Sediment and Stream Water Quality in a Changing Environment: Trends and Explanation
(Proceedings of the Vienna Symposium, August 1991) IAHS Publ. no. 203, 1991.

CLIMATIC AND GLACIOLOGICAL INFLUENCES ON SUSPENDED SEDIMENT TRANSPORT FROM AN ALPINE GLACIER

DAVID N. COLLINS
Alpine Glacier Project, Department of Geography, University of Manchester, Manchester M13 9PL, UK

ABSTRACT Measurements of suspended sediment concentration in meltwaters of the Gornera, which drains from Gornergletscher, Pennine Alps, Switzerland, were undertaken at hourly intervals during seven ablation seasons between 1983 and 1989. Flows in this period were anomalously high by comparison with the 1970-1989 mean, although mean summer air temperatures and precipitation totals were less extreme. Considerable year-to-year variation in suspended sediment transport from Gornergletscher resulted from contrasting seasonal patterns of thermal energy inputs, differing timing, order and size of spatial instabilities in the subglacial drainage system, and varying incidence of high-magnitude hydrological events attributable to emptying of the ice-dammed Gornersee and summer rainstorms. Subglacial spatial instabilities usually occur during periods of rising flow, and are associated with development of the basal drainage system, the quantity of sediment removed depending on the area of glacier subsole involved and the length of time elapsed since the preceding hydraulic integration.

INTRODUCTION

Both the seasonal pattern of suspended sediment transport in meltwaters draining from mountain glaciers and annual total yield of fine sediment evacuated from glacierised basins vary considerably from year to year (Collins, 1989, 1990). These variations are influenced by year-to-year differences in spring and summer hydrometeorological conditions, which result in contrasting seasonal patterns of discharge and differing rates and extents of development of the subglacial drainage system. Climate directly influences runoff but how variations of flow during the ablation season are translated into suspended sediment transport depends on the areal interaction between elements of the evolving basal drainage system with the glacier subsole. Development of the basal drainage network and areal interaction between flowing meltwaters and the subsole are both related to the absolute timing, relative magnitude and position in the sequence of runoff events during spring and summer (Collins, 1990). Although small quantities of sediment continually enter suspension in flowing meltwaters through gradual development of the drainage network in areal extent and in cross-sectional dimensions of the passageways, and through frictional melting of channel margins in ice, sudden injections of large quantities of sediment occur during one or several days, indicative of large-scale spatial instabilities of the subglacial hydrological system. Spatial instabilities allow meltwaters access to areas of glacier subsole which have remained hydraulically-isolated for sufficiently long for products of glacial abrasion to accumulate in large quantities.

How much of the subsole becomes integrated with the drainage net and how spatially-stable the drainage system remains during a summer both interact with the seasonal pattern of hydrometeorologically-forced discharge in a year to determine the evacuation of suspended sediment from beneath a glacier. Variations between years in both climatic and glaciological conditions might be expected therefore to influence suspended sediment yield from year to year.

Timing, order and magnitude of hydrometeorologically-determined runoff events and the incidence of spatial instabilities associated with large releases of suspended sediment to meltwaters are examined in this paper for the Gornera, draining from Gornergletscher, which lies adjacent to the southern drainage divide of the Alpine Rhone basin, Pennine Alps, Kanton Wallis, Switzerland (Fig. 1), during the seven ablation seasons of 1983 through 1989.

Year-to-year variability of suspended sediment yield from the basin of Gornergletscher is also assessed, in relation to climatic and runoff differences between the seven years, and in the context of longer-term climatic and discharge fluctuations.

In all the summers of the measurement period except 1984, total runoff in the months June-September was well above the mean for 1970-1989 (107.13 x $10^6 m^3$), these years taking second to seventh highest rank positions amongst the 20.

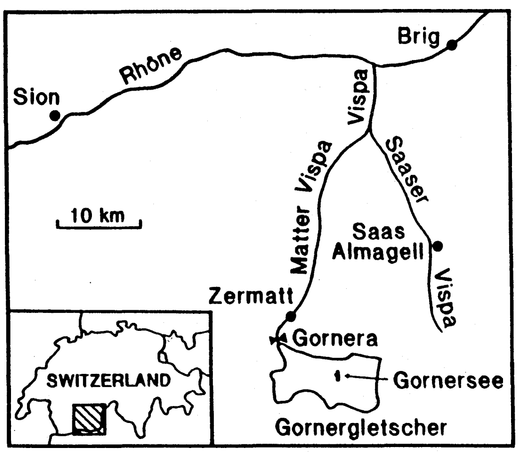

FIG. 1 Location of the Gornera gauge, Gornergletscher, and the meteorological stations at Sion and Saas Almagell in the Alpine Rhone basin, Pennine Alps, Switzerland.

MEASUREMENTS IN THE BASIN OF GORNERGLETSCHER

Discharge records from the gauging structure located on the Gornera about 0.75 km downstream of the present position of the snout of Gornergletscher are available for the months May through September in all the years between 1970 and 1989. Of the area of 82 km^2 contributing runoff to the gauge, about 83.7% is covered by perennial snow and ice. From the higher southern catchment boundary, several tributary glaciers descend to join Gornergletscher, one ice-stream of which, Grenzgletscher, actually forms the main body of the trunk glacier towards the snout. In the apex of the junction between Grenzgletscher and

Gornergletscher, an ice-dammed marginal lake, the Gornersee, forms at an axial distance of about 6 km from the portal from which the Gornera emerges. The Gornersee empties in most summers under the ice during two or three days, the Gornera reaching flow maxima which are normally the largest instantaneous discharges of the year.

A Manning S-4050 automatic pumping sampler was programmed to draw up samples of meltwater and suspended sediment from the Gornera at the gauging station every hour, 24h d^{-1}, from the same fixed position in the cross section with the orifice at the same depth, from as early in the season as practicable until September in each of the seven ablation seasons. Samples were filtered through Whatman No. 1 papers and the quantity of sediment retained was determined gravimetrically (see Collins, 1989, 1990). Suspended sediment flux (kg s^{-1}) was obtained as the product of sampled sediment concentration (g l^{-1}) and hourly average discharge (m^3 s^{-1}). Daily total sediment load was computed from the 24 hourly suspended sediment flux values, except on days on which fewer than 24 sediment samples were successfully collected, when total load was estimated from the mean of the available values. With a view to calculation of total sediment yield in a summer, values of daily total load had to be interpolated for those few days within the otherwise continuous record on which no samples were collected at all. The mean of daily sediment transport on the three days before and the three after the interruption was used in such interpolation.

HYDROMETEOROLOGICAL MEASUREMENTS IN THE PENNINE ALPS

Routinely-collected climatic data from meteorological stations at Couvent des Capucins, Sion (542 m a.s.l.) in the main Rhone valley and at Saas Almagell (1669 m) in a tributary mountain valley (Fig. 1), provide hydrometeorological information relevant to runoff from highly-glacierised basins throughout the Alpine Rhone basin. Mean summer air temperatures for the months May through September (T_{5-9}) at the two stations are highly correlated ($r = 0.93$, 1968-1977), differences in elevation, situation and location (c 45 km) notwithstanding. There is a strong link between T_{5-9} at these stations and discharge in the same months (Q_{5-9}) from many glacierised basins widely-distributed across the area, and this association strengthens with increasing percentage ice-cover in a basin (Collins, 1987). Winter precipitation variables, for example total precipitation in the months October through April (P_{10-4}), at mountain stations such as Saas Almagell, have weak negative associations with ensuing Q_{5-9}, but increase levels of explanation of variance of summer runoff in regression models above those given by T_{5-9} alone. Meteorological measurements at Sion were taken continuously between 1865 and 1977, and were initiated at Saas Almagell in 1968.

RUNOFF FROM GORNERGLETSCHER AND HYDROMETEOROLOGICAL CONDITIONS IN THE PERIOD 1970-1989

Q_{6-9} of the Gornera ranged between -33.0% of the 1970-1989 period mean (in 1978) and +25.3% (1982), with a coefficient of variation of 0.17. Runoff was generally lower in the 1970s than in the 1980s (Fig. 2). Flow between June and September in 1982 ranked ahead of that in 1987, and then as listed in Table 1. For May through September discharge (Q_{5-9}), descending rank order is 1982, 1986, 1988, 1987, 1989 and 1983. 1982 remains the year with highest flow, however viewed, and the other five years in differing rank order complete the top six. The year with lowest flow was 1978, followed in increasing rank order by

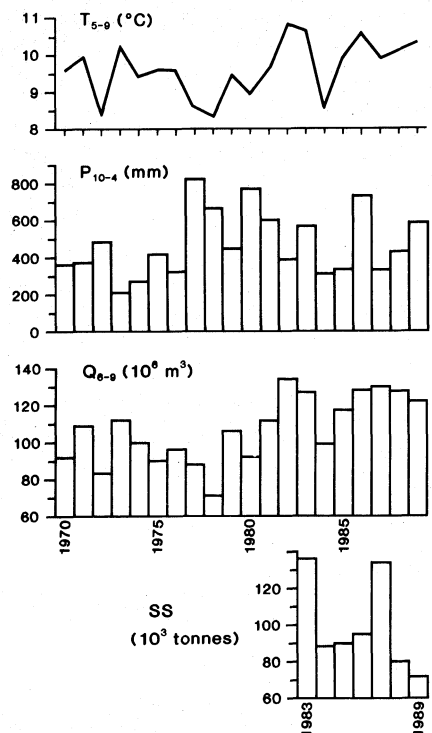

FIG. 2 Annual variations of mean summer air temperature(T_{5-9}) and total winter precipitation (P_{10-4}) at Saas Almagell, total summer runoff in the months June through September in the Gornera (Q_{6-9}) in the years 1970-1989, and suspended sediment transport (SS) in meltwaters of the Gornera between 27 June and 11 September in 1983-1989.

1972, 1975 and 1977. Thus, six of the seven highest summer total flows in the two decades occurred in the seven years between 1983 and 1989 during which suspended sediment transport was measured. These flows were from 10.1 to 21.9% greater than the 20-year mean. In those seven years, only in 1984 was summer discharge lower (-7.5%) than the 1970-1989 period mean.

TABLE 1 Placings of the years 1983 through 1989 in descending rank order within the two decades 1970-1989 by mean summer air temperature (T_{5-9}) at Saas Almagell and total summer runoff in the Gornera (Q_{6-9}).

Year	Rank	
	T_{5-9}	Q_{6-9}
1983	2	5
1984	17	13
1985	8	7
1986	3	3
1987	9	2
1988	6	4
1989	4	6

Values of T_{5-9} at Saas Almagell are also plotted in Fig. 2. Maximum mean summer air temperature in the period 1970-1989 was experienced in 1982, followed by the three years 1983, 1986 and 1989, which are included in the sediment measurement period. The pattern of year-to-year variation of summer discharge of the Gornera broadly reflects that of T_{5-9} between 1970 and 1989. Direct accord between thermal input and runoff is indicated in those years in which high and low extremes of both occur. In the two coolest summers, 1978 and 1972, runoff was also respectively at lowest levels. Maximum runoff was experienced in 1982. Overall, the associations between both T_{5-9} and Q_{6-9}, and T_{5-9} and Q_{6-9} in the two decades yield correlation coefficients of 0.88. Precipitation in winter and summer, however, interacts with energy input in controlling discharge. Heavy winter snowfall maintains a high albedo retarding melt of underlying ice in early summer, whereas summer rainfall contributes directly to runoff. In the seven year sediment measurement period, summer flow of the Gornera was noticeably augmented by liquid precipitation in the summers of 1984 and 1987 and suppressed during 1983 and 1989 by snow accumulated in the preceding winters. Hence, although summer 1989 was warmer than that of 1988, runoff was slightly reduced (Table 1). Runoff was greater in 1987 than in the two warmer succeeding years as a result of lower winter precipitation and the occurrence of summer rainstorms. Nevertheless, for the two decades, addition of a winter precipitation variable to T_{5-9} increases explanation of summer runoff by less than 1% in multiple regression. Mean T_{5-9} at Saas Almagell between 1970 and 1989 was 9.65°C, and 10.03°C in the sediment measurement period, but, during the latter, rank placings of warm summers are generally lower than those of Q_{6-9} (Table 1). Only four of the top seven warm summers of the two decades occurred between 1983 and 1989.

Mean annual precipitation (P_{10-9}) for the two decades (802 mm) was exceeded only in 1982/1983, 1983/1984 and 1985/1986 during the sediment measurement period. The second wettest summer (P_{5-9}) in the 20 years was in cool 1984, but 1987 received only a close to average May-September total. Winter 1985/1986 was particularly snowy, but the negative influence on discharge was offset by ice melt in the ensuing warm dry summer. More than average precipitation characterizes the years 1976/1977 through 1980/1981 (Fig. 2). Mean P_{10-9} at Saas Almagell for the period 1983-1989 was 770 mm, close to the 20-year average.

SEDIMENT TRANSPORT IN THE GORNERA 1983-1989

Comparison of quantities of suspended sediment transported annually in the Gornera is complicated by the length of summer measurement period varying between years, and by necessary interpolation of missing data in the important month of July in both 1984 and 1985. Total sediment transport has been calculated for the 77-day period 27 June through 11 September each year. Interpolation may have led to under-estimation of load if a spatial instability occurred during a period in which values have had to be estimated (not improbable on 13-14 July 1985).

Year-to-year variation of total sediment transport for the 77-day summer periods is considerable (coefficient of variation = 0.26, mean = 99.72 x 10^3 t), in the range 72.29 (1989) - 136.64 (1983) x 10^3 t. Above average loads were transported in 1983 and 1987 (Fig. 2). No clear relationship exists between total sediment transport and Q_{6-9} ($r = 0.37$), nor between load and actual discharge in the 77-day periods ($r = 0.46$).

At best, taking first differences of the sediment and Q_{6-9} series slightly improves the calculated level of association, first differences representing the deviation, smaller or greater, of a measurement in one year by comparison with that in the previous year (r = 0.58). Parallel behavior in sign but not in relative magnitude of deviations between years is indicated (Fig. 2). That seasonal incidences of spatial instabilities in the basal drainage system and of high-magnitude hydrological events influence sediment transport in the Gornera is therefore supported.

SUSPENDED SEDIMENT FLUX EVENTS IN THE GORNERA

Suspended sediment flux events in the Gornera are generally associated with, but can be independent of, increases in runoff induced by thermal conditions, rainstorms, and emptying of the Gornersee. Such increases in flow can trigger spatial instability in the drainage system beneath Gornergletscher. Relationships between seasonal patterns of discharge and sediment flux in the Gornera are shown in Fig. 3.

1983

Two short periods of substantially-enhanced sediment flux in July account for 59% of the total load transported in 1983. Between 8 and 10 July, as discharge increased to levels not reached since September 1982, a massive instability resulted from spatial re-organization of the drainage net at the sole of Gornergletscher, integrating subglacially-stored sediment with flowing water. A diffuse cavity drainage system probably collapsed to fewer larger conduits (Walder, 1986) as the basal hydrological network became established after closure under ice overburden pressure in winter. Locations of hydrological pathways appear to have remained fixed, despite increasing flow, until 18 July, when further areas of bed were flushed by meltwaters. The maximum daily total sediment transport in the seven years, 9921 t, was achieved on 23 July. Only minor fluctuations of sediment flux occurred during the flows of later summer, which failed to reach earlier levels.

1984

In the period 8-14 July, flow of the Gornera rose to levels not reached since July 1983, and an early season sediment flux event occurred. A second event, on 30-31 July, occurred at an unexceptional discharge, probably relating to a temporary subglacial storage of water as a result of blockage of basal drainage channels. These two events account for over 50% of the small annual load.

1985

The Gornersee drained between 12 and 14 July, producing the highest flow in the Gornera since the warm summer of 1982, but sediment measurements were discontinuous. A minor spatial instability occurred during rising flow in mid-August after a snowfall-induced recession.

1986

In late June, a major sediment-flushing instability, accompanying the highest flow since July 1985, occurred after total daily flow had been steadily rising for two weeks. A further instability followed a few days later, on 4 July, during unexceptional discharge. Meltwaters emptying from the Gornersee on 23-24 July escaped without engaging basally-stored sediment, remaining in areas of subsole integrated by the preceding two events.

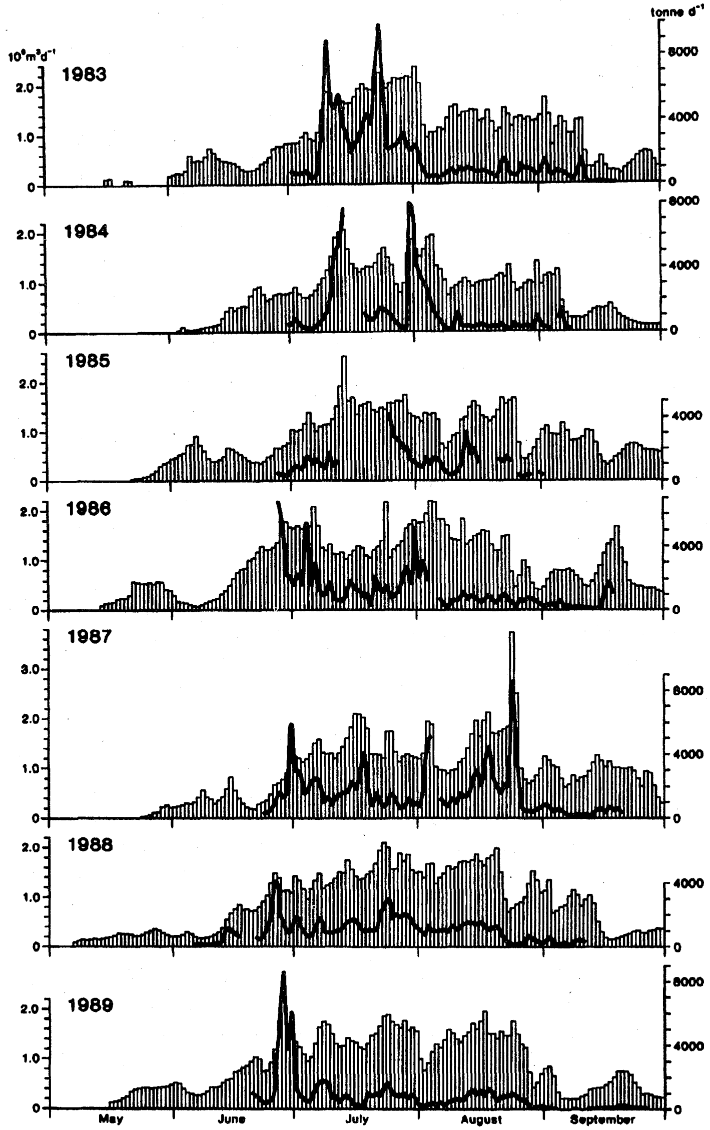

FIG.3 Seasonal variation of daily total discharge (columns) and measured daily total suspended sediment transport in the Gornera (curves) between May and September in the years 1983 to 1989.

<u>1987</u>

Most of the near average $P_{5\text{-}9}$ fell as rain over much of the basin during five summer storms on 7, between 15 and 18, and on 24-25 July, and on 18 and 23-24 August. With the exception of 24-25 July, runoff in the Gornera resulting from these storms was superimposed on flows already rising in response to thermal conditions. However, the first major spatial instability of the year, on 30 June, as the subglacial drainage system expanded, was unrelated to precipitation but occurred within a period of rising flow. An instability between 5-7 July preceded the storm, during the highest discharge since September 1986. An instability occurred under similar circumstances between 15 and 17 July. The third storm raised flow but not sediment flux, which next increased as the drainage network was disrupted during the emptying of the Gornersee from 2 to 4 August. Subsequently, generally increasing flow was accompanied by sediment pulses to a maximum on 18 August. The final storm produced the highest runoff in the Gornera in the 20-year period, as runoff in excess of the twenty-year flood occurred in many rivers with long gauging records in Kanton Wallis (Bundesamt für Umweltschutz, 1988). Nevertheless, daily total sediment transport (8575 t) on 24 August was only fourth in rank order in the seven-year measurement period, as, late in summer, much of the subsole had already been integrated with flowing meltwaters.

1988

Step increases in discharge on 14 and 24-25 June were associated with suspended sediment flux events, in the former case related to precipitation. An unspectacular drainage of the Gornersee happened before 4 July. Discharge peaked on 1 July, and rose between 5 and 7, 9 and 13, 18 and 23, and 27 and 29 July, rising above previous levels in 1988 during the 13 and 22 July events only. Minor sediment flux events occurred in association with each event, although subdued between 27 and 29 July, and related to precipitation of at least 10 mm day^{-1} on 1 and 27 July. Similar precipitation levels were recorded on 3 and 24 July, but only increased sediment flux during the latter event, which followed a thermally-related increase in flow.

1989

Drainage of the Gornersee between 27 and 29 June, during a period of thermally-driven increase in discharge, produced the highest daily flow of the Gornera since 24 August 1987 and the third highest total daily sediment load of the seven-year period. There was no other early season sediment flux event, and either the drainage network was first opened up by the escaping lake waters or lake drainage was permitted by the sudden development of the basal conduit system. Subsequently, the pattern of small fluctuations in sediment flux was parallel with that of discharge, which never returned to the level of late June.

DISCUSSION

Although summer discharges of the Gornera in the seven-year period 1983 through 1989 were largely exceptional by comparison with the 1970-1989 average, mean summer air temperature (T_{5-9}) and seasonal and annual precipitation were less extreme. Anomalous high flows resulted from interacting effects of precipitation with thermal activity. In the longer term, the three warmest summers (1983, 1986 and 1989) are ranked 12, 16 and 22 (respectively) in the 124-year homogenous series from Sion (measured to 1977 and simulated from the Saas Almagell record after 1978). Mean T_{5-9} for 1866 to 1989 of 17.24°C compares with 17.72°C for 1983-1989.

Both timing and magnitude of sediment flux events are related to the incidence of individual runoff events and seasonal pattern of discharge each year and also to intra-annual runoff fluctuations. All large sediment flux events occurred during periods of rising flow, suggesting high water pressures building up inside Gornergletscher, allowing conduit systems to develop from, and integrate, cavities purging sediment from wide areas of subsole. Such developments in the basal drainage network will appear in the sediment record only if the simplification of drainage occurs over an area of subsole maintaining stored sediment. Sediment will be contributed to such storage by glacial abrasion during the time elapsed since the area of subsole was last integrated with flowing meltwater. Rising flows at the onset of the melt season are most likely therefore to enlarge the area of subsole over which drainage passageways sweep as cavities are transformed to conduits. Zones so integrated will have remained hydraulically-isolated for eight or more months. Sequentially greater discharges in spring and summer might be expected to be associated with high water pressures which will lead to enlargement upglacier of the area of subsole from which sediment is flushed, as the melt season progresses. However, fresh areas of bed may be added without discharge exceeding preceding levels, according to local basal conditions, and high discharges may not displace the drainage net from within the boundaries of recently-flushed partial areas of bed.

Major sediment flux events rarely occur after the beginning of August, as the drainage system has either stabilized in the first half of the ablation season or later migrates only over the area of subsole already depleted in sediment. 1987 was exceptional, with a late emptying of the Gornersee and substantial rainfall events in August. The magnitude and timing of the spatial instability on 24 August 1987 appears to have so depleted subsole sediment storage that little remained to be flushed from the areas of subsole that became integrated with flow in 1988.

Some sediment additional to that derived from the subsole of Gornergletscher will be contributed to the Gornera by runoff arising from precipitation over the ice-free largely vegetation-free portion of the catchment, including unstable Neoglacial lateral moraines. This quantity is probably small, since many precipitation events which result in increased flow of the Gornera barely raise the sediment flux above the summer background level. Precipitation-induced increases in water input to Gornergletscher affect sediment transport from the portal through the interaction of flowing water with the partial areas of subsole in which sediment is available, as do hydro-glaciologically determined spatial instability events and emptyings of the Gornersee.

In 'noisy' ablation seasons, those in which sediment flux events are frequent and well-distributed in time, spatial instabilities yielding large fluxes of sediment are absent at the onset of melt. Throughout summer, high intensity rainstorms and thermally-related fluctuations of discharge over periods of days both lead to increased noise. The impact of the draining of the Gornersee is determined by the magnitude of outburst and position in the season, the latter also in relation to the distribution of other large flows during the season.

CONCLUDING PERSPECTIVES

Measurement of suspended sediment concentration of meltwaters in glacier-fed rivers should clearly extend throughout the complete runoff season in order to characterize adequately temporal pattern and seasonal total quantity of sediment flux. It is unlikely that measurements during several weeks in one summer, or throughout just one summer, can provide reliable information representative of the total quantity of sediment that might be expected to be flushed from beneath a glacier in the long term. Timing, scale and order of both glaciological and hydrometeorological events strongly influence the pattern of sediment flux during summer ablation seasons, and hence annual yield of sediment from Alpine glaciers.

The seven-year sediment measurement period experienced generally above average summer discharges by comparison with the 1970-1989 mean through an interaction of effects of thermal and precipitation episodes. Such interactions also occur in years with lower flows, but it remains to be seen what patterns and quantities of sediment flux result in years when the general level of runoff is reduced below average.

Almost all sediment flux events occur during periods of sustained rising meltwater flow, suggesting that spatial instability is related to increasing water pressure. This synchronism is consistent with the need for high discharge to prevent closure of infant conduits when forming from cavities, as passageway orientation changes from transverse to the direction of glacier sliding to parallel. High pressure would be necessary to maintain the form of conduits against ice deformation closure while sweeping over protuberances on the glacier bed, as suggested by Walder (1986). Successive spatial instabilities closely-spaced within a few days with continuing rising flow might point to additional areas of subsole undergoing change in style of drainage system from linked cavities to conduits. Where two sediment flux events are separated by a period of low flow, and the second event accompanies recovery of discharge, drainage in a particular area of subsole may have reverted to linked cavities during low water pressure, before restoration of conduit drainage. This may have occurred in mid-August 1985. The quantity of sediment flushed from beneath the glacier will be much reduced in the second event.

Additional information, from dye-tracer tests before, during and after events, and from continuous measurements of water pressure in boreholes penetrating the bed, is however required in order to demonstrate directly the link between those spatial instabilities which produce sediment flux events with re-organization of the basal drainage network.

ACKNOWLEDGEMENTS The assistance of A. Bezinge, A. Kronig, H. Kronig and J.-P. Perreten, Grande Dixence, S.A., with logistical support and in supplying discharge records, is gratefully acknowledged. Members of the University of Manchester Alpine Glacier Project assisted with collection of the samples. Schweizerische Meteorologische Zentralanstalt provided meteorological data. Grant support was received in 1983 and 1984 from the Natural Environment Research Council (GR3/4787) and in 1987, 1988 and 1989 from the Royal Society (Overseas Research Grants).

REFERENCES

Bundesamt fuer Umweltschütz (1988) Hochwasserereignisse im Jahre 1987 in der Schweiz. *Mitt. Landeshydrol. -geol.* **10**

Collins, D.N. (1987) Climatic fluctuations and runoff from glacierised Alpine basins. In: *The Influence of Climatic Change and Climatic Variability on the Hydrologic Regime and Water Resources* (Proc. Vancouver Symp., August 1987). IAHS Publ.**168**:77-89.

Collins, D. N. (1989) Seasonal development of subglacial drainage and suspended sediment delivery to meltwaters beneath an Alpine glacier. *Ann. Glaciol.* **13**:45-50.

Collins, D. N. (1990) Seasonal and annual variations of suspended sediment transport in meltwaters draining from an Alpine glacier. In: *Hydrology in Mountainous Regions I: Hydrological Measurements; the Water Cycle* (Proc. Lausanne Symp., August 1990). IAHS Publ.**193**:439-446.

Walder, J. S. (1986) Hydraulics of subglacial cavities. *J. Glaciol.* **32**(112):439-445.