Annals of Glaciology 13 1989

SEASONAL DEVELOPMENT OF SUBGLACIAL DRAINAGE AND SUSPENDED SEDIMENT DELIVERY TO MELT WATERS BENEATH AN ALPINE GLACIER

by

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ABSTRACT

During the ablation seasons of 1983 and 1987, measurements of discharge and suspended sediment concentration of melt waters draining from Gornergletscher, Switzerland, were obtained at hourly intervals, permitting estimation of total daily sediment flux. Seasonal patterns of variation in sediment flux are interpreted in terms of development of the subglacial drainage network. Variations in flux relate to contrasting temporal patterns of run-off, and the differing incidence of subglacial hydrological events in the 2 years. During such events, in which basal water pressure is raised, large areas of previously hydraulically isolated sub-sole are integrated with flow, releasing quantities of sediment from basal storage. Several types of event are identified, arising during periods of generally increasing discharge in the early ablation season, resulting from temporary blocking of subglacial passageways or from outbursts emptying a marginal, ice-dammed lake, and related to rain-induced floods. Flow spreads out over the glacier bed as pressure increases, suggesting that the basal drainage system consists of a diffuse network of many linked cavities rather than fewer major conduits, particularly at the start of the season. A distributed cavity system may be simplified to fewer conduits, dimensions of cavities may enlarge or the area of bed over which cavities are developing may be expanded to supply debris to melt waters during events. Different partial areas of sub-sole become progressively integrated with flow during sequences of hydrological events. Later in summer, melt waters are confined to basal areas within which only limited sediment remains available for acquisition.

INTRODUCTION

Measurements of temporal variation in suspended sediment concentration and discharge of melt waters emerging from the portal can provide information concerning the interaction of flowing melt water with sediment beneath a glacier. Re-organization of channels, and relocation of passageways making up the basal hydrological network with respect to the bed, result in the evacuation of large quantities of fine sediment in portal melt streams. Events in which high basal water pressures are coupled with rapid basal sliding produce marked increases in melt-water turbidity. Greatly enhanced suspended sediment content occurs during floods resulting from the emptying of ice-dammed lakes (Collins, 1979, 1986) when water pressure and ice-sliding velocity are increased (Röthlisberger, 1980). Pulses in turbidity accompanied quasi-periodic mini-surges of a surge-type glacier in the years preceding a major surge, but without corresponding increases in discharge (Humphrey and others, 1986). Sediment content of melt water was maintained at high levels during the surge itself (Kamb and others, 1985). Peaks in both concentration and transport of sediment in melt waters draining from glaciers which do not surge are produced by high flows resulting from periods of sustained ice melt, and following heavy rainfall events (Østrem and others, 1967; Østrem, 1975). Events involving high basal water pressure and enhanced sliding also occur in Alpine glaciers, particularly in spring (Iken and others, 1983; Iken and Bindschadler, 1986), but which as yet remain unrelated to melt-water turbidity pulses. How the subglacial drainage network becomes established, and how the system subsequently evolves through the ablation season, are both influenced by occurrences of high water-pressure events as well as by seasonal patterns of hydro-meteorological conditions.

The aim of this paper is to examine those interactions between melt waters and sedimentary material at the sole of an Alpine glacier which are indicated by variations in water and sediment outflow from the terminus. Patterns of such variations throughout two ablation seasons with contrasting hydro-meteorological conditions are considered with a view to determining periods of change and stability of channels during annual development cycles of the subglacial drainage system through spring and summer. Seasonal interaction between the developing basal drainage network and subglacial sediment delivery to melt waters is suggested by observations at several glaciers that the concentration of silt is generally lower towards the end of summer than at the beginning (e.g. Østrem and others, 1967). Flood events, in which substantial fractions of the annual total sediment load are transported, again observed for several glaciers (e.g. Østrem, 1975), point to either abrupt dislocations of subglacial flow nets or to supply of sediment, additional to that derived from the glacier sub-sole, by rainfall running off ice-free areas. The influences of large events on seasonal patterns of sediment transport and on the development of the basal hydrological system are also evaluated in this study.

GORNERGLETSCHER CATCHMENT AREA

The observations were made in the basin containing Gornergletscher, Kanton Wallis, Switzerland. About 83.7% of the 82 km^2 basin area tributary to the gauging structure on the Gornera, the only pro-glacial stream draining from Gornergletscher is currently covered with permanent snow and ice (Fig. 1). The basin extends 2629 m from the gauge to the highest point, Dufourspitze (4634 m a.s.l.). Trunk Gornergletscher, which is joined by several tributary glaciers before reaching to 2100 m a.s.l. at a distance of 0.75 km from the gauge, originates in a snowfield from which Findelengletscher also descends. Melt-water flow is concentrated towards the portal through a steep-sided subglacial gorge. An ice-dammed marginal lake, the Gornersee, forms in the apex of the junction between Gornergletscher and Grenzgletscher, at an axial distance of about 6 km from the portal. In most years, drainage of the

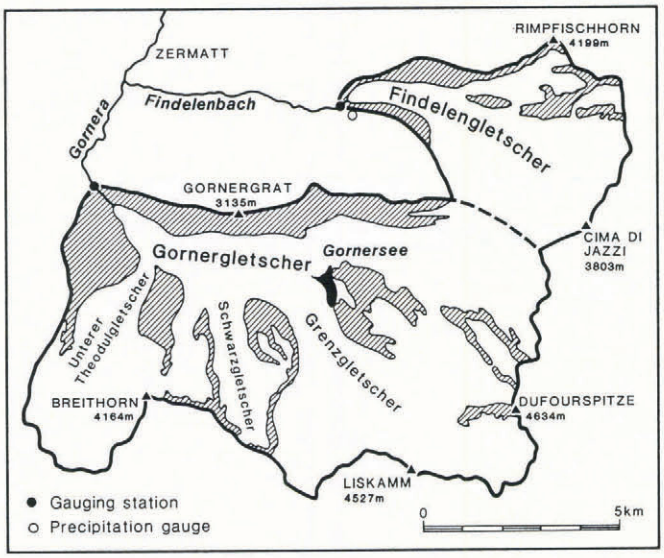

Fig. 1. Map of basins containing Gornergletscher and Findelengletscher, showing locations of the gauging station on the Gornera and the autographic rain gauge close to the snout of Findelengletscher. Ice-free areas within the basin watersheds are shown by cross-hatching.

lake produces the highest instantaneous discharge of the Gornera, and maintains high flows for 2 or 3 d, although there are years in which outbursts have not occurred. For almost all the distance between the portal and the gauge, the Gornera flows in a single channel with stable margins and an armoured bed.

MEASUREMENTS

A Manning S4050 automatic pumping sampler was programmed to collect samples of melt water at the gauging station every hour, 24 h/d, from the same fixed position in the cross-section. In the periods, 1 July–20 September 1983 and 23 June–20 September 1987, 1743 and 1880 samples, respectively, were collected. Between 160 and 300 ml of melt water were collected on each occasion. The volume of each sample was measured, and the samples filtered through individually pre-weighed, numbered circles of Whatman No. 1 filter paper. Clean filter papers and filters laden with sediment were air dried at 105 °C in 1983 before weighing, but in 1987 drying was carried out during determination using a Mettler infra-red balance attachment (also at 105 °C). The quantity of sediment in a sample was determined gravimetrically to a precision of 1 mg, by subtraction of original filter weight from the weight of sediment and filter together.

Hourly mean values of discharge were derived from continuous records of stage throughout both sampling periods. Suspended sediment flux (kg s^{-1}) was obtained as the product of sampled instantaneous suspended sediment concentration (g l^{-1}) and average instantaneous discharge ($m^3 s^{-1}$). This flux is effectively the suspended sediment load at the sampler-hose intake position and, as such, is only an indicator of the actual load of the Gornera. Whilst turbulence might be expected to lead to suspended sediment being well distributed throughout a cross-section, local structures in sediment concentration may occur, for example, as a result of upwelling from the bed. Change of concentration with depth in a given vertical in a cross-section is complicated by variation in fall velocity with particle size, and the probability that size and concentration of suspended particles and of saltation material increase with depth. As stage increases, even at constant average sediment concentration, a fixed-position sampler intake would be expected to collect more sediment as a result of being proportionally lower in the vertical profile. Total daily sediment transport was computed using individual values of suspended sediment flux, except for days on which fewer than 24 sediment samples were successfully processed, when the total was estimated from mean flux as derived from the available information.

Precipitation was recorded by an autographic rain-gauge located close to the snout of Findelengletscher (Fig. 1) at an elevation of about 2490 m a.s.l. Daily totals of precipitation (0.00–23.59 h) are used in this paper.

SEASONAL PATTERNS OF PRECIPITATION, RUN-OFF, AND SUSPENDED SEDIMENT FLUX

Run-off regime of the Gornera during the ablation season of 1983 (Fig. 2) was influenced by persistent, clear, warm dry conditions throughout the month of July until a period of colder weather set in from 4 August. Occasional storm rainfall occurred between 7 and 11 July. Flow increased markedly between 9 and 11 July, with a general rising trend to the beginning of August, after which daily total discharge was halved. Discharge increased, but to lower levels than the previous highs, with the return of warmer conditions from 10 to 16 August, and fluctuated at around the same level to the end of the month. High radiation inputs then raised flows to a peak on 5 September. Snowfall at higher elevations from 10 September but with some melt on 11–12 September greatly reduced run-off. The annual maximum instantaneous flow of 33.1 $m^3 s^{-1}$ on 2 August followed 7.2 mm of rain in the preceding 24 h. There was no outburst from the Gornersee during 1983.

Suspended sediment flux first increased on 9 July, when maximum hourly mean instantaneous discharge (14.75 $m^3 s^{-1}$) exceeded that of 6 July by 0.33 $m^3 s^{-1}$. Further increased flow on 10 July raised flux to a high point of 7.175 × 10^3 tonne d^{-1}. Even higher discharge on 11 July failed to produce a higher load. Sediment flux declined to 16 July with flows remaining high but not exceeding those of 11 July. Increasing discharge to 20 July produced a parallel rise in flux. Season maximum daily transport was

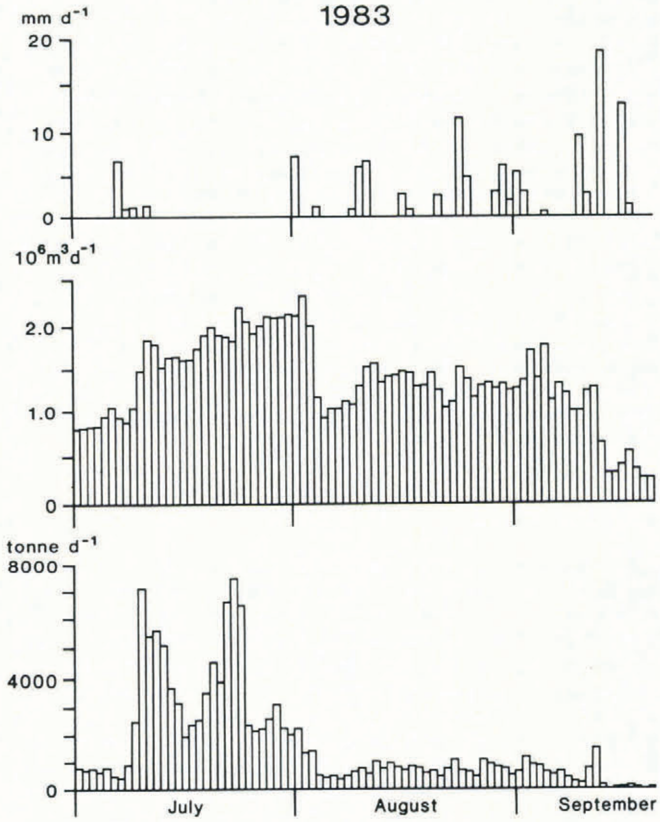

Fig. 2. Seasonal variation of total precipitation, recorded each day between 00.00 and 23.59 h at the gauge close to the terminus of Findelengletscher (upper); total daily discharge of the Gornera (centre), and daily total suspended sediment transport in the Gornera (lower), between 1 July and 20 September 1983. Sediment transport is calculated for sampler-hose intake position, as explained in the text.

https://doi.org/10.3189/S026030550000762X Published online by Cambridge University Press

achieved on 23 July (7.542×10^3 tonne d^{-1}), when total discharge was less than on adjacent days. Actually, the diurnal minimum discharge on 23 July was substantially lower ($13.38\ m^3\ s^{-1}$ at 08.00 h) than equivalent values on previous days, whereas diurnal maximum flow ($27.50\ m^3\ s^{-1}$) was higher than on 22 July. The diurnal range of flow was also anomalous on 24 July, with high minimum and maximum values ($24.50–29.05\ m^3\ s^{-1}$). Greater sediment transport on 29 July than during the following days with higher flows appears to relate to a diurnal minimum flow larger by comparison with those of surrounding days. Subsequent fluxes remained small; of the slightly raised daily totals on 12, 23, and 27 August, and 2 and 12 September, only those on 23 and 27 August were unrelated to precipitation events.

The pattern of seasonal variation in run-off from Gornergletscher in 1987 (Fig. 3) differs significantly from that of 1983. Discharge generally increased to 7 July, despite cool overall conditions which continued to 10 August. During this period, rainfall produced three rises in run-off: on 7 July, following two warmer days; between 15 and 18 July, again after two warmer days; and on 24–25 July. Precipitation later in July had negligible impact on flow. Increased discharge between 2 and 4 August resulted from the draining of the Gornersee. Warm, clear weather from 11 August raised flow to the highest levels in 1987 related to thermal conditions, on 15 and 17 August and continued to 22 August. Heavy rainfall on 18 August was reflected in run-off. Exceptionally heavy precipitation on 23–24 August produced the maximum instantaneous flow of 1987, of $60\ m^3\ s^{-1}$ on 24 August, on which day 40.6 mm of precipitation was recorded at Findelengletscher. Subsequently, discharge was raised in two warmer periods in early and mid-September.

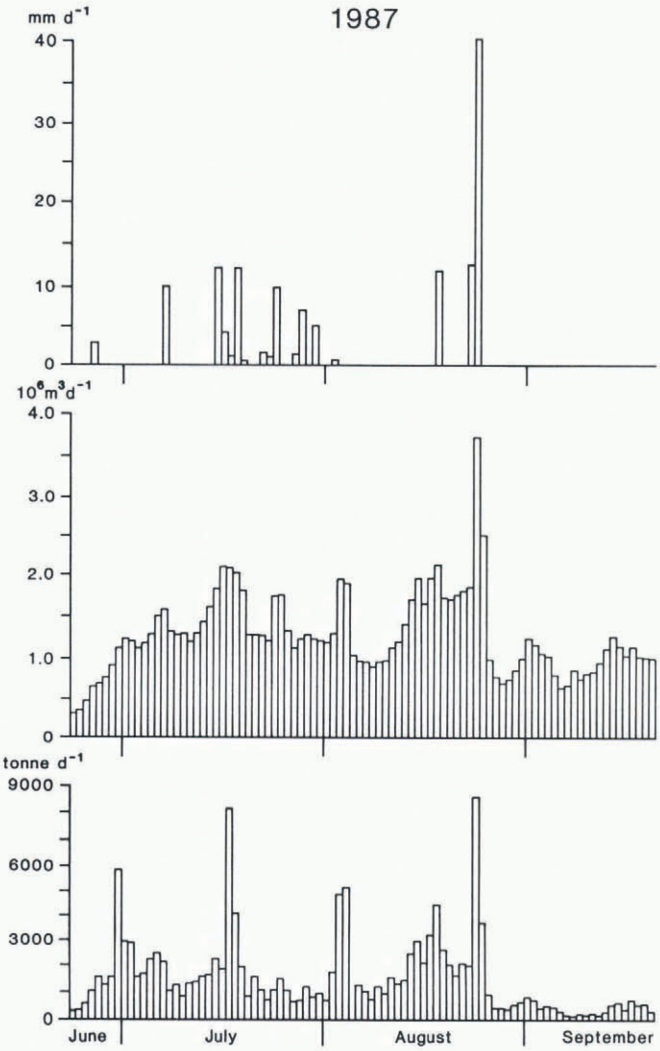

Fig. 3. Seasonal variation of total daily precipitation recorded at the Findelengletscher gauge (upper), total daily discharge of the Gornera (centre), and daily total suspended sediment transport in the Gornera (lower), between 23 June and 20 September 1987.

The seasonal variation in suspended sediment flux of the Gornera in 1987 broadly followed the pattern of flow regime, but with marked short-term deviations. A major sediment-transport event occurred on 30 June, in a period when each day the maximum instantaneous flow exceeded that of the previous day. Sediment flux reduced on 1 July, although maximum flow was again increased. The previous maximum instantaneous flow of the season was exceeded on each of 5, 6, and 7 July; a small sediment-flux peak occurred on 6 July, which was maintained on 7 July by ensuing rainfall. Previous maximum flow of the season was also breached each day from 14 to 17 July. There was little impact on sediment flux, despite heavy rain, until 17 July. Sediment load remained relatively high during further rain on 18 July. Discharges augmented by rainfall on 24–25 and 29 July had minimal effects on loads subdued following the event of 17–18 July. Sediment flux increased throughout rising flows from the drainage of the Gornersee, reaching a maximum daily total of 5.132×10^3 tonne on 4 August. A daily maximum of $23.26\ m^3\ s^{-1}$ on 14 August, much higher than on the previous day ($19.8\ m^3\ s^{-1}$), raised sediment flux; still higher maximum discharge on 15 August ($25.0\ m^3\ s^{-1}$), part of an anomalously narrow diurnal flow range, further increased sediment flux. Sediment load increased again on 17 August, as the previous daily maximum discharge level was exceeded. Rain over the basin on 18 August produced yet greater sediment evacuation (4.437×10^3 tonne), exceeded again during the storm of 23–24 August (8.574×10^3 tonne), after which event the rate of transport of suspended material remained less than 1.0×10^3 tonne d^{-1} up to the end of the season.

SUBGLACIAL SEDIMENT SUPPLY AND DELIVERY TO MELT WATERS

Sediment will be produced by glacial erosion processes over wide areas of bed throughout the year, whereas melt-water flow with sufficient velocity and turbulence to maintain traction and suspension of fine particles is limited temporally to the ablation season and spatially to passageways constituting the basal drainage system. It is unlikely that sediment would continue to accumulate in particular areas of bed either from year to year or during an ablation season. Debris will be removed by migration of subglacial channels over wide areas of the bed during summer, or by a network of small passageways with high enough flow, which covers a large proportion of the sub-sole in the ablation season. Evidently, rate of sediment supply to melt waters beneath Gornergletscher bears no constant relationship to the rate of flow of melt waters to the portal; not all aliquots of melt water have equal access to debris. Sediment will be released to melt waters in the basal hydrological system by melting of debris-rich basal ice from the glacier sole, and by deformation of basal sediment into passageways through glacier sliding. Migration of channels *en masse* with sliding ice, and movement of channels relative to surrounding ice by melting of channel margins, may allow melt waters to impinge on patches of basal sediment. Some fine debris will be derived from wear of bedrock by flowing melt waters charged with sediment, particularly within incised channels.

As fine sediment will be readily washed out from basal zones in contact with flowing melt water, sediment transport to the portal in a period of time will be supply-related in effect, through what size of area of unworked glacier sole and sub-sole becomes integrated with flow, and how much sediment is held there. The latter will presumably be influenced by the length of time elapsed since melt water previously covered an area. How much sediment is available will also depend on the thickness and debris content of the basal ice layer, and whether there is bedrock or an unconsolidated, deforming-debris sub-sole. Areal integration of sub-sole with flowing melt water will depend on the type of basal passageway system and how the system develops in response to changes in water pressure arising from seasonal and diurnal variations of surface-water input.

https://doi.org/10.3189/S026030550000762X Published online by Cambridge University Press

Frictional melting of ice from the margins of basal conduits deforming inwards under ice-overburden pressure provides a small but continuing debris supply to melt waters in channels incised up into ice or down into bedrock. The bulk of sediment delivery probably results from glacier sliding either bringing basal ice and deforming basal sediment from up-glacier into contact with flowing melt waters or relocating conduits incised upwards into ice on to areas of basal sediment down-glacier. These interactions will be more effective the more transverse the orientation of the conduit system is to the direction of sliding. A dense network of small conduits arranged at an angle to the direction of glacier flow would be expected to gather more sediment than a few larger conduits with alignment parallel with flow. The theoretical water-pressure-discharge relationship for conduits suggests that larger conduits develop at the expense of smaller ones (Röthlisberger, 1972). Development of the conduit system in this way would form a plausible explanation of the decline in sediment flux with progression of the ablation season. Variations in sliding velocity from day to day, together with changes in conduit dimensions with discharge through-put which alter the area of debris in contact with flowing water, will also influence sediment load. Sediment supply will be favoured in conduits which respond to increased flow by enlarging cross-sectional areas through widening over the bed (and hence decreasing the width–depth ratio), rather than growing as cylindrical tubes in surrounding ice.

Enhanced sliding also appears to be associated with high pressure in distributed basal drainage systems consisting of many small conduits or of a network of linked cavities localized by topographic features of the bed (Humphrey and others, 1986; Iken and Bindschadler, 1986). Expansion of cavities enlarges the area of melt water in contact with basal ice and sub-sole debris. Abrasion rates increased by enhanced sliding may generate additional fine sediment. High subglacial water pressure and sliding events in Alpine glaciers occur in the early part of the melt season (Iken and others, 1983; Iken and Bindschadler, 1986). How a system of interconnected cavities might develop during the ablation season and how it would relate to enlarging conduits is not clear. Water pressure has been shown theoretically to increase with flux in linked cavity systems (Walder, 1986; Kamb, 1987), so that dense networks of small anastomosing passageways are favoured rather than a few large ones.

High water pressure, however, with greater area of ice–bedrock separation and accelerated sliding, might permit the formation of conduits parallel with the direction of ice flow from coalescing enlarged cavities. Sustained high discharge would be needed to prevent closure of such infant conduits while sweeping across high-pressure zones of the bed, where they might otherwise be squeezed out (Walder, 1986). Successive cycles of conduit formation followed by restoration of cavities might therefore be expected, especially during the relatively low flows of spring, as might be inferred from the results of Iken and Bindschadler (1986). These episodes would lead to flushing of sediment from "fresh" areas of glacier bed, whereas repeated growth and decline of topographically anchored cavities would merely re-integrate the same basal zones. Movement of basal ice over protuberances will, however, supply some material for release through melting of the sub-sole by water in cavities.

SPATIAL STABILITY OF THE DRAINAGE SYSTEM BENEATH GORNERGLETSCHER

Integration with flowing melt waters of areas of glacier sole and sub-sole which have remained hydraulically isolated for sufficiently long to allow debris to accumulate will increase suspended sediment flux at the portal above the "background" level. This level reflects supply of debris from melting ice from channel margins, also exposing some sub-sole, under diurnal variations of flow. The complication of diurnal variation in sediment concentration is reduced in this investigation by the use of daily totals of sediment flux (Figs 2 and 3). Substantial changes in topological configuration of channels, resulting in relocation of the network of passageways with respect to the sub-sole or in changed network dimensions should be apparent in plots of daily sediment flux, particularly if the events are large and sudden. Such spatial instabilities, which may or may not relate to changes in discharge, indicate stages in the seasonal development of the subglacial drainage system.

A period of stability is indicated between 1 and 6 July 1983, when rising discharge was accompanied by a reduction in already low flux levels. Rising flows led to considerable re-organization of the drainage system on 9 and 10 July, with expansion of the hydraulically integrated area. Sediment evacuation then declined for several days, despite higher flows on 11 July, indicating that instability continued but integrating smaller areas of fresh sub-sole. Sediment loads representing the removal between 9 and 16 July of a minimum of 28.46 and a maximum of 104.45 tonne $km^{-2}\,d^{-1}$ (28–104.45 g $m^{-2}\,d^{-1}$) of debris averaged over the entire glacier bed, and hence considerably larger quantities in the hydraulically integrated partial area, point to sweeping from a wide area of the bed of the store of basal sediment which was accumulated during the period of isolation from flow in winter. In a phase of instability of the basal hydrological system from 17 July, previous discharge levels were exceeded on 19 and 20 July, although sediment flux remained lower. Outflow seems to have been constricted on 22 and 23 July, presumably raising pressure in basal passages and integrating further areas of bed to produce the season's maximum daily total flux. Flow but not flux peaked on 24 July as the blockage was released. The blockage probably affected a relatively large passageway, some way down-glacier, collecting flow from a wide area rather than simultaneously blocking many small, interlinked cavities. Further fresh areas of bed were probably integrated with flow, as insufficient time would have elapsed since discharge previously reached the same level for sediment storage to build up in the formerly wetted areas. Development of the network on 29 July, during another constriction of subglacial through-flow, raised sediment flux, but to a lower level than the event of 22–23 July. After 22 d of sediment flux above the background level, much of the basal area would already have been integrated with flow at least once. The highest daily total discharge of the year on 2 August produced the lowest daily total sediment load since 8 July.

While apparent stability of the basal drainage network in the months of August and September might relate to the restriction of flow to limited areas of bed, spreading of the wetted area may have occurred but incorporated only areas from which sediment had already been removed. Precipitation events affected sediment flux on 12 August and 2 and 12 September 1983, but rainfall over the Gornergletscher basin on 16 August, heavy on 24, 25, and 29–31 August, made no impact above usual background fluxes of under about 15 tonne $km^{-2}\,d^{-1}$ averaged over the glacier bed. Precipitation on and after 13 September fell as snow. It can be concluded that only a limited quantity of suspended sediment is derived from the unvegetated, Neoglacial lateral moraines during rainfall events. Small sediment flux maxima on 23 and 27 August appear to have resulted from constriction to flow, reducing discharge through the basal drainage system on the respective preceding days. From a previous highest flow on 5 August until 3 September, subglacial erosion processes should have restored some debris to areas not hydraulically integrated at intervening low flows. The failure of the high discharges on 3 and 5 September to impinge on this sediment suggests that flow had remained limited in stable channels rather than spreading out over the bed.

A major spatial instability occurred in the subglacial drainage system of Gornergletscher on 30 June 1987, with further activity on 1 and 2 July, suggesting considerable extension of the drainage net over the bed. Limited growth of the area integrated with flow, from 5 to 7 July and 14–16 July 1987, occurred when previous levels of discharge in the season were exceeded. Another major relocation of subglacial drainage paths occurred on 17 July, with sediment flux remaining elevated on 18 July. A rise in flow on 24–25 July, but to levels beneath those previously transmitted, appears to have been accommodated within the earlier wetted area. However, drainage of the Gornersee, while producing discharges lower than had occurred 15 d before, expanded the drainage net, with sediment flux continuing to increase throughout the rising hydrograph. Integration of zones of unworked bed between the Gornersee and the already existing trunk drainage system is suggested by the availability of sediment during this event. Sustained spreading of the drainage network in that area during the rise of flow is suggested by these data and by interpretation of measurements of sediment transport during drainage events in the 1970s (Collins, 1986) and by enhanced sliding velocities (Röthlisberger, 1980). Spatial instability of the remainder of the drainage network is also probable, but at the modest level of discharge melt waters were presumably confined within the basal area that had previously been integrated with flow.

Unusually high overnight discharges on each of 13/14, 14/15, and 16/17 August 1987 suggest the release of water which had been unable to escape quickly from the drainage system during the time of maximum outflow. High pressure in basal channels seems to have forced water to areas of the bed retaining sediment storage, resulting in sediment transport events. Additional spreading to unworked areas is indicated on 18 August. However, some sediment may have been derived from the ice-free part of the basin during rainfall, and some sediment may have accumulated in the period since 17 July when flow last reached this level. Further instability, indicated by high overnight flows, continued to the storm of 23–24 August, when the basal drainage expanded yet more. Subsequent smaller flows in late August and September 1987 were conducted through channels with limited access to sediment.

EVOLUTION OF THE SUBGLACIAL DRAINAGE SYSTEM OF GORNERGLETSCHER DURING THE ABLATION SEASON

Areal extension of the basal passageways during successively high discharges in both summers suggests that the hydrological system under Gornergletscher, at least initially, consists of a distributed diffuse network. Spatial growth of the net under high pressure is also indicated during sediment-transport events involving constriction to melt-water outflow. Lodgement of boulders or jamming of ice blocks collapsed from the glacier sole in passageways, and sliding of major conduits with the mass of the glacier into bedrock obstacles, may result in blockages. Sediment-transport events other than drainage of the Gornersee imply sudden flushing of the bed, as typically the sediment-flux signal associated with an event is asymmetrical. It consists of a sudden large increase in load on the first day of channel re-organization, declining to background levels within a few days. This behaviour is consistent with development of interconnections between enlarging cavities, which would allow water under pressure to be released. Possible growth of conduits from extended cavities, as hypothesized by Walder (1986), could account for the sediment-flux signal. During simplification of a diffuse cavity network to fewer conduits, sediment would be flushed from previously hydraulically isolated areas of bed, initially as threads of flowing water change course and coalesce. Settling of the basal ice back on to different bed contours immediately down-glacier, and migration, straightening and selective growth of newly formed conduits, maintain the reduced sediment supply after the first large pulse. Events of this type, occurring at the beginning of the ablation season, in which sudden changes in basal drainage are coupled with enhanced glacier sliding, seismic activity, and simultaneous uplift of the glacier surface, have been termed "spring events" by Röthlisberger and Lang (1987). It is unclear from sediment-flux evidence whether such changes to the hydrological network during events are bequeathed to the system for the remainder of the ablation season. Further developments, in a particular area of bed, such as repeated recovery and collapse of a distributed cavity system of drainage, will not influence sediment outwash once the initial sediment accumulation from winter has been removed, unless sufficient time elapses to permit build-up of debris between events.

The quantities of sediment evacuated during the subglacial hydrological events of 1983 and 1987 suggest that the dimensions of the areas of bed over which concerted hydraulic re-organization occurred were not insignificant. Sequences of events closely spaced in time point to a different partial area of bed undergoing development for the first time on each occasion. Continuous measurements of melt-water turbidity in the Gornera in late May and June 1979 also indicated the occurrence of a series of subglacial hydrological events (Collins, 1988). The pulses of 10 July 1983 and 30 June 1987, beneath Gornergletscher, at mid-range discharges during respective periods of several days with generally rising flows, are characteristic of early ablation-season events which may relate to conversion from linked cavity to conduit network.

Except at the beginning of spring, when almost all of the channels of the previous summer over the entire sub-sole will have been closed through ice deformation, different partial areas of bed can be expected to be traversed by different styles of basal drainage network. This may explain the absence of diurnal surface-velocity variations during a short period of observations at Gornergletscher early in an ablation season (Iken, 1978). Sediment-flux evidence for existence and persistence of a few major conduits throughout the length of Gornergletscher in the later ablation season, after the event with the highest discharge of the summer, remains ambiguous.

SUBGLACIAL HYDROLOGICAL EVENTS AND SEDIMENT FLUX

Relationships between discharge and suspended sediment load in portal melt waters are made complex by the occurrence of subglacial hydrological events. High-pressure events in basal passages are themselves unrelated to discharge, although, with the exception of the drainage of the Gornersee, such events tend to occur during periods with generally increasing flow. Levels of discharge which exceed previous flows of the season do not always have an impact on sediment flux. There is no relationship between the quantity of sediment evacuated during an event and discharge magnitude. The impact of a subglacial hydrological event is related to timing of occurrence and position in the seasonal series, and presumably also to the area of sub-sole involved.

A comparison of the impacts of the five major subglacial events on sediment flux in 1987 is given in Table I. Each event accounted for between 3.18 and 8.80% of the total measured sediment yield from Gornergletscher in that year. These proportions are substantially lower than those reported (during rainstorms only) in other glacierized basins. For example, 60% of the total suspended sediment transport from the basin of Decade Glacier, Baffin Island (68% glacierized, 12.8 km^2 area) in the period 11 June–19 August 1965 occurred in one day during rainfall (Østrem and others, 1967), and proportions of between 15 and 20% of annual load have been observed in Norway (Østrem, 1975). In the Alps, the summer of 1987 was particularly stormy; rain on 24–25 August produced run-off in excess of the 20 year flood in many rivers with long records in Kanton Wallis (Bundesamt für Umweltschutz, 1988). The highest daily total sediment yield from Gornergletscher during the measurement period occurred on 24 August. The comparatively low percentages of the annual sediment load

TABLE I. PERCENTAGES OF THE SEASON TOTAL OF SEDIMENT YIELD FROM GORNERGLETSCHER ASSOCIATED WITH PRINCIPAL SUBGLACIAL HYDROLOGICAL EVENTS IN 1987

Date	Type of event	Maximum sediment concentration	Sediment load as percentage of total sediment yield
		g l^{-1}	%
30 June	Spring	15.430	4.18
17–18 July	Storm	10.567	8.76
2–4 August	Gornersee drainage	4.832	8.41
18 August	Storm	3.924	3.18
24–25 August	Storm	4.538	8.80

https://doi.org/10.3189/S026030550000762X Published online by Cambridge University Press

transported by the individual events at Gornergletscher may relate to area-by-area integration of the bed with the drainage system, or suggest greater sediment availability to flow at lower discharges. There appears to be little difference in frequency of rainfall events between the observed basins. Varying types of drainage systems beneath glaciers (conduits, linked-cavities, and mixed) and differing forms of bed (solid rock, deformable sediments, or a mixture) might be expected to reveal contrasting temporal patterns of sediment flux.

CONCLUSION

Patterns of suspended sediment flux during ablation seasons provide an indirect insight into the evolution of the subglacial drainage system. Some of the inferences are positive, whereas interpretations of others remain ambiguous. There are sudden perturbations in the spatial stability of subglacial drainage systems which result in sediment-delivery events. These subglacial hydrological events tend to occur during periods of increasing flow, and are more easily discerned during the first part of the melt season, before the maximum discharge of the summer. The events indicate that melt water spreads out over the glacier bed at times of increasing water pressure, and suggest that diffuse flow in linked cavities probably occurs over wide areas of sub-sole, particularly at the start of the melt season. Substantial partial areas of the basal drainage system undergo concerted re-organization during events, which persist for one or several days. Whether this corresponds to collapse of a linked cavity to a major conduit system and whether the changed network structure persists subsequently are unclear. Sequences of events during the early season indicate successive integration of partial areas of sub-sole with flow. Spring events, rain-induced floods, subglacial blocking events, and outbursts from ice-dammed lakes have been identified as hydrological events which influence sediment flux and evolution of the basal drainage network. Each year, together with the seasonal pattern of discharge, the timing, magnitude, and order of events influence the seasonal variation of suspended sediment flux, which culminates in a period with low-level, low-variability transport.

This interpretation of total daily sediment flux in terms of development of the subglacial drainage network has implications for the understanding and modelling of the continuously changing relationship between sediment concentration in melt waters and discharge from glacier portals. Investigation of diurnal variations in that relationship should also provide more detailed information about the nature of subglacial hydrological events. While measurement of sediment flux in melt waters can provide much information about interactions of the subglacial drainage system with glacier sub-sole, combined observations of these variables together with water-level variations in bore holes, short-term fluctuations of glacier sliding, and other water-quality indicators would usefully identify which basal areas are involved in particular events, and would provide more detail of the nature and behaviour of basal hydrological networks.

ACKNOWLEDGEMENTS

The author wishes to acknowledge the assistance of A. Bezinge, H. Kronig, and J-P. Perreten, Grande Dixence S.A., for logistical support and for supplying records of the discharge of the Gornera and of precipitation at Findelengletscher. Members of the University of Manchester Alpine Glacier Project assisted with collection of the samples. Grant support was received in 1983 from the U.K. Natural Environment Research Council (GR3/4787) and in 1987 from the Royal Society.

REFERENCES

Bundesamt für Umweltschutz. 1988. Hochwasserereignisse im Jahre 1987 in der Schweiz. *Mitt. Landeshydrol. -geol.*, **10**.

Collins, D.N. 1979. Sediment concentration in melt waters as an indicator of erosion processes beneath an Alpine glacier. *J. Glaciol.*, **23**(89), 247-257.

Collins, D.N. 1986. Characteristics of meltwaters draining from the portal of an Alpine glacier during the emptying of a marginal ice-dammed lake. *Mater. Glyatsiol. Issled. Khron. Obsuzhdeniya*, 58, 224-232.

Collins, D.N. 1988. Suspended sediment and solute delivery to meltwaters beneath an Alpine glacier. *Eidg. Tech. Hochschule, Zürich. Versuchsanst. Wasserbau, Hydrol. Glaziol. Mitt.*, 94, 147-161.

Humphrey, N., C.F. Raymond, and W.D. Harrison. 1986. Discharges of turbid water during mini-surges of Variegated Glacier, Alaska, U.S.A. *J. Glaciol.*, **32**(111), 195-207.

Iken, A. 1978. Variations of surface velocities of some Alpine glaciers measured at intervals of a few hours. Comparison with Arctic glaciers. *Z. Gletscherkd. Glazialgeol.*, **13**(1-2), 1977, 23-35.

Iken, A. and R.A. Bindschadler. 1986. Combined measurements of subglacial water pressure and surface velocity of Findelengletscher, Switzerland: conclusions about drainage system and sliding mechanism. *J. Glaciol.*, **32**(110), 101-119.

Iken, A., H. Röthlisberger, A. Flotron, and W. Haeberli. 1983. The uplift of Unteraargletscher at the beginning of the melt season — a consequence of water storage at the bed? *J. Glaciol.*, **29**(101), 28-47.

Kamb, B. 1987. Glacier surge mechanism based on linked cavity configuration of the basal water conduit system. *J. Geophys. Res.*, **92**(B9), 9083-9100.

Kamb, B., *and 7 others*. 1985. Glacier surge mechanism: 1982–1983 surge of Variegated Glacier, Alaska. *Science*, 227(4686), 469-479.

Østrem, G. 1975. Sediment transport in glacial meltwater streams. *In* Jopling, A.V. and B.C. McDonald, *eds. Glaciofluvial and glaciolacustrine sedimentation*. Tulsa, OK, Society of Economic Paleontologists and Mineralogists, 101-122. (Special Publication 23.)

Østrem, G., C.W. Bridge, and W.F. Rannie. 1967. Glacio-hydrology, discharge and sediment transport in the Decade Glacier area, Baffin Island, N.W.T. *Geogr. Ann.*, **49A**(2-4), 268-282.

Röthlisberger, H. 1972. Water pressure in intra- and subglacial channels. *J. Glaciol.*, **11**(62), 177-203.

Röthlisberger, H. 1980. Gletscherbewegung und Wasserabfluss. *Wasser, Energie, Luft*, **72**(9), 290-294.

Röthlisberger, H. and H. Lang. 1987. Glacial hydrology. *In* Gurnell, A.M. and M.J. Clark, *eds. Glacio-fluvial sediment transfer; an alpine perspective*. Chichester, etc., John Wiley and Sons, 207-284.

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