Long-term close-interval monitoring of suspended sediment transport in meltwaters draining from an Alpine glacier

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BACKGROUND

Suspended sediment concentrations and fluxes in meltwater rivers draining from mountain glacierised basins vary considerably at a range of temporal scales, from hour to hour, day to day, month to month during the annual cycle of runoff, and from year to year. These variations are influenced both by changing hydrometeorological and climatic conditions, and by interactions between evolving characteristics of the subglacial drainage network and the glacier bed. Irregularity of sediment flux through time results from residual winter flow through remaining small pathways having inadequate velocity to entrain even fine sediment. Rising discharge in spring and early summer transports disproportionately large quantities of sediment by comparison with higher flows later in the ablation season (e.g. Østrem 1975, Collins 1990). This seasonal pattern of sediment flux is punctuated, particularly in the earlier part of the season, by pulses lasting for hours through several days, as rising discharge, initial increased water pressure in subglacial hydrological pathways and concomitant glacier motion develop subglacial drainage pathways. Evolution of the drainage network beneath a glacier each year follows the timing, quantity and seasonal pattern of discharge, which in turn reflect climatic conditions. Winter snow accumulation interacts with summer energy conditions for melt to generate the seasonal discharge cycle. Measurements of sediment content of meltwaters, together with discharge, have to be sufficiently closely spaced in time to capture pulses which provide glaciologically-relevant information about sudden changes in, and seasonal development and evolution of the subglacial drainage network, as well as indicating seasonal and year-to-year variations in suspended sediment flux associated with climatic variation at the scale of tens of years.

MEASUREMENT PROGRAMME AT GORNERGLETSCHER

Samples of meltwater and suspended sediment have been collected from the Gornera, the only river draining from Gornergletscher, Pennine Alps, Switzerland, at the gauging station located ~750 m from the glacier portal, every hour, 24 h d^{-1}, from as early in the ablation season as practicable until mid-September, every year for 28 years, since 1974. Initially, this close-interval sampling programme was designed with a view to determining sediment concentration-discharge dynamics in order to provide information on subglacial processes and conditions. The measurements have continued, providing estimates of sediment concentration and flux in the Gornera from year to year through almost three decades. In that period, mean summer air temperature at Grächen, about 20km north of the basin, increased by 1.7ºC, and annual total discharge of the Gornera varied in the range -40 % to +30 % of the period mean, being generally lower in the 1970s than subsequently (Collins *et al.* (in press)).

Since 1983, a Manning S-4050 automatic pumping sampler has been programmed to draw up samples of meltwater and suspended sediment. The samples have been collected from the same position in the cross section with the orifice at the same fixed height above the base of the gauging structure. Until 1982, samples were collected using a mechanical North Hants Engineering Company Mark 4 automatic liquid sampler, which was initially located about 400 m upstream of the gauge, with the aim of collecting samples as close as practicable to the glacier terminus. Subsequently the sampler was repositioned on the gauging structure, with the sampler hose intake nozzle at the same position as that subsequently occupied by the Manning sampler. All samples were filtered under pressure or vacuum through individually pre-weighed Whatman No. 1 papers and the quantity of sediment retained determined gravimetrically. 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}), and daily total suspended sediment load was calculated from the 24 hourly suspended sediment flux values. The aims of this paper are to examine characteristics of the dataset assembled for the Gornera with respect to long term homogeneity, and to compare estimates of sediment concentration obtained from samples collected by Manning and North Hants instruments.

LONG-TERM SUSPENDED SEDIMENT FLUX DATA

Examples of suspended sediment data collected for the Gornera, resolved as daily total sediment fluxes, are shown in Fig. 1 for the five years 1990 through 1994. Salient features of the annual pattern of suspended sediment flux result from the interaction of the developing glacier drainage system with glacially-abraded sediment stored beneath the glacier sole.

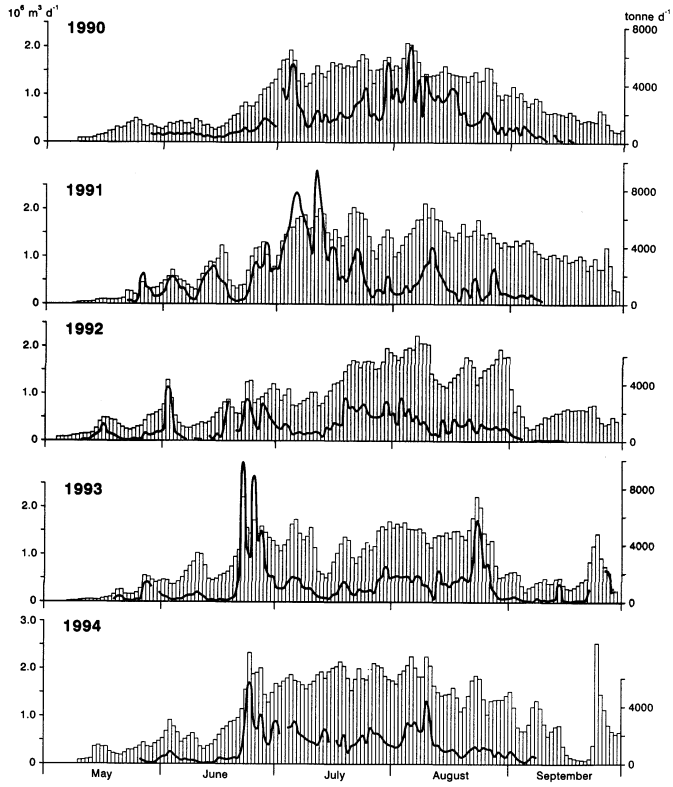

Fig. 1 Daily total discharge (columns) and daily total suspended sediment flux (curves) in the Gornera, in the months May-September in the years 1990 through 1994.

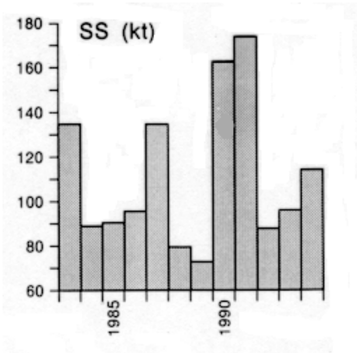

Fig. 2 Suspended sediment flux (SS) in the Gornera between 27 June and 11 September for the years 1983 through 1994.

Major instabilities in the subglacial drainage network are indicated when sediment flux rises for a few days above the background level for a particular part of a season. Almost all the major sediment flux events occurred during times of generally rising discharge, and were more frequent and often larger at the start of summer. Later in the season, flux events were usually associated with rainfall events. Significant flux events occurred each time discharge exceeded levels not previously reached for some time, as meltwater penetrated areas of glacier bed formerly hydraulically isolated, on which sediment remained stored (Collins 1996). Interpolating for missing data, considerable variation occurred from year to year in total suspended sediment flux in the Gornera for the period 27 June through 11 September each year (Fig. 2).

Mean annual suspended sediment flux for the period was 117 kt (1.427 kt km^{-2} yr^{-1}), and the range –35% to +45% of the mean. There appears to be no simple relationship with annual discharge and climatic conditions. In the years illustrated, 1994 had the largest annual

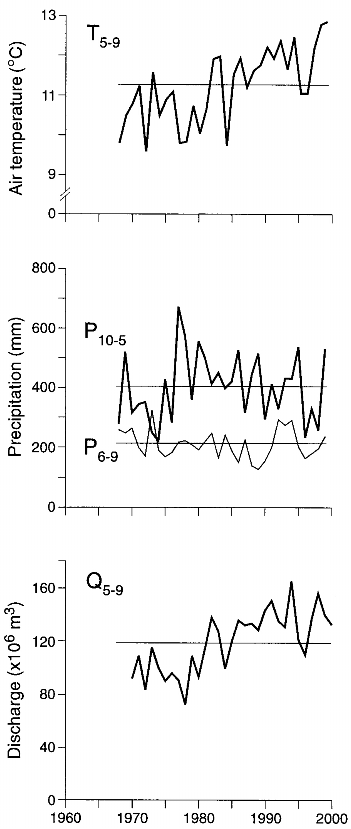

Fig. 3 Year to year variations of T_{5-9}, P_{10-5}, P_{6-9} and (Q_{5-9}), 1970 – 1999.

discharge in the period 1970-2001 (but was only the third warmest summer), 1991 and 1990 third and fourth, respectively, and 1989 thirteenth. Variations in mean summer air temperature (T_{5-9}) and winter (P_{10-5}) and summer (P_{6-9}) precipitation at Grächen, and total summer runoff in the Gornera (Q_{5-9}), between 1970 and 1999 are shown in Fig 3.

DATA HOMOGENEITY

Samples from which suspended sediment concentration data for the Gornera have been derived were collected by a Manning pumping sampler operating under standard conditions since 1983. The samples collected, of between 150 and 230 ml, are unlikely to be representative of sediment concentration throughout the cross section. With the intake a fixed distance from the bed, samples are collected at varying fractional depths of changing water surface levels in the gauging structure. Hence, sampled sediment concentrations between warmer years, with higher discharge, and cooler are likely to be influenced by nozzle position. Experiments to compare sampled suspended sediment with nozzles suspended at a fixed depth and a depth varying with water surface level fluctuations have been undertaken.

Before 1983, and without an overlap period with the Manning sampler, a vacuum North Hants sampler was used for 9 ablation seasons. An experiment to compare suspended sediment concentration obtained by simultaneous collection by the two instruments from the same depth throughout a range of discharge levels has been undertaken, with a view to assessing relative sampling efficiency. Aliquots of between 450 and 750 ml of meltwater and sediment were collected by the North Hants sampler, fired in a parallel hourly sampling programme alongside the Manning.

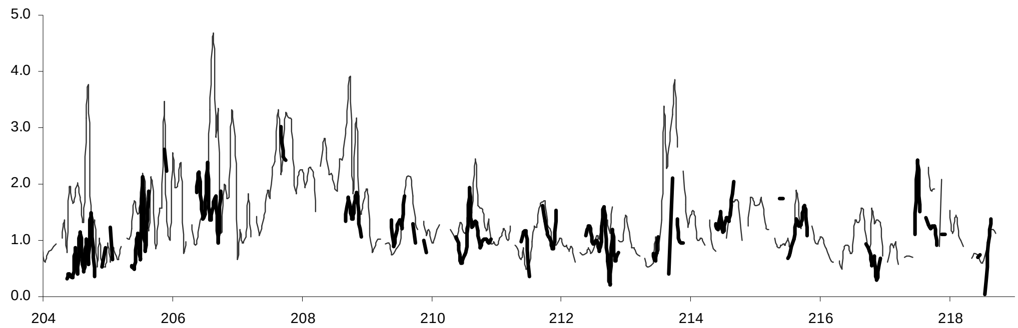

Fig. 4 Sediment concentration (g l^{-1}) in simultaneous pairs of samples collected from the Gornera by Manning pumping sampler (thin) and North Hants (thick) during 15 days from 23 July to 6 August.

The North Hants sampler appears to collect samples which generally imply lower suspended sediment concentrations in the Gornera than those drawn up simultaneously by the Manning. At times when sediment concentration in the Gornera is relatively low, however, the North Hants can outperform. A plot of the pairs of sediment concentration estimates obtained from the two samplers indicates poor association, the correlation coefficient being 0.33 (Fig. 5). Intra-sampler variability is great, and individual pairs of estimates can differ 4 fold. Sediment pulses are identifiable using both samplers. Estimation of suspended sediment flux is more problematic. However, comparison of estimates of sediment concentration provided by replicate samples collected by the Manning sampler (actually not

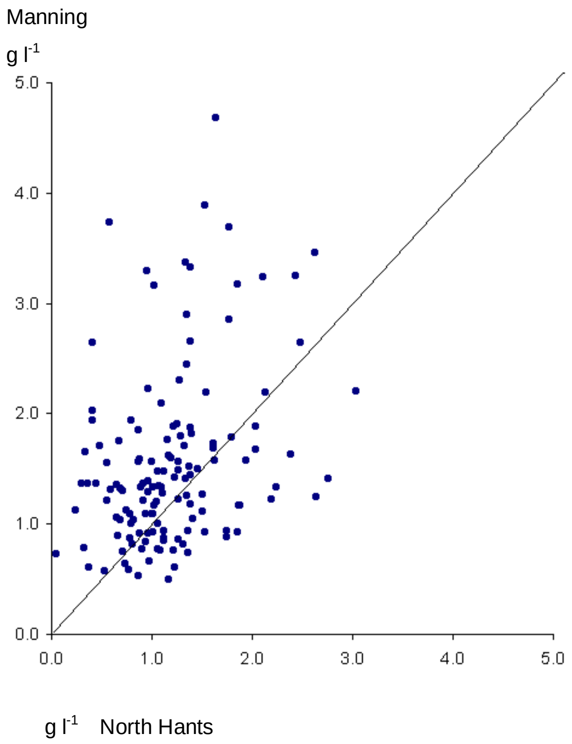

Fig. 5 Plot of paired estimates of suspended sediment concentration obtained from Manning and North Hants samplers. The diagonal line indicates equal estimates from both samplers.

simultaneously but over three minutes at xx.59 h, xx+1.00 h and xx+1.01 h for logistical reasons) suggest precision may be low. Analyses are presented of how precision and intra-sampler variation are influenced by discharge.

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