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Year-to-year variability of solute flux in meltwaters draining from a highly-glacierised basin*

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Abstract Electrical conductivity was monitored continuously in the Gornera, which drains the 83% glacierised basin of area 82 km^2 containing Gornergletscher, Pennine Alps, Switzerland, during the summer months, in order to provide an indication of meltwater solute content during each of the four years 1979, 1983, 1987 and 1998. Discharge was also recorded between 1970 and 1999. Solute flux, calculated as the product of electrical conductivity and discharge, was used to assess how the year-to-year variability of discharge influences solute transport. Total May through September discharge of the Gornera was in the range -39.1% (1978) to +38.9% (1994) of the 1970–1999 period mean of 118.75×10^6 m^3. The range of variability of July through September electrical conductivity was between -25.0% and +29.1% of the mean of 19.6 μS cm^{-1} for the four study years. The intra-annual range of total July through September solute flux in the Gornera extended from -22.4% (in 1987, during which, of the four years, discharge for the three months was greatest) to +12.4% (in 1979, when discharge was the lowest) of the four study year means, which represents an average cationic load of $\sim 25 \times 10^6$ eq. Variability of total solute flux (c_v=0.142) was greater than that of total discharge (c_v=0.127) in the three month period over the four years. Considerable intra-annual variability of total discharge over the three decades suggests that the total annual solute flux also fluctuated significantly from year to year.

Keywords Glacierised basin; intra-annual variability; meltwater; solute content; solute flux

Introduction

Substantial quantities of dissolved material are transported in the large specific discharges arising from headwater glacierised mountain basins. Both high annual runoff, resulting from orographically enhanced levels of precipitation, and rapid dissolution of finely divided suspended sediment derived from glacial erosion and entrained in flowing meltwaters lead to solute fluxes in rivers draining from mountain glaciers being greater than the global average for the continents (e.g. Anderson *et al.* 1997; Collins 1983, 1999). Estimates of such large fluxes of water and dissolved material in rivers draining from glacierised basins are of interest from a range of viewpoints. Glacierised headwater basins influence both flow and hydrochemistry of the great continental rivers and contribute nutrients to alpine lakes (Psenner and Schmidt 1992) and fjords (Lewis 2000). Large solute fluxes suggest that chemical weathering in glacierised basins may have a strong influence on global carbon cycling at present. During glacial and/or tectonic periods in the past, when the extent of glaciation was increased, the CO$_2$ content of the atmosphere may have been reduced (e.g. Gibbs and Kump 1994; Lyons *et al.* 2002; Raymo *et al.* 1988).

More than 95% of the annual total solute flux is evacuated from highly glacierised basins in the five warm summer months of May through September, during which period more than 90% of the annual total runoff is discharged as the available heat energy releases meltwater from long-term storage as glacier ice and from seasonal storage as accumulated winter

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snowpack (Collins 1983). Estimates of solute fluxes from glacierised basins tend to be based on samples collected and discharge measured during one ablation season only (Anderson *et al.* 1997). However, annual solute flux, the product of solute concentration and discharge, is likely to be influenced by the overall level of discharge during an ablation season. Hence, year-to-year fluctuations in runoff resulting from climatic variability might be expected to translate into intra-annual fluctuations of solute flux. Although year-to-year variability of runoff reduces with increasing glacierisation of basins (Krimmel and Tangborn 1974), annual total water yields from highly glacierised basins nonetheless lie in a fairly wide range. For example, in the European Alps, total discharge between June and September from the basin containing Gornergletscher (Pennine Alps, Switzerland), in the period 1970–1979, varied between −25% and +29% of the decadal mean (Collins 1982). For the basin of Vernagtferner (Ötztaler Alps, Austria) between 1974 and 1993, the total summer discharge varied between −40% and +47% of that 20-year mean (Escher-Vetter and Reinwarth 1994). The aim of this paper is to provide estimates of solute fluxes from a glacierised Alpine basin in summer in each of four years, with a view to assessing both the extent to which the flux varies from year to year and how discharge might influence intra-annual variability.

Study area

Measurements of discharge and solute content of meltwaters were recorded at the gauge at the outlet of the basin of the Gornera, which is located in the Pennine Alps, Switzerland (Figure 1). The Gornera basin area of 82 km^2 contains Gornergletscher, perennial ice and snow occupying 83% of the catchment. The gauge is ~750 m from the glacier terminus. The larger part of the basin, which extends from 2005 to 4634 m a.s.l., is underlain by granite, gneiss and other metamorphic rocks of the Monte Rosa group, the remainder being based on metamorphosed Mesozoic sediments.

Measurements

Discharge (Q) of the Gornera was recorded between May and September from 1970 through 1999. Electrical conductivity (EC) of meltwater in the Gornera was monitored as near continuously and for as much of the ablation season as possible in each of the four years 1979, 1983, 1987 and 1998. EC was taken as a measure of overall solute concentration. An index of solute flux (S), in arbitrary units analogous to kg s^{-1}, was calculated as the product of paired values of Q and EC ($S = Q \times EC$), all three variables being resolved as hourly averages. EC was successfully monitored for 77% of the period between 25 June and 21 September in

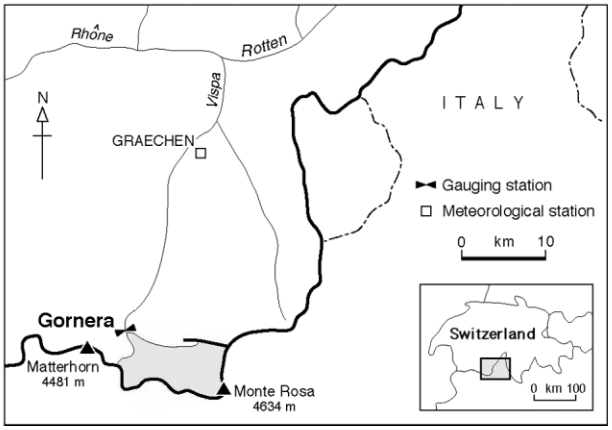

Figure 1 Location of the Gornera basin, which contains Gornergletscher, in the Pennine Alps, Switzerland

1979, 75% of that between 5 June and 30 September in 1983 and 93% between 24 May and 30 September in 1987, but for only 63% of the short period 8 July through 14 September in 1998. Monthly and overall ablation season means of both electrical conductivity and solute flux were estimated in order to provide intra-year comparison of variability in meltwater solute content and dissolved load transport. Monthly values were estimated only where reasonable runs of near-continuous *EC* permitted, all the available hourly values of *EC* in a given month being utilised in the calculations. An ablation season mean *EC* was then estimated from the data used in derivation of the monthly values. Monthly and annual totals of solute flux were calculated similarly from available hourly *EC* and *Q* values. The sum of cationic equivalents was estimated from *EC*, through regression with sums of individual determinations of principal cations in samples of meltwater (as described by Collins 1983). Air temperature and precipitation have been monitored routinely since 1967 by the Schweizerische Meteorologische Anstalt (MeteoSchweiz) at a meteorological station at Grächen (1617 m a.s.l.), located on the east side of Mattertal, about 25 km north of the Gornera basin (Figure 1).

Results

Range of variation of discharge in the Gornera

The overall range of annual discharges in the Gornera for the period 1970–1999 provides the context for the four years during which solute flux was monitored. Total discharge between May and September ($Q_{5\text{-}9}$) in an individual year was in the range − 39.1% (in 1978) through +38.7% (1994) of the three-decadal mean of $118.75 \times 10^6\,\mathrm{m}^3$, with a coefficient of variation (c_v, standard deviation/mean) of 0.191. The highest total ablation season discharge in 1994 was 2.3 times greater than the lowest. The May through September mean air temperature ($T_{5\text{-}9}$) at Grächen generally increased from the 1970s to the 1990 s. The minimum $T_{5\text{-}9}$ of 9.6°C occurred in 1972 and the maximum, 12.9°C, in 1999, with a 30-year mean of 11.4°C. Precipitation in both winter and summer interacts with summer energy input to determine total annual discharge from a glacierised basin, so that, although year-to-year variation of $Q_{5\text{-}9}$ in the Gornera broadly followed that of $T_{5\text{-}9}$ at Grächen, the rank orders of the years for each of the two variables, arranged from highest to lowest, differ considerably. Total summer discharge, mean summer air temperature and rank orders of the four years for which water quality data are presented are given in Table 1. Discharge was above the 1970–1999 period mean of $Q_{5\text{-}9}$ in three of the years and the range of flow in the four years was between − 8.4% and +31.4% of that average.

Seasonal and annual variations of discharge, electrical conductivity and solute flux in the Gornera

Seasonal patterns of variation of discharge, solute content as indicated by *EC* and solute flux in the Gornera are shown for the four study years in Figure 2. May through October monthly means of *EC* for each of the four years are given in Table 2, together with the average of the monthly means for the four years. The latter values, together with the temporal patterns of

Table 1 Characteristics of total discharge of the Gornera and summer air temperature at Grächen in the four study years 1979, 1983, 1987 and 1998, with rank orders within the period 1970–1999

	$Q_{5\text{-}9}$		$T_{5\text{-}9}$	
Year	$\times 10^6\,\mathrm{m}^3$	Rank	°C	Rank
1979	109.342	20	10.78	23
1983	127.442	14	12.03	7
1987	131.600	11	11.26	17
1998	156.185	2	12.85	2

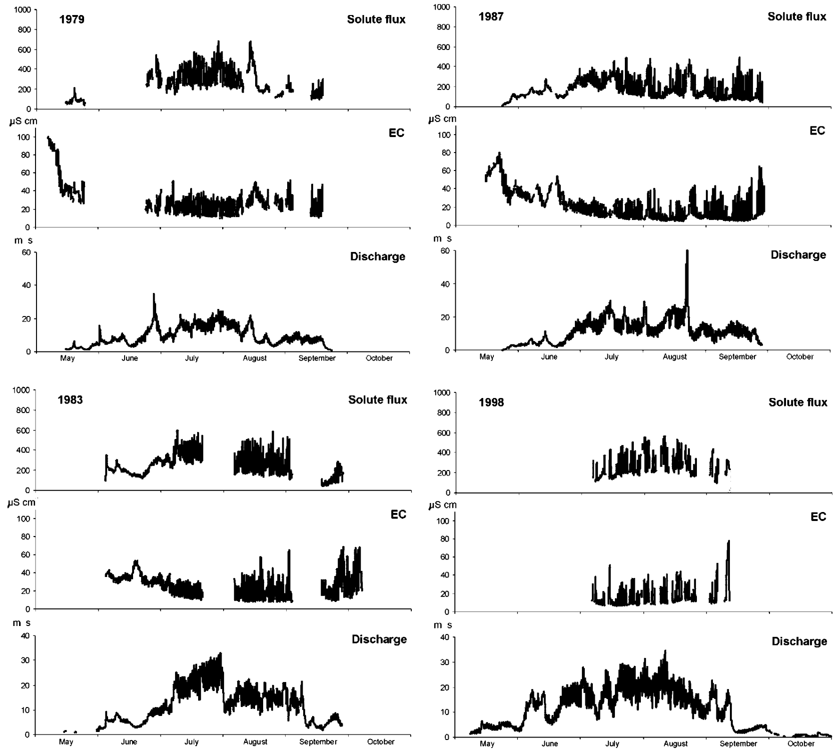

Figure 2 Hourly average variations of instantaneous solute flux represented by index *S* (electrical conductivity × discharge in arbitrary units) (upper), electrical conductivity (*EC*) (centre) and discharge (lower) of the Gornera during the months May through October, in the years 1979 (top left block), 1983 (lower left block), 1987 (upper right block) and 1998 (lower right block)

Table 2 Mean electrical conductivity ($\mu S\,cm^{-1}$) of meltwater in the Gornera for individual months and for the period July–September ($EC_{7\text{-}9}$) in the four study years 1979, 1983, 1987 and 1998

Year	May	June	July	August	September	October	$EC_{7\text{-}9}$
1979	55.5		23.5	26.9	25.5		25.3
1983		35.9	23.1	19.5	23.2	34.9	21.9
1987	51.8	31.0	15.9	13.0	15.1		14.7
1998			13.5	18.1	17.9		16.5
Mean	53.7	33.5	19.0	19.4	20.4	34.9	19.6

diurnal minimum values of *EC* for the four years (which can be discerned from the *EC* plots in Figure 2), indicate the general seasonal variation of solute content of meltwater draining from Gornergletscher. Diurnal minimum and mean *EC* decrease sharply with the onset of snow melt, continuing generally to decline gradually through May to late July in response to ice melt raising discharge. Diurnal minimum *EC* may remain at relatively low levels through August and much of September. When flow starts to recede, *EC* tends to rise fairly rapidly, commencing between late August and early October. This asymmetrical seasonal "sag" in the pattern of variation in diurnal minimum *EC* occurred in all four years (Figure 2). The sag in solute content is the inverse of the seasonal pattern of discharge, with flow increasing slowly in May, rising rapidly in June and then on an upward trend to peak in early August, before falling at a more rapid rate during late August and September, a behaviour broadly exhibited in all four years (Figure 2). Whilst the seasonal pattern of solute flux variation is indicated in Figure 2, monthly total solute flux values are presented in Table 3. Both show solute transport rising steeply with increasing discharge as ice melt increases, to a maximum generally in July, before falling gently through August and September.

Several anomalies punctuate the annual water quality and discharge records. In 1979, the highest instantaneous discharges of the season, at the end of June, were associated with the annual drainage of an ice-dammed lake, the Gornersee, which builds up in the apex of the junction between the tributary Grenzgletscher and the trunk Gornergletscher. Solute flux was raised above levels usual in June during this event, which lasted for several days, but missing data in that month make it difficult to assess the contribution to total solute flux. Two snowfall events, on 18 and 25 August, raised the albedo so reducing discharge and increasing *EC*. During the first recession in flow, *EC* rose above 50 μS cm^{-1} on 19 August but solute flux was reduced with declining discharge. High discharge, sustained during what otherwise would have been low flow periods at night, had unusually been maintained between 16 and 18 August. Coupled with high *EC*, the maximum instantaneous solute flux of the year was delivered overnight on 16–17 August by a probable outburst of chemically enriched water, which had been stored in contact with reactive lithospheric material. During the two days, 11.8% of the total solute flux for the month of August was transported from Gornergletscher.

Sustained elevated solute fluxes occurred throughout July 1983, after which a sudden end to extremely warm conditions reduced the discharge markedly. Solute flux remained in a range lower than that achieved in July before snowfall greatly reduced discharge in September, further suppressing solute flux.

Snowfall events in June, July and early August 1987 interrupted flow. Then, superimposed on the rising discharge, sustained heavy precipitation, which fell as rain at high elevation over bare rock and ice with the transient snow line standing high in the basin, produced the season discharge maximum of 60 m^3 s^{-1} on 25 August (Collins 1998). *EC* was reduced during the storm, but daily solute flux was enhanced substantially by comparison with the days before and after. Whilst an unusually warm September maintained flow late in the season, solute flux remained low (Table 3).

In 1998, an exceptionally dry winter was followed by a warm spring and discharge had increased rapidly in early June. The overall level of discharge continued to increase in the generally warm conditions to the season maximum on 11 August, whose thermally induced peak exceeded that of the Gornersee outburst in early July. Solute flux also increased to an early August maximum.

Range of variability of annual solute flux in the Gornera

Adequate data for intra-annual comparison of total solute flux in the Gornera are available only for the months July through September ($S_{(7\text{-}9)}$ in Table 3) and those for just four years.

Table 3 Individual monthly and July through September ($S_{(7\text{-}9)}$) totals of solute flux (as index $S \times 10^6$) in meltwater in the Gornera for the four years 1979, 1983, 1987 and 1998

Year	May	June	July	August	September	$S_{(7\text{-}9)}$
1979	61.238		245.227	220.953	126.879	593.059
1983		142.711	266.203	206.683	118.418	591.304
1987	44.590	105.400	180.092	133.345	96.081	409.518
1998			172.654	232.107	111.286	516.047
mean	52.914	124.056	218.044	198.272	113.166	527.482

$S_{(7\text{-}9)}$ accounts for about 75% of the total annual solute flux in a year (Collins 1983). The range of variability of $S_{(7\text{-}9)}$ extended from -22.4% (1987) to +12.4% (1979) of the mean for the four years of 527.482×10^6 arbitrary units, which represents transport of an average cationic load of $\sim 25 \times 10^6$ eq. in the three-month period. For the months July through September, variability of total solute flux for the four years (c_v=0.142) was greater than that of the corresponding discharge $Q_{(7\text{-}9)}$ (c_v=0.127). The latter was, however, somewhat reduced by comparison with the coefficient of variation of 0.180 for $Q_{(7\text{-}9)}$ and 0.191 for $Q_{(5\text{-}9)}$ for the entire 30 year discharge record. The range of variability of $Q_{(7\text{-}9)}$ in the four years was between -21.9% (1979) and +8.7% (1987). For *EC*, or solute concentration, in the months July through September, the range of variability was between -25.0% (1987) and +29.1% (1979) of the mean of 19.6 μS cm^{-1} (c_v=0.216) for the four study years (Table 2). With respect to intra-annual variability in the Gornera, wide-ranging *EC* appears to be moderated by discharge such that the solute flux is less variable than *EC* but still shows considerable year-to-year fluctuations.

June–September solute flux, $S_{(6\text{-}9)}$, which, according to Collins (1983), accounts for 93% of the total solute flux in a year, can be obtained for two of the study years (Table 3). The range of variability of $S_{(6\text{-}9)}$ extends from $-$ 26.9% (in 1987) to +4.2% (1983) of the mean of 704.452×10^6 for the two years. The proportion of the total June–September solute flux in the Gornera transported during the months July through September varied little, however, being 80.6% in 1983 and 79.5% in 1987. These percentages suggest that year-to-year variation in that proportion may not be great. In 1987, the year in which the *EC* record was least perturbed, $S_{(7\text{-}9)}$ accounted for 73.2% of the May through September solute flux. Taking the May–September flux as a minimum 95% of the total annual solute flux in the Gornera following Collins (1983), then *pro rata* $S_{(7\text{-}9)}$ would have accounted for at least 70% of the annual solute load in 1987.

Discussion

Relationships between water quality variables and discharge during an ablation season

As indicated in Figure 2, solute concentration always declines as discharge increases. Nonetheless, a wide range of solute concentration (*EC*) values is associated with a given discharge. For example, Figure 3 shows the typical relationship between *EC* and discharge at the hourly level, for 1987. There is a base level of about 10 μS cm^{-1} below which *EC* is not reduced, even at higher levels of discharge. The range of *EC* values associated with a given level of flow is also inversely related to discharge.

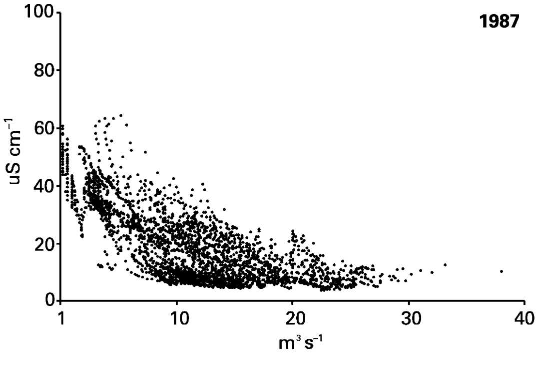

Figure 3 Plot of hourly average values of *EC* of meltwater between May and September 1987 against those of discharge of the Gornera

A wide range of solute flux values is also associated with a given discharge, but solute flux tends to increase with discharge, at least at lower levels of flow. At higher flows, the rate of increase of solute flux is reduced. Evidently at higher levels of flow, solute flux may actually decline with further enhancement of discharge (Figure 4).

For a given discharge, solute flux tends to be higher at the start of the season, when solute concentration also tends to be relatively high. Thus, solute fluxes in July are generally higher than those associated with equivalent discharge levels occurring in August, and, at lower absolute levels of flow, solute fluxes in June are similarly higher than those in September. The range of solute flux levels associated with a given discharge is greatest at intermediate flows.

Solute flux is determined by interactions between mineral dissolution kinetics and the average length of time suspended sediment is in contact with meltwater, which influences solute concentration, and discharge (Collins 1995, 1999). Sediment–meltwater contact time depends on meltwater transit time through subglacial hydrological pathways, which in turn is controlled by overall levels of discharge. At high discharge, flow velocity is increased, and hence reduced contact time in transit limits solute concentration. At the onset of melt, solute-rich groundwater may contribute to flow, the proportion declining as snow and ice melt increase. Higher solute content in early summer presumably also results from slower transit times for a given discharge than later, allowing more time for dissolution reactions to produce higher concentrations. Transit times thus probably depend not only on discharge but also on dimensions (or capacity) of the basal drainage system. As the season progresses, pathways widen, allowing meltwater at a given discharge faster passage to the terminus. Falling energy inputs for melt reduce volumetric throughput of water and flow velocity, increasing transit time and hence solute concentration from mid-August through October, depending on climatic conditions. Decline of sediment concentration in the Gornera through a summer (Collins 1989) will lower the rate of dissolution and hence the level of solute concentration reached in a given period of time.

Relationship between annual total fluxes of solute and water in the months July through September

Aggregated as annual totals (i.e. as $S_{(7\text{-}9)}$ and $Q_{(7\text{-}9)}$) solute flux was little changed between 1979 and 1983, in spite of greatly increased discharge. However, solute flux was reduced considerably in 1987 and 1998, years in which discharge was little higher than in 1983. Figure 5 shows the relationship between $S_{(7\text{-}9)}$ and $Q_{(7\text{-}9)}$ for the four years 1979, 1983, 1987 and 1998.

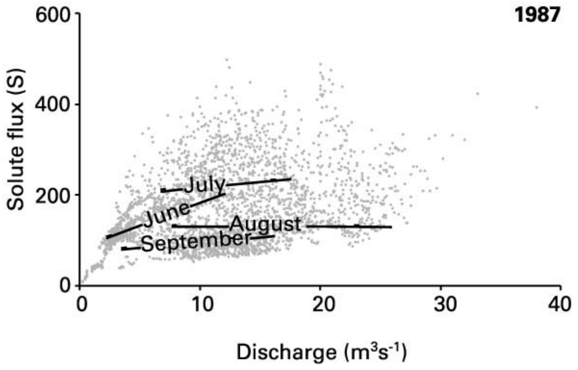

Figure 4 Plot of hourly average values of solute flux between May and September 1987 against those of discharge of the Gornera. The solid lines indicate the approximate centres of gravity of points reflecting values representing the stated months

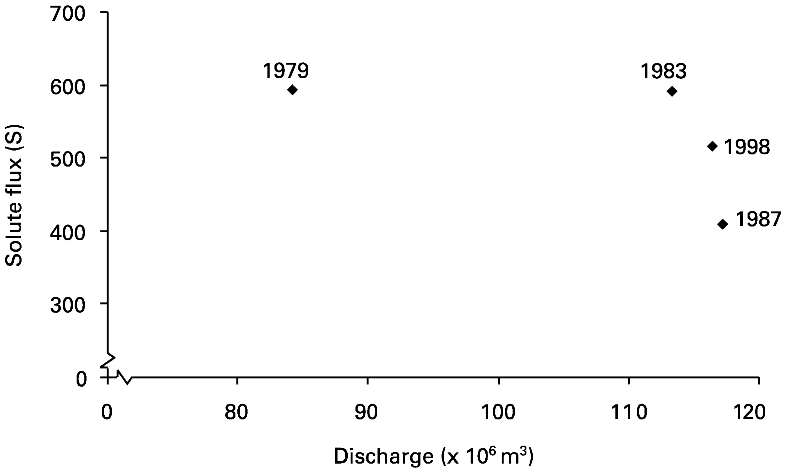

Figure 5 Plot of total solute flux ($S_{(7\text{-}9)}$) against total discharge ($Q_{(7\text{-}9)}$) of the Gornera for the four years 1979, 1983, 1987 and 1998

The cool summer of 1979 limited ice melt. *EC* remained high, particularly in August, and maintained solute flux (Table 4). High discharges in early through mid-July 1983 (the warmest July in the three decades) contributed to a sustained elevated solute flux, which may have been further increased later in the month as flow continued to rise, but data were missed. In 1987, flow remained high later in summer, through August rainfall and the warmest September in the three decades. Thus higher discharges occurred after *EC* was already relatively low, so maintaining relatively limited levels of solute flux. Throughout July and August 1998, solute content stayed low, reduced early in the season by overall high levels of flow brought about by a warm June followed also by a warm July and August. Exceptionally, the month with maximum total solute transport was August, the temporal variation of solute flux mimicking that of discharge.

Conclusions

Whilst missing data have restricted intra-annual comparison to the period July–September, nonetheless the range of estimates of solute flux in the Gornera for those months, from −22.4% to +12.4% of the mean of the four study years, suggests considerable year-to-year variability of dissolved solids transport in rivers draining from glacierised basins. Solute flux in such streams appears to be more variable from year to year than discharge. That the coefficient of variation of 0.180 for $Q_{(7\text{-}9)}$ over the entire 30 year discharge record was substantially greater than that of 0.127 for the four study years suggests that the total solute

Table 4 Characteristics of total discharge and total solute flux in the Gornera, and mean air temperature at Grächen, for the months July through September, in the four years 1979, 1983, 1987 and 1998. Rank orders for discharge and air temperature relate to the period 1970–1999

	$Q_{7\text{-}9}$		$T_{7\text{-}9}$		$S_{7\text{-}9}$	
Year	× $10^6 m^3$	Rank	°C	Rank	× 10^6	Rank
1979	84.196	22	11.55	24	593.059	1
1983	113.392	6	14.27	2	591.304	2
1987	117.177	3	13.67	7	409.518	4
1998	116.490	4	13.70	5	516.047	3

flux will have varied more widely during the three decades than indicated by the range for the four study years. Indeed, the study years relate only to annual water yields ranked in the upper three-quarters of those occurring in the 30 year discharge record. Constrained estimates of solute fluxes from glacierised basins require measurements of solute concentration and discharge during several ablation seasons. Four years are probably not enough to define intra-annual coefficients of variation.

Seasonally, solute flux for a given discharge tends to be higher at the start of the ablation period, when solute concentration also tends to be relatively high. In general, total monthly solute flux in meltwater is generally higher in July than in the other summer months. When transit times of meltwater, in contact with suspended sediment through constricted subglacial pathways, remain extended at the onset of the melt season, levels of solute content are maintained. Such concentrations of solute are coupled with high discharge to yield significant solute fluxes. Both duration and timing during the ablation season of periods with persistent weather conditions determine how year-to-year variations in solute flux in meltwaters draining from highly glacierised basins are influenced by climate.

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