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Meltwater Hydrology and Hydrochemistry in Snow- and Ice-Covered Mountain Catchments

David N. Collins and Gordon J. Young

Department of Geography, University of Manchester and
National Hydrology Res.Inst., Environment Canada

Electrical conductivity, a surrogate measure of total dissolved solids content, and discharge of meltwaters draining from two adjacent contrasting watersheds in the Rocky Mountains, Canada, were recorded continuously from mid-May – August 1979, throughout the ablation season, in order to investigate the influence of snow- and ice-melt on alpine hydrochemistry. Solute concentration varied inversely diurnally with discharge in both nival and glacial meltwaters. Solute content and discharge of the snowmelt-fed Amiskwi River declined with decreasing availability of snowcover through July, followed by increased solute content during low flows in August. In the glacially-fed Peyto Creek, conductivity decreased with increasing flow during spring snow-melt, but during ice-melt domination of flow from mid-July oscillated daily through a limited range. Snow- and ice-melt are shown to have contrasting roles in determining distinctive patterns of diurnal and seasonal temporal variations of discharge and hydrochemistry in mountain basins. Continuous monitoring of water quality is essential in characterising the hydrochemistry of alpine environments.

Introduction

Both the quantity and quality of runoff from high mountain basins are regulated by the accumulation and melting of seasonal snowcover and melting of permanent glacier ice. Studies of the formation of mountain runoff are of considerable importance, since flows in the headwaters of many great continental rivers originate in the alpine zone, and such sources are extensively utilised by engineering developments for irrigation and hydro-electric power, especially in the western cordillera of North America, the European Alps, Scandinavia and central Asia. Investigation of meltwater hydrochemistry in mountain drainage basins is of interest as a technique in the study of quantity aspects of hydrological behaviour and intrinsically with respect to hydrochemical aspects of the alpine hydrological cycle. In snow- and ice-free catchments, temporal variations of ionic concentrations and discharge in streams have been widely used to identify individual runoff components (Kunkle 1965; Pinder and Jones 1969; Nakamura 1971). In an alpine basin, Zeman and Slaymaker (1975) showed the potential use of major cations, chloride and silicate to differentiate ice-melt, snow-melt and baseflow components. Measurements of meltwater electrical conductivity were used by Collins (1979a) to separate components of flow by routing within alpine glaciers, and by Oerter, Behrens, Hibsch, Rauert and Stichler (1980) to separate groundwater flow, from ice-free areas of a partially-glacierised catchment and subglacial moraine, from meltwaters produced by melting glacier ice.

Studies of short-term discharge variations in response to changing hydrometeorological conditions (e.g. Derikx 1973; Gottlieb 1980) have primarily utilised essentially lumped representations of the alpine hydrological system. In the few studies of the actual physical processes involved in the formation of runoff within mountain basins, environmental isotopes have proved useful. In nival basins, tritium data have allowed separation of baseflow from snow-melt runoff (Dincer, Payne, Florkowski, Martinec and Tongiorgi 1970) and in glacial basins tritium, deuterium and oxygen-18 have determined runoff portions from ice-melt, snow-melt and springwater (e.g. Behrens, Bergmann, Moser, Rauert, Stichler, Ambach, Eisner and Pessl 1971; Oerter and others 1980). Occasional samples for isotopic determinations, collected monthly, or at best every few hours during isolated periods of about 48h, provide limited information for the development of distributed catchment models, and there appears to be considerable advantage if separation of alpine runoff components might be achieved on the basis of hydrochemical parameters which can be continuously recorded alongside discharge.

This study was designed to provide basic hydrological and hydrochemical data to allow examination of the potential of natural water quality in the separation of snow-melt, ice-melt and groundwater components of alpine runoff. Previous investigations of detailed temporal variations of alpine hydrochemistry have been restricted to partially-glacierised basins (Collins 1979b) where seasonal fluctuations of meltwater solute content suggest the effects of variable component contributions (Oerter and others 1980; Collins 1981). By monitoring water quality in adjacent contrasting nival (seasonally snow-covered but ice-free) and partially-glacierised basins simultaneously, a comparison of data from the two catchments should show any distinctive features of snow- and ice-melt runoff patterns, and allow investigation of the role of glacierisation in alpine hydrochemistry. The aim of this paper is to describe the hydrology and hydrochemistry of runoff from two basins from winter conditions through an ablation season.

Components of Runoff from Alpine Mountain Catchments

Discharge

The total discharge of an alpine meltstream draining from a partially-glacierised basin is composed of contributions derived from two sub-catchments

$$Q_t = Q_n + Q_z \tag{1}$$

where Q represents the discharge of a component of runoff, and the subscripts refer to total discharge (t), discharge from the ice-free areas of the catchment (n) and from the glacier (z). In a nival watershed, $Q_z = 0$, and

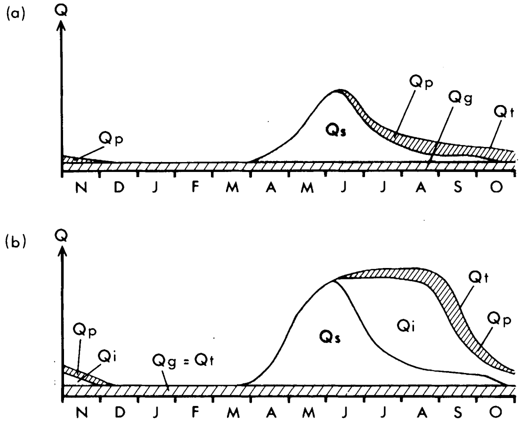
$$Q_t = Q_n = Q_p + Q_g + Q_s \tag{2}$$

where (p) is flow derived from rainfall over snow-free areas, (s) snowmelt, and (g) groundwater flow. A schematic annual hydrograph for a stream draining a nival basin is given in Fig. 1(a). In winter, discharge results from groundwater flow only. As temperatures rise above 0° Celsius in spring, snowmelt from the lower slopes of the basin increasingly contributes, and a partial source area of snowmelt passes up-basin, leaving a snow-free zone in lower areas to return rainfall inputs. During summer, the declining snow reservoir reduces the quantity of melt, but increases the contributing area for rainfall. Q_g is assumed to be time -invariant.

In a glacial catchment

$$Q_z \equiv Q_g + Q_i \tag{3}$$

where (i) represents the flow from the glacierised area, icemelt, firnmelt, seasonal snowmelt on the glacier, and rainfall over the ablation area. Q_i is a lumped component, since after entering the glacier, water from the differing sources will



Q_t ≡ total discharge
Q_s ≡ snowmelt runoff from ice-free areas
Q_p ≡ runoff from rainfall
Q_g ≡ groundwater discharge
Q_i ≡ glacial component of discharge (incl. icemelt, firnmelt and snowmelt from the icecovered area)

Fig. 1. (a) Schematic annual discharge hydrograph of a stream draining a nivel catchment, with seasonal snow cover, but no perennial ice storage.

Fig. 1. (b) Schematic annual discharge hydrograph of a stream draining a glacial (partially-glacierised) catchment.

not be chemically distinct. Temporal variations of the total flow ($Q_t = Q_n + Q_z$) and its components are schematically shown in Fig. 1(b). In early winter, some ice meltwater which remained stored in the internal hydrological system of the glacier may contribute to Q_t. In spring, as snowmelt progresses, underlying ice is melted, which reservoir continues to supply meltwater throughout summer, becoming increasingly important as snow supply is exhausted. Absolute quantities and relative proportions of runoff derived from each source vary temporally, together with source areas accounting for diurnal and seasonal patterns of discharge.

Solute Supply

In hydrochemical balances for mountain basins, ionic budgets show that terrestrial sources are the major contributors of solute load to runoff (Reynolds and Johnson 1972), with little impact from near-climax stage forest ecosystems (Zeman 1975). Initially-dilute rain, snowmelt and icemelt become chemically enriched depending on their routing across a catchment, according to the interaction of solute sources and runoff pathways. In ice-free unvegetated areas, soluble material is readily taken up by rain (Rainwater and Guy 1961) and snowmelt (Feth, Roberson and Polzer 1964). The bed of an alpine glacier is probably the richest source of solute, since ionic evacuation is at a maximum at times of highest discharge (Collins 1981), but the extent to which Q_i becomes enriched depends on the fraction of that component which is routed subglacially (Collins 1979a). The relative importance in the solute *load* (discharge x solute concentration) between the components Q_z and Q_n in a glacierised basin is unknown. High solute concentration in winter discharge from glaciers has suggested the existence of subglacial springs (Stenborg 1965), since groundwater will acquire considerable dissolved load. The solute content of meltwater from a glacierised basin is

$$Q_tC_t = Q_pC_p + Q_gC_g + Q_sC_s + Q_iC_i. \tag{4}$$

where C represents the solute concentration of a runoff component. C_g may approach a constant value, but C_p, C_s and C_i can vary non-linearly inversely with Q_p, Q_s and Q_i respectively.

Study Area

Two catchments, with existing gauges, based on Cambrian sedimentary rocks, interbedded permeable limestones, shales, dolomites and sandstones in the Rocky Mountains, Alberta and British Columbia, Canada (51°35'N, 116°38'W) were studied (Fig. 2). Peyto Creek basin contains Peyto Glacier, from which meltwaters drain in one outwash stream to the Mistaya River, tributary to North Saskatchewan River. About 40 per cent of the glacier area lies in the ablation zone in summer, contributing rapidly to runoff. Nineteen per cent of the non-glacierised

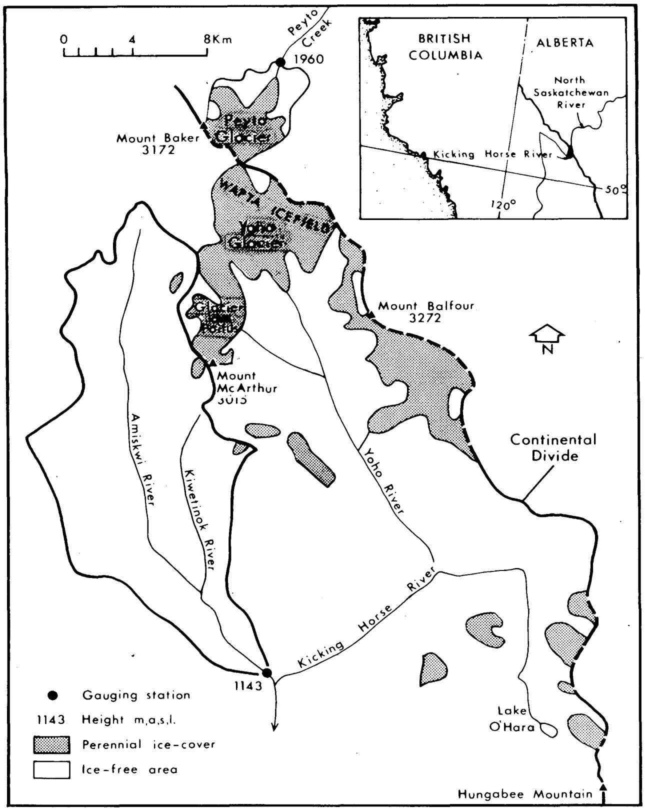


Fig. 2.
Map of the catchments of Peyto Creek, and Amiskwi River, Rocky Mountains, Alberta and British Columbis, Canada, Showing the extent of glacierisation.

area is ice-cored moraine, the remainder bare rock, with residual snow patches, but contributing no surface runoff to Peyto Creek above the gauge. Hydrometeorological, hydrological and mass balance data have been collected since 1967 (Young 1978).

Table 1 – Characteristics of the study catchments

Characteristic		Catchment	
		Peyto Creek	Amiskwi River
Catchment area	km^2	23.0	192.7
Glacierised area	km^2	14.1	2.2
Percentage glacierisation	%	61.0	1.1
Glacier altitude range			
snout	m a.s.l.	2090	2345
highest elevation	m a.s.l.	3172	2591
Catchment elevation			
gauging station	m a.s.l.	1950	1143
highest elevation	m a.s.l.	3172	3015

Amiskwi River basin has a westerly aspect, and is effectively ice-free. About 30 per cent of the catchment area is bare rock, and the remaining lower slopes (beneath *c* 2300m a.s.l.) are densely covered by mature stands of predominantly Engelman spruce (*Picea engelmanni* (Parry)) and Subalpine fir (*Abies lasiocarpa* (Hook.) Nutt) with Douglas fir (*Pseudotsuga menziesii* (Mirb.)) (Parks Canada 1979). Details of the catchments are given in Table 1.

Measurements

Strategy

Simultaneous continuous measurements of discharge and hydrochemical characteristics were required throughout the hydrological year at the two gauging stations, in order to describe temporal variations. Electrical conductivity was used as a surrogate measure of total dissolved solids content of meltwater, since it has proved useful in characterising glacial water quality (Collins 1979b), and can be recorded at remote sites. The measurements were only possible from May-September for logistical reasons, but it was intended to cover hydrological conditions from before the onset of melt through the ablation season.

Measurement Records

Electrical conductivity was recorded continuously at Peyto Creek gauging station from 19 May – 2 September 1979, and discharge from 10 June – 29 July, 5-11 August, 20-25 August and 27 August – 3 September. At the Amiskwi River gauge, conductivity was recorded from 26 May – 27 July, 29 July – 14 August and 17-28 August, and discharge from 31 May – 5 August. Techniques for measuring conductivity have been described elsewhere (Collins 1979a). No compensation was introduced to standardise observed electrical conductivity to a reference temperature.

Results

Discharge

Peyto Creek. Daily maximum and minimum instantaneous discharges of meltwaters in Peyto Creek during the observation period are given in Fig. 3. Upper and lower limits of the daily ranges of flow are plotted. From late winter conditions of minimal flow (<0.1 m^3s^{-1}), beneath the operational level of the gauge, increasing temperatures from 1 June slowly increased snowmelt, introducing limited amplitude diurnal rhythm in the hydrograph by 10 June. Snowmelt on the ice-free area proceeded in repeating sequences consiting of fine warm days increasing discharge followed by fresh snowfall and low temperatures suppressing flow. Dur-

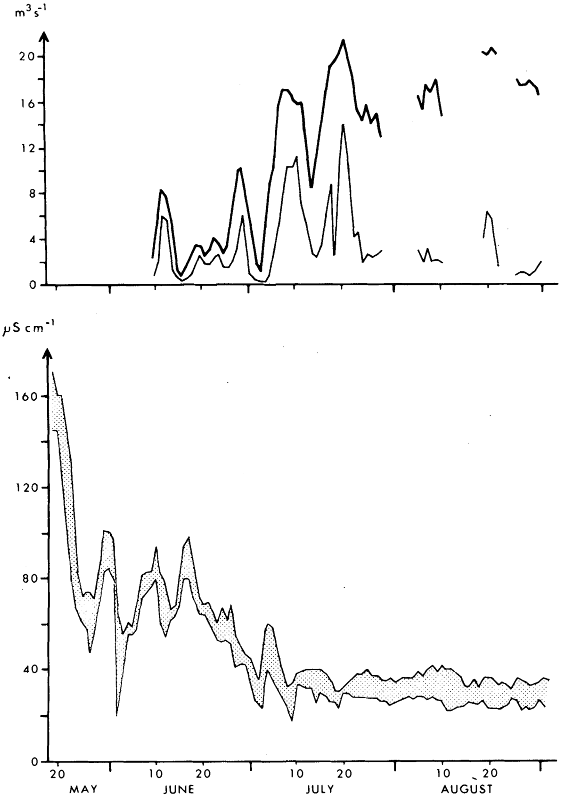


Fig. 3.

Seasonal variations of discharge and electrical conductivity of meltwater in Peyto Creek from 19 May – 2 September 1979. Maximum and minimum daily discharges, and maximum and minimum daily values of electrical conductivity for the upper and lower limits of the respective distributions.

ing the fourth cycle, discharge was reduced from 10.5 m^3s^{-1} to 0.9m^3s^{-1}. From 5 July, glacier ice became exposed in the lower part of the ablation area, and the usual marked diurnal large-amplitude rhythm of icemelt discharge commenced, reflecting diurnal variations in the energy supplied for melting ice. Maximum recorded discharge of 21.6 m^3s^{-1} was reached on 21 July. From 29 July, discharge measurement was interrupted by mechanical failure of the limnigraph, but ice ablation continued to produce large amplitude diurnal oscillations with maxima in excess of 12 m^3s^{-1}.

Amiskwi River. Daily maximum and minimum discharges of Amiskwi River are presented in Fig. 4. Unfortunately, snowmelt was well initiated by the beginning of the measurement programme, and low amplitude diurnal variations of discharge (1-2 m^3s^{-1}) were already superimposed on high daily flows. Snowmelt was characterised by repeating sequences of short periods of hydrometeorological conditions favouring melting, interspersed with fresh falls of snow at high altitude, rain, and cooler cloudy conditions retarding melt for several days. These sequences led to the pattern of discharge from 30 May – 24 July. Each individual episode in the repeating sequences consisted of several days of rising mean flows, terminated by a steep fall in discharge until favourable melt conditions returned,

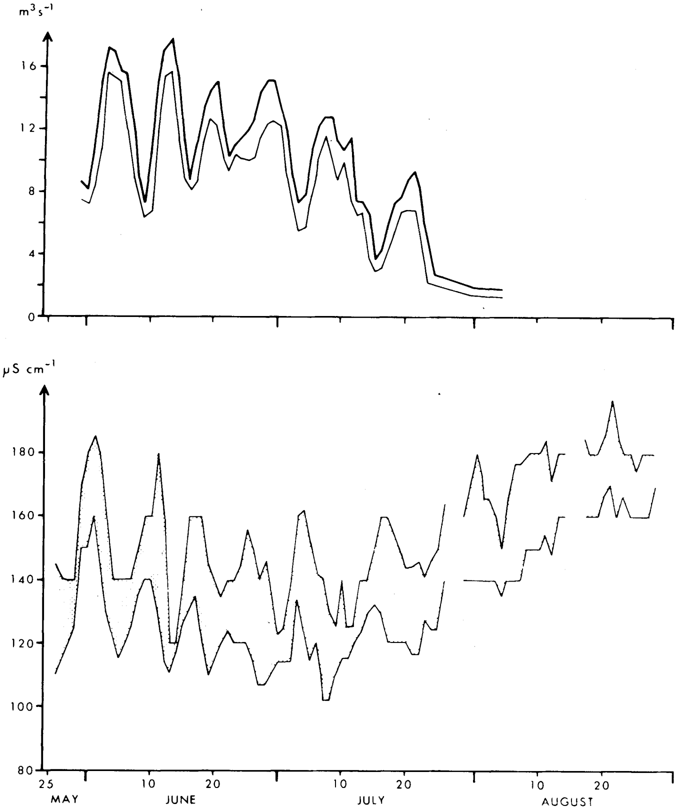


Fig. 4. Seasonal variations of discharge and electrical conductivity of meltwaters in Amiskwi River, from 26 May – 28 August 1979.

all superimposed on a general background flow of between 5-10 m^3s^{-1}. Diurnal range of discharge was widened on days with higher flows. Maximum instantaneous discharge was achieved on 13 June (17.8 m^3s^{-1}), and from mid-June, the snow reserve declined, with the ascent of the transient snowline. Subsequent melt sequences were superimposed on a downward trend, daily maximum at the height of rising flow periods declining from 15.1 – 9.4 m^3s^{-1}. Daily minimum flows during recessions were reduced from 9.9 – *c* 3.0 m^3s^{-1}. By early August, most of the catchment area was free of snowcover, and discharge fell beneath the operational range of the gauge.

Comparison of the hydrographs of Peyto Creek and Amiskwi River (Figs. 3 and 4) reveals qualitatively simultaneous responses during the period 10 June – 25 July to successive sequences of hydrometeorological events experienced in the area. Differing scales of response relate to altitude, especially the areal extent of cover by fresh snow and temperature, basin aspect, the nature of the substrate for melt, snow or ice, and the area of substrate exposed for melting.

Electrical Conductivity

Peyto Creek. Results of continuous monitoring of electrical conductivity of meltwaters in Peyto Creek are also given in Fig. 3. Summary daily data are shown to describe the pattern of seasonal variation of solute concentration in meltwaters. Daily maximum and minimum values of electrical conductivity form the upper and lower limits of the distribution and daily ranges are represented by the vertical width of the shaded block. The highest conductivity (170μS cm^{-1}) was recorded on 19 May, when the entire catchment remained covered with snow and little, if any, melt appeared to have occurred. It is suggested that discharge at this time resulted from groundwater flow (Q_g), the conductivity of Peyto Creek meltwaters being higher than that of waters emerging from a bedrock spring *c* 1 km downstream of the gauging station. Limited snowmelt, which failed to increase discharge above 0.1 m^{3}s^{-1}, reduced conductivity to the range 47-72 μS cm^{-1} by 28 May, as snowmelt runoff reached the gauge with little chemical enrichment. During cooler conditions, melt was restricted, resulting in conductivity rising to 101 μS cm^{-1} on 1 June. A rainstorm on 2 June melted much snow, and dilute rain and snow-meltwater reached the stream with little chemical enrichment lowering conductivity to 20.5 μS cm^{-1}. Snowfall on 4-5 June raised the albedo and decreased snowmelt, conductivity subsequently increasing. The earliest high flows of the snowmelt period, from 10-14 June, reduced conductivity, but meltwater appears to have contributed ionic material, since minimum conductivity remained high at 54 μS cm^{-1}. From 15 June to 2 July, two successive sequences of melt produced little runoff, meltwater presumably remaining held in the snowpack, and a third producing the highest flow to date. Persistent falling solute concentration in meltwaters through this period suggests an exhaustion of available ionic matter in snowmelt pathways in lithospheric material, or the contribution of snowmelt runoff routed over the glacier surface. From 2-5 July a marked recession reduced the dilute component of runoff, and conductivity was restored to the range 40-59 μS cm^{-1}. From the resumption of ablation, ice had become exposed, and from 10 July to the end of the observation period, conductivity remained in the range 22-42 μS cm^{-1}, daily ranges reflecting the usual out-of-phase diurnal periodic variations of conductivity and discharge (e.g. Collins 1979b). Icemelt (Q_i) contribution dominates runoff and solute concentration throughout late July and August, and although runoff portions from other sources occasionally contribute, conductivity remains in narrow bounds.

Groundwater spring. Electrical conductivity of groundwaters emerging from the spring, 1 km downstream of the Peyto gauging station, was measured on several occasions for periods of 48-72h between May and August 1979. In mid-May, conductivity of springwater was in the range 130-162 μS cm^{-1}. During June, values were lower, in the range 110-130 μS cm^{-1}, gradually declining to about 100 μS cm^{-1} by late August, suggesting that dilute meltwater has progressively entered the groundwater system.

Amiskwi River. Summary data in the form of daily maximum and minimum values of electrical conductivity recorded for meltwaters of Amiskwi River are presented in Fig. 4. Each sequence of hydro-meteorological events producing and terminating periods of enhanced snowmelt influence on the hydrograph during June and July was reflected by a period of decreased electrical conductivity with a lag of 1-2d between the peak discharge and the minimum conductivity. Each successive snowmelt sequence in spring, until mid-July, cumulatively reduced conductivity, minimum determined conductivities during increased snowmelt periods declining from 114-102 μS cm^{-1}, and maxima from 186-156 μS cm^{-1}. However, the final snowmelt sequence (15-21 July), while reducing daily maxima of conductivity from 160-141 μS cm^{-1}, failed to reduce the lowest minimum daily conductivity (117 μS cm^{-1}) to the level of the previous sequence (102 μS cm^{-1}), and marked the end of the general trend of decreasing solute content. Considerable diurnal variation in conductivity during May, June and July reflects the diurnal cycle of snowmelt. The downward trend of conductivity accompanying decreasing snowmelt input is suggestive of exhaustion of solute supply in the snowmelt runoff pathways. From 23 July, the level of conductivity increased slowly, to a maximum in late August of 197 μS cm^{-1}, probably as a result of the increased importance of groundwater flow (Q_g). Storms on 2-3 August reduced conductivity markedly for 2-3d. Continued diurnal variation in solute content during August probably related to melt from high altitude snowpatches and the small glacierised area.

Solute-Discharge Relationships

Diurnal Variations

Peyto Creek. Examples of the diurnal rhythm of discharge and electrical conductivity of meltwaters in Peyto Creek from 6-10 August 1979 during a period of sustained ablation are presented in Fig. 5. The turning points of the curves for each 24h period form the limits of the respective distributions shown in Fig. 3. With the onset of ablation in the morning, discharge increases rapidly from *c* 08.00h, to reach a peak between 15.00-19.00h. Decreasing ablation from late afternoon yields a slightly asymmetrical diurnal hydrograph with a minimum flow between 06.00 and 10.00h. Conductivity falls rapidly as dilute ice-melt water arrives at the gauge, via moulins and major conduits, and rises steadily as chemically-enriched meltwater routed more slowly through basal tunnels, cavities and subglacial moraine reaches the portal. This inverse diurnal solute-discharge relationship has been reported for other glacial meltstreams (e.g. Rainwater and Guy 1961; Behrens and others 1971; Collins 1979a). During the icemelt-dominated summer ablation season, the range of variation of conductivity of Peyto Creek meltwaters was lower than those of larger glaciers located on igneous and

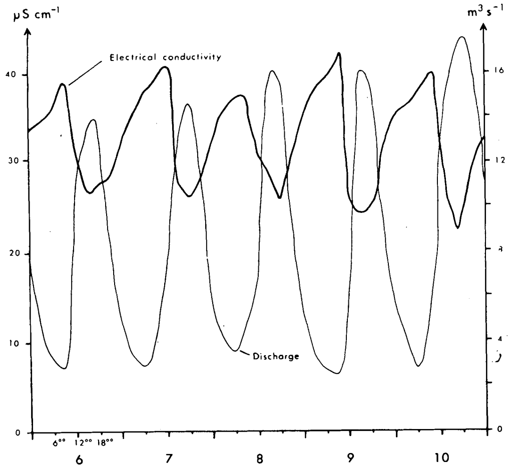


Fig. 5.
Diurnal variations of discharge and electrical conductivity of meltwaters in Peyto Creek during a period of icemelt-dominated runoff, resulting from sustained ablation, 6-10 August 1979.

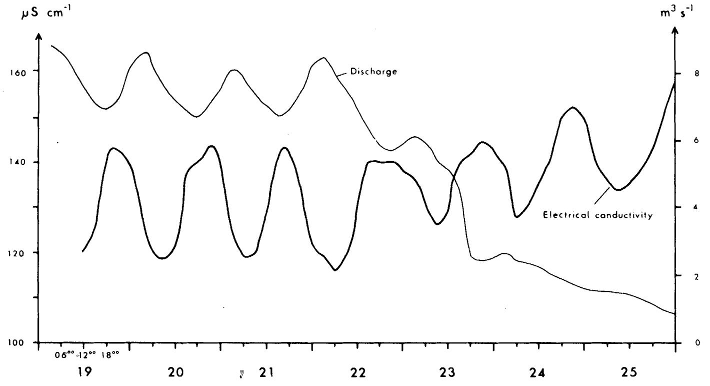


Fig. 6. Diurnal variations of discharge and electrical conductivity of meltwaters in Amiskwi River from 19-25 July 1979. After sustained melting from 19-21 July, heavy rain and overcast conditions reduced flow from 22 July.

metamorphic substrates (Collins 1979b, Table 4), and this may have resulted from a chemically-concentrated groundwater component of discharge beneath Peyto Glacier.

Amiskwi River. In contrast, diurnal variation of flow of Amiskwi River during sustained melting consists of a small daily peak superimposed on a steady background flow, the latter accounting for about 80 per cent of the total daily discharge (Fig. 6). Daily peaks were asymmetrical, in the period 19-22 July, with steeper rising than falling limbs to the hydrographs. Maximum daily flow appears in the early hours of the morning (03.00-06.00h), and the minimum between 18.00-22.00h, out of phase with variations in meteorological conditions, and lagged by 12h in comparison with the Peyto Creek hydrograph. Slow percolation of meltwater through snowpack, soil and regolith, and distance from sites of melt to the stream gauge in this large catchment probably account for the delay in runoff. Each daily peak flow was associated with a limited decrease in conductivity. Although runoff from snowmelt decreases solute concentration, Q_s is a chemically-enriched component in the Amiskwi River basin, in contrast to Q_s around Peyto Glacier, and diffuse snow-meltwater follows solute-enriching pathways across the basin. In terms of solute load, increasing discharge of Amiskwi River compensates for decreased solute concentration. Cooler meteorological conditions, with heavy rainfall on 22-23 July, reduced snowmelt, and gave vestigial daily peaks to the recession from 23-25 July (Fig. 6). Rising electrical conductivity during the afternoon on 22 July was truncated by a rainfall-produced component of runoff, but the diurnal rhythm of variation of conductivity was subsequently restored, with a rising trend.

Seasonal Variations

Peyto Creek. Temporal variations of hydrochemistry and discharge distinguish three main periods of runoff, characterised by principal discharge components (Table 2). Winter conditions remained until 20 May, with a spring snow-melt dominated transition period from 21 May – 10 July. After 11 July, summer is characterised by rhythmic diurnal variations of discharge and electrical conductivity. The seasonal runoff pattern of Peyto Creek supports the schematic glacial basin hydrograph shown in Fig. 1(b). The three main distinctive periods of runoff are similar in character to those described by Collins (1981) for Gornergletscher, Pennine Alps, Switzerland.

Amiskwi River. Two periods of contrasting hydrological and hydrochemical behaviour are discriminated (Table 2). A snowmelt-dominated period, which had commenced before the start of the measurements described here, was characterised by disjointed incremental stages of melt. From 21 July, a phase of runoff conditions with rising solute concentrations related to rain and groundwater domination. Amiskwi River has the seasonal runoff pattern of a nival basin (Fig. 1(a)).

Table 2 – Seasonal variations of electrical conductivity and components of discharge for Peyto Creek and Amiskwi River.

Basin	Period 1979	Discharge m^3s^{-1}	Principal components of discharge	Electrical conductivity $\mu S\ cm^{-1}$	Water temperatur range °C
Peyto Creek	19-20 May	< 0.1	Q_g	145 – 170	1.0 – 1.2
	21 May – 10 July	≤15.8	Q_s	18 – 100	0.9 – 1.7
	11 July – 2 September	–	Q_i	22 – 42	0.7 – 1.5
Amiskwi River	26 May – 20 July	7.2 – 17.8	Q_s	102 – 185	3.2 – 11.1
	21 July – 28 August	1.7 – 9.2	Q_p, Q_g	116 – 197	–

Discussion

Snow- and Ice-Melt Runoff and Alpine Hydrochemistry

The data presented in this paper are of intrinsic value in adding a temporal framework for sampling and interpretation of alpine hydrochemistry in the Rocky Mountains. Previous data for this area, (e.g. Ford 1971; Environment Canada 1980) consist only of spot samples or repeated samples during short summer periods. The electrical conductivity variations presented here while providing no information about the behaviour of individual anions and cations, show the importance of diurnal and seasonal changes in runoff components contributing to discharge, which should be considered in the formulation of sampling designs for water quality experiments. Ford (1971) noted that annual and seasonal variations in hydrochemistry would result from temporal fluctuations of discharge, but ignored the role of daily variations in water quality, and variations resulting from sequences of several days experiencing similar hydrometeorological conditions, in a study of karst waters in the southern Rocky Mountains. Continuous recording of chemographs alongside hydrographs is essential if waters are to be accurately characterised and distinguished, and their hydrological responses explained, in *any* alpine mountain environment.

The data of the present study show how seasonal and diurnal variations of the discharge hydrographs of both Peyto Creek and Amiskwi River result from distinctive temporal fluctuations of the contributions of snow- and ice-melt portions of total runoff. Further, the distinctive temporal patterns of electrical conductivity of nival and glacial basin meltwater streams have been qualitatively shown to be determined by changing quantities of meltwater arising from different sources, and source-areas within the basins, through time. It is apparent that many glacial basins exhibit similar seasonal and diurnal hydrochemical variations to those described for Peyto Creek, and comparative studies of different basins, each with long-period investigations of discharge and water quality, may allow a better understanding of hydrological, glaciological and lithospheric controls on solute yield from alpine glacierised basins. The pattern of hydrochemical variation for the Amiskwi River, although relating to a specific catchment area, may be of more general occurrence and suggests an alpine nival hydrochemical model, dependent on temporal patterns of runoff formation from the melting of snow.

The data presented in this paper are at the aggregate drainage basin level, and it is clear that more detailed investigations of the dynamics of solute-discharge relationships for the individual components of runoff are necessary before explanatory and predictive models of alpine hydrochemistry can be formulated. Variations of C_s with Q_s in tributary streams of the Amiskwi River and in small ephemeral streams in the non-glacierised area of Peyto Creek basin flowing only during spring snow-melt require investigation in order to understand the interaction of runoff pathways with solute supply. Further, C_g showed seasonal variation and although dilution of springwaters with increasing flow is well-known (e.g.

Ford 1971), the role of snow- and ice-melt waters entering groundwater is of increasing importance because of possible return of solute-rich ground-waters to the beds of alpine glaciers (Stenborg 1965; Oerter and others 1980). The relative contributions of the non-glacierised areas and the glacier bed to solute yield has not been assessed in this study because of the limited availability of discharge data necessary for the calculation of load. Simple dissolved solids-discharge relationships of the form $c = a\ Q^{-b}$ (where c is dissolved solids concentration, and a and b empirically-determined parameters) (Church 1974) are inappropriate for nival and glacial meltwaters because of the non-stationary relationships between discharge and concentration of each individual runoff component, and the time-variant contributions to total discharge of runoff components. However, distinctive temporal patterns of hydrochemistry of meltwaters and diagnostic solute concentrations relating to each runoff component suggest the potential of water quality for quantitative separation of alpine runoff components.

Runoff Contribution Separation

Quantitative separation of runoff components based on their hydrochemical characteristics is not attempted here since winter hydrochemical and summer discharge data are inadequate. Also, the two basins investigated are insufficiently comparable for the transfer of Amiskwi River basin separations to the non-glacierised areas draining to Peyto Creek. The use of paired basins would be a useful advance if the effects of aggregation of upstream variations in hydrological and hydrochemical responses (Walling and Webb 1980), resulting from varied hydrological behaviour of forested, subalpine and bare-rock subcatchments, were not present in the Amiskwi River basin. Ideally, a small bare-rock non-glacierised catchment should be used for comparative purposes with a partially-glacierised basin, to separate the effects of seasonal snowcover from glacial runoff behaviour.

Conclusion

Seasonal variations of electrical conductivity in meltwaters result from distinctive temporal variations of snow- and ice-meltwater supply to runoff in nival and glacial catchments. During snowmelt, nival and glacial basins in the same area show qualitatively similar responses to hydrometeorological events, though hydrochemical behaviour of snowmelt is modified by the presence of glacier ice. In summer, differing hydrological and hydrochemical characteristics result from the exhaustion of snowcover for runoff generation in nival basins, and the release of the enormous ice reservoir to runoff by melting in partially-glacierised catchments. It is suggested that measurements of discharge and ionic variations in suitable paired nival and glacial basins will allow the quantitative separation of the contributions to solute yield and runoff arising from non-glacierised areas and icecovered parts of alpine basins.

Continuous records of solute concentration in meltwaters over annual cycles provide a temporal framework for the understanding of discharge-related aspects of alpine water quality. This framework permits the establishment of spot sampling strategies to accurately characterise the overall variations of alpine hydrochemistry, for both chemical (individual ion) and isotopic parameters, in surface water quality surveys, and provides for the contextual setting of short-term investigations of particular aspects of the hydrological cycle. Because of the role of snow and ice storage regulating the release of meltwater in alpine basins, the hydrology of glaciers should be investigated in a drainage basin framework, if spatial and temporal variations of runoff sources and source-areas are to be included in distributed, physical systems, models of mountain runoff formation.

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Address: David N. Collins,
Department of Geography,
University of Manchester,
Manchester, M13 9PL,
England.

Gordon J. Young,
National Hydrology Research Inst.,
Environment Canada,
Ottawa,
Ontario, K1A OE7,
Canada