1975) discriminated three distinct components contributing to runoff by the concentration of dissolved material in meltwaters. Snowmelt over regolith, glacier melt and groundwater flow were sufficiently diverse in content of major cations, chloride and silicate to characterise total runoff quality according to changing contributions from each source between May and July.

Chemical separation of flow-routing components

Immediately after production, snow- and ice-meltwaters are characterised by low solute contents, determined by atmospheric ionic input and subsequent self-purification during re-crystallisation (Glen and others, 1977). Snowmelt runoff over lithospheric material can acquire significant quantities of soluble material within a metre of the edge of the snowpack (Zeman and Slaymaker, 1975), probably resulting from some meltwater having passed beneath the snowpack as subsurface flow in soil. Water percolating laterally within snowpack will retain its original dilute character. Waters arising from snow- and ice-melt at the glacier surface descend moulins to the glacier bed to contact basal morainic sediments, some of which become entrained in meltstreams as suspended load. Precipitates of calcite (Ford and others, 1970) and silicate (Hallet, 1975) on former beds of recently retreated glacier snouts suggest that the ice-bedrock interface provides a ready source of dissolved load to dilute meltwaters flowing slowly at the bed in either films or small conduits. Other meltwaters, following major arterial conduits in en- and sub-glacial locations, are subject to rapid transit through the glacier as evidenced by the tracing of fluorescent dyes (Krimmel and others, 1973). They probably retain much of their dilute character, although some solute may be supplied by dissolution or ion-exchange from suspended sediment in transport. Slow percolation of meltwater through basal moraine may also concentrate ions from lithospheric sources. Any seepage through a bedrock groundwater system will provide high concentrations of solutes to meltwaters.

In a simplified model, three flow-routing components of runoff can be discriminated hydrochemically: (1) dilute meltwaters flowing through arterial, often ice-walled, conduits in the glacier, neither delayed nor enriched after production, (2) meltwaters passing subglacially through small basal conduits and percolating through basal morainic sediments and (3) groundwater flow. The mixing of waters from these routes downstream produces seasonal and diurnal variations in both discharge and solute content at the glacier portal, depending on melt conditions. In the absence of rainfall, total flow is made up of discharges from the three individual flow-routing components:

$$Q_t = Q_i + Q_s + Q_g \qquad (1)$$

where Q represents component discharge, and the subscript i dilute meltwaters, s subglacial enriched runoff and g groundwater flow. The contribution of solutes from each component of total runoff is given by:

$$Q_t C_t = Q_i C_i + Q_s C_s + Q_g C_g \qquad (2)$$

where C is the solute concentration of a component. Equation (2) applies only for mixing of waters of uniform density and when there is no chemical reaction when components mix.

Field observations

Electrical conductivity was used as a measure of solute concentration in meltwaters on account of its suitability for continuous recording, and since it previously proved a useful parameter for runoff analysis (Behrens and others, 1971; Nakamura, 1971). Conductivity was recorded for waters in various hydrochemical environments in each of two glacierised catchments.

Gornergletscher is a large valley glacier (68 km^2) in the Pennine Alps, Valais, Switzerland, occupying a catchment of area 82 km^2 draining to a single meltwater stream, Gornera, discharge of which is recorded during the period May-September by Grande Dixence, S.A. The catchment has a vertical extent of 2629 m from 2005 m a.s.l. to 4634 m. The catchment is underlain by igneous and metamorphic rocks, granite, gneiss and schists, all of which are impermeable, with a very small area of calcareous rocks (Bearth, 1953). Conductivity was continuously monitored at a site 250 m from the glacier portal, and on a supraglacial meltstream about 2.5 km upglacier, over several periods in the summer ablation season of 1975 and during spring snowmelt in 1976.

Observations were also undertaken in the summer of 1978 in the contrasting catchment of Peyto Creek, draining Peyto Glacier, Rocky Mountains, Alberta, Canada. Peyto Creek is gauged during summer months about 550 m from the glacier snout. Sixty-one per cent of the catchment area of 23 km^2 is currently covered with perennial snow and ice. The basin, extending from 1900-3200 m a.s.l., is underlain by interbedded limestones, dolomite, shales and sandstone. Electrical conductivity of meltwater was measured adjacent to the Peyto Creek gauge. Some groundwater flow feeds a spring downstream of the catchment tributary to the gauge, and conductivity of springwater was measured 2 m from the source. A stream draining from Caldron Lake in an adjacent ungauged catchment with limited snow and ice cover was also monitored.

Measurement results

The results of field measurements are given in Tables I and II. Although it is usual to standardise electrical conductivity to a reference temperature of 25°C, normal compensation factors are inappropriate for glacial meltwaters (Østrem, 1964; Collins, 1978). No temperature compensation has been used. The probable error incorporated in the results presented is about 10 per cent, assuming correction to a reference temperature of 1°C.

Electrical conductivity of the Gornera showed low amplitude oscillation during spring snowmelt. The surface of Gornergletscher remained covered with snow throughout the period 7-13 May, 1976. Conductivity varied inversely with discharge which ranged from about 1-2 m^3s^{-1}. Whilst snow meltwater would be expected to have a conductivity similar to that of icemelt (0.1-5.4 $\mu S\ cm^{-1}$), snowmelt flowing in small rills over unvegetated moraine about 5 m from the snow margin became considerably enriched in solutes. During the glacier ice ablation season in July and August 1975, a marked diurnal rhythm of discharge occurred inversely in phase with variations of electrical conductivity (Collins, 1978). At high discharge in late afternoon, conductance was so low that dilute meltwaters from the glacier surface appeared in such large quantities as to mask any lithological influence on solute load. Runoff of the dilute component reached a maximum very soon after maximum melting in the afternoon. The highest conductivity (44.0 $\mu S\ cm^{-1}$) repeatedly recurred at times of depletion induced by snowfall over the glacier surface, when dilute meltwater component of runoff ceased to appear. This value was taken as a minimum estimate of a presumed equilibrium chemical environment beneath Gornergletscher, which it proved impossible to sample directly. This subglacial environmental concentration was considerably lower than the solute level of snowmelt runoff over moraine. During spring snowmelt, the Gornera meltstream never reached the subglacial environmental concentration.

In the Peyto catchment, electrical conductivity of springwater was almost constant (98-100 $\mu S\ cm^{-1}$), and spring discharge was not noticeably variable. Icemelt on the surface of Peyto Glacier produced meltwater of low solute concentration, with no influence from lithospheric ionic sources. Large amplitude diurnal variations of electrical conductivity occurred inversely and roughly in phase with fluctuations of discharge in Peyto Creek (Fig. 1), as at Gornergletscher. Peyto Creek always remained considerably richer in solute load than the surface meltstreams, probably as a result of the presence of a groundwater component of flow from basal limestone springs. When usual afternoon discharges of dilute meltwater from the surface was prevented by snowfall, the conductivity of Peyto Creek increased to 48.0 $\mu S\ cm^{-1}$. Only after 10 d reduced flow was conductivity raised to daily maxima in excess of 70.0 $\mu S\ cm^{-1}$ on 19-22 August 1978. By 1-2 October, relatively dilute meltwaters were reduced to such an extent that the concentration of waters in Peyto Creek approached that of groundwater, with a discharge of 0.5 m^3s^{-1}.

Quantitative estimation of runoff component contributions to total flow

Several models may be used for the calculation of flow-components as separated by hydrochemical characteristics. Assuming no groundwater flow on impermeable catchments such as Gornergletscher ($Q_g = 0$), equation (2) can be simplified to a two-component system:

TABLE I

Summary of observations of electrical conductivity of water from various hydrological environments in Gornergletscher catchment

Hydrological environment	Observation period	Range of observed electrical conductivity $\mu S\ cm^{-1}$	Water temperature ^{o}C
Proglacial meltstream, Gornera.	15 July - 2 Sept. 1975	6.5 - 44.0	0.1 - 1.2
	7 - 13 May 1976	20.0 - 32.0	0.1 - 0.5
Supraglacial icemelt streams Gornergletscher:			
large stream	13 - 15 Aug. 1975 (continuous)	2.7 - 5.4	0.1
small streams	Summer 1975-1977 (12 samples)	0.1 - 1.6	0.1
Snowmelt runoff on moraine	10 May 1976 (2 samples)	87.0 - 91.0	2.3

TABLE II

Summary of observations of electrical conductivity of water from various hydrological environments in and adjacent to the catchment of Peyto Creek, 1978

Hydrological environment	Observation period	Range of observed electrical conductivity $\mu S\ cm^{-1}$	Water temperature ^{o}C
Proglacial meltstream, Peyto Creek	14 July - 22 Aug.	26.0 - 74.0	0.4 - 0.5
	1 - 2 October	89.5 - 94.5	-
Supraglacial icemelt stream, Peyto Glacier	28 July - 2 Aug.	0.56 - 0.80	0.1
Outflow from Caldron Lake catchment	2 - 5 August	105.0 - 120.0	10.5 - 12.5
Spring	6 - 7 August	98.0 - 100.0	-

$$Q_t C_t = Q_i C_i + Q_s C_s \qquad (3)$$

where $Q_t = Q_i + Q_s$. Folling Hem (1970), C_s and Q_s may be considered constant, and the dilute component obtained from:

$$Q_i = (Q_t C_t - K)/C_i \qquad (4)$$

where K is a constant, measured when $C_t = C_s$. In reality, while C_s may be constant and represent a subglacial environmental level, it is unlikely that Q_s will remain constant. In non-glacierised basins, Pinder and Jones (1969) have shown that subsurface enriched runoff is highly variable. Discharge at the glacier bed will probably vary diurnally as a function of changing water pressures within the firn-glacier hydrological system (Collins, 1978). The proportion of runoff undergoing chemical enrichment is then given by:

$$Q_s = \left[(C_t - C_i)/(C_s - C_i)\right] Q_t \qquad (5)$$

and the dilute component by substraction:

$$Q_i = Q_t - Q_s \qquad (6)$$

Field observations suggest that the model given by equations (5) and (6) is appropriate since since $C_t \rightarrow C_i$ at high Q_t, resulting from the near cessation of flow of component Q_s.

This model has been used to separate components of flow through Gornergletscher, using the following observed parameters, Q_t, C_t, C_i, and with C_s estimated as the maximum observed value of C_t (44.0 µS cm^{-1}). The curves of total discharge of the Gornera (Q_t), and of flows of the enriched and dilute components are shown in Fig. 2, for a period of sustained ablation 3-8 August, 1975. The hydrograph of the dilute meltwater component (Q_i) is in phase with that of total discharge (Q_t), and both are characterised by asymmetrical peaks superimposed on a background flow which shows limited fluctuation. Following the onset of surface melting of ice and snow, both Q_i and Q_t increase rapidly to a peak between 15.00-18.00 h, as large quantities of dilute meltwaters flow quickly to the snout. A smaller portion of total flow is routed subglacially (Q_s) and a steady background discharge between 2-4 m^{3}s^{-1} was increased during diurnal reductions of Q_t, but with a hydrograph of reverse asymmetry to those of Q_i and Q_t. Flow of Q_s increases slowly and irregularly to a maximum which coincides with or follows several hours behind minimum discharge of Q_i and Q_t. Q_s is suddenly reduced as Q_t increases as snow and icemelt resumes in the morning. This behaviour has been suggested to result from the existence of subglacial reservoirs in cavities at the glacier bed, which store meltwaters during high diurnal water pressure, and in which chemical enrichment probably takes place (Collins, 1978). At low discharge, decreasing water pressure leads to reservoir depletion.

During snowmelt, before the ice ablation season, a considerable chemically enriched component of flow makes up 30-70 per cent of total discharge from Gornergletscher. This suggests that much of the snowmelt flow may pass through morainic environments either surrounding or beneath the glacier, which may account for some delay to runoff.

In the limestone catchment of Peyto, the model of equation (2) must be used since a groundwater component of flow was observed within the catchment. C_g was determined from observations of springwater concentration. Subglacial waters probably enter the groundwater system, and groundwaters emerge from springs into the subglacial system. In this paper, C_s and C_g are assumed to be the same, the concentration (C_b) taken as 100 µS cm^{-1} of a joint component Q_b, where $Q_b = Q_s + Q_g$. At no time during the observation period was C_t reduced to C_i, suggesting a large component of groundwater flow, also supported since $C_t \rightarrow C_g$ when snow- and ice-melt input were reduced. Equation (5) can be rewritten, taking $C_i = 0$:

$$Q_b = (C_t/C_b) \; Q_t \qquad (7)$$

and $Q_i = Q_t - Q_b$. It is probable that a distinct value of C_s lower than C_g may be associated with water movement in subglacial channels and tunnels in limestone rather than slow percolation and seepage in moraine and bedrock characterised by C_g. A more complex mass-balance mixing model is required to describe this relationship.

Results of the separation of flow-components by chemical characteristics for Peyto

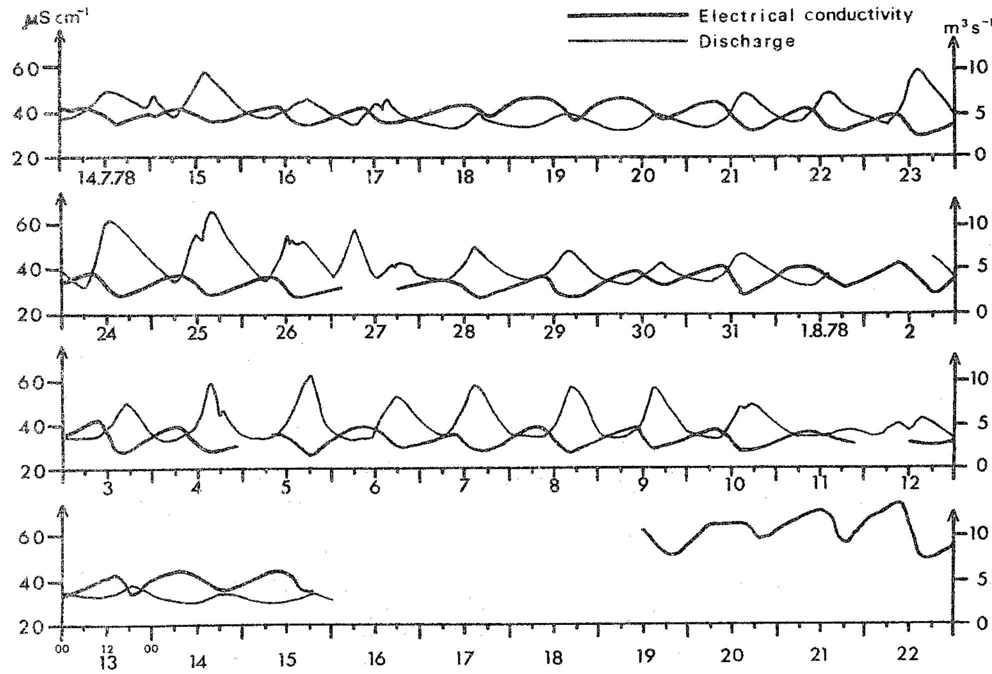

Figure 1. Temporal variations of discharge and electrical conductivity of meltwaters in Peyto Creek, 14 July - 22 August 1978.

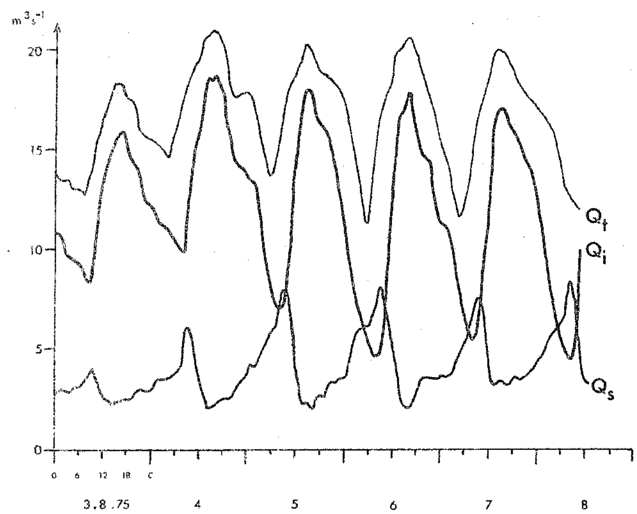

Figure 2. Discharge hydrographs of flow components separated by hydrochemical analysis for Gornergletscher, 3-8 August 1975. The curves of total discharge (Q_t) and dilute component (Q_i) vary together in phase, whereas the flow of the enriched component (Q_s) shows out of phase fluctuation with reversed asymmetry.

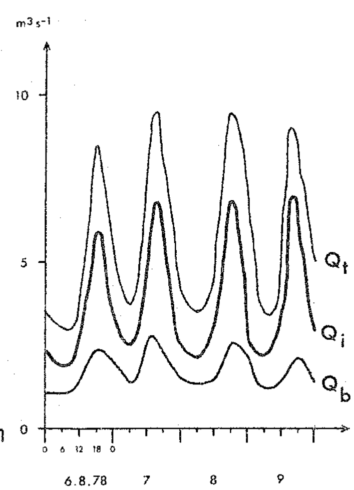

Figure 3. Curves of total discharge (Q_t), and dilute runoff component discharge (Q_i) and enriched subglacial and groundwater flow (Q_b) at Peyto Creek, 6-8 August 1978, as separated by hydrochemical analysis.

Creek calculated from equation (7) are given in Figure 3. The curves of Q_t and Q_i varied in phase, both showing steep rises to peaks superimposed on general background flows which account for about 40 per cent of total daily flow of each hydrograph. The discharge of the chemically enriched component remained above 1 m^3s^{-1}, accounting for 25-35 per cent of Q_t. Superimposed on this background flow, peaks occurred daily roughly in phase with variations of total discharge. The peaks accounted for about 30 per cent of total daily flows of the component Q_b.

Discussion

Two contrasting types of runoff behaviour are indicated within temperate glaciers. At Gornergletscher, where groundwater flow is limited on account of igneous and metamorphic bedrock, chemically enriched flow shows temporal variations out of phase with those of total discharge. Much of the diurnal peak flow is composed of dilute surface meltwaters. At Peyto Glacier, both enriched and dilute components of discharge vary in phase with total discharge, but again a large proportion of the diurnal peak flow results from the increase in discharge of waters passing through the catchment without chemical change. The in-phase variation of the enriched component probably results from water passing through vadose passages in cavernous limestone, thus becoming enriched but not suffering the delay to flow experienced when storage occurs in cavities and morainic sediments. The results suggest that subglacial tunnels beneath Peyto Glacier may interconnect with karstic groundwater systems, and that there is little water storage in cavities. It is probable that the rapid flow through Peyto Glacier is in channels which are independent of the thin films of water which are considerably enriched and from which solutes are precipitated at the bed. Peyto Glacier appears to behave in similar fashion hydrologically to Hintereisferner, where about 40 per cent of basal flow in July-September was made up of a stable groundwater component (Ambach and others, 1976).

The method of separation of runoff components by water chemical characteristics does not permit identification of the relative contributions to discharge of snow- and ice-melt sources. The origin of solutes from peri-glacial and sub-glacial sites cannot be discriminated. Water percolating from melting of seasonal snowpack accumulation into moraine appears as part of the same component as chemically-enriched waters from icemelt passing subglacially and waters entering or leaving the groundwater system.

The observations have been limited to a short period in spring and summer ablation seasons, and measurements are clearly required from other seasons, especially during March-July. Investigations of chemical components at sub-catchment levels would permit an improved knowledge of snowmelt routing in the icefree areas of glacierised watersheds. More information is required concerning the individual hydrochemical behaviour of the individual flow-components identified in this study.

Despite probable errors in parameter estimation and over-simplification in the models utilized, separation of total discharge into flow components by hydrochemical characteristics provides much insight into the formation of runoff from snow and icemelt in glacierised catchments. In particular, it points to the importance of routing within the internal hydrological network of glaciers and groundwater systems in translating meteorologically controlled inputs into summer discharge from alpine watersheds.

Conclusion

This study demonstrates the use of water quality characteristics in determining flow components contributing to the formation of runoff in glacierised mountain watersheds. The nature of hydrological processes operating inside temperate glaciers can be determined from analysis of chemical composition of water draining in proglacial meltstreams. Electrical conductivity provides a useful parameter for the discrimination of water types in runoff analysis. Hydrochemical runoff analysis enables separation of components of flow by routing which cannot be achieved by classical analysis of hydrographs alone.

The method of hydrochemical separation described here provides information about temporal variation of runoff components, and the structure and behaviour of drainage networks within alpine catchments, without the need for extensive networks for measurement of spatial, temporal and altitudinal variations of source inputs and source areas. Although the results presented refer to the catchment scale and summer ablation season only, it is suggested that the hydrochemical method of flow-component separation provides a powerful technique in the understanding of alpine runoff formation.

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