Sediment Dynamics for a Changing Future (Proceedings of the ICCE symposium held at Warsaw University of Life Sciences - SGGW, Poland, 14–18 June 2010). IAHS Publ. 337, 2010.

Sediment dynamics of glacier-fed rivers

JIM BOGEN

Norwegian Water Resources and Energy Directorate, PO Box 5091, Maj. 0301 Oslo, Norway

jbo@nve.no

Abstract The sediment dynamics of glacier-fed rivers differ from those of unglaciated catchments. Monitoring programmes in glacier-fed rivers demonstrate that their sediment dynamics have several distinctive characteristics, which are the focus of this paper. In the meltwater outflow from the Nigardsbreen glacier in Norway the seasonal variations in sediment response may be divided into three different periods. Sediment concentrations vary unpredictably in the first part of the runoff season. During the summer peak of glacier melting there is some dependency on water discharge, but observations show no obvious direct correlation that persists beyond a single flood event. During the period of autumn rainfall, the magnitude of the sediment concentration is controlled by the access of the runoff to the subglacial drainage system. High sediment concentrations may occur at the start of this period, but concentrations tend to fall as the subglacial conduits close. The pattern of variability of sediment concentrations may be interpreted in terms of a conceptual model, where sediment is introduced into the subglacial waterways by melting of debris-rich ice at the glacier sole. It is believed that the irregular fluctuations of sediment concentrations early in the season are associated with the establishment of a subglacial conduit system. Later in the season, flood discharges expand the conduits, melting ice and adding sediment to the meltwater. In periods of low water discharge, less sediment is added, but movement of the glacier and its plastic deformation will eventually expose more sediment-laden ice to melt-out processes. High concentrations most often occur towards the end of the glacier-melt period when floods are generated by a combination of rain and glacier melt. These rain floods drain through an open conduit system, melting out further sediment. The sediment transport from the polythermal Brøggerbreen glacier in the high Arctic was also studied. It was found that the low deformation rates in the cold ice of the subglacial drainage systems beneath polythermal glaciers make them more stable. Therefore a stronger correlation between sediment transport and water discharge may exist on an annual basis.

Key words suspended sediment; sediment dynamics; glacier fed rivers; subglacial drainage

INTRODUCTION

The sediment dynamics of glacier fed rivers differ from those of unglaciated catchments. A large proportion of the sediment transported by glacier meltwater rivers originates from subglacial processes and is delivered by subglacial drainage systems. Many authors have reported high variability of suspended sediment concentrations in glacier fed rivers, on both short-term and seasonal scales. This variability has been related to changes in the availability of sediment (Østrem, 1975), exhaustion effects (Gurnell *et al.*, 1994) or release of sediments from basal storage (Collins, 1989). Singh *et al.* (2003) documented a high erosion rate for the Dokraini glacier in the Himalayas, but found a very poor correlation between sediment concentration and water discharge. For the Midtdalsbreen glacier in Norway, Willis *et al.* (1995) found that the occurrence of major pulses of suspended sediment correlated with periods of enhanced glacier motion. Evidence was also found that the subglacial hydrological system evolved over the summer from a distributed to a more channelized configuration.

The purpose of this paper is to discuss observations of the sediment dynamics of glacier fed rivers in Norway, including Svalbard in the high Arctic, in relation to the development of subglacial hydrological systems in the glaciers. The sediment flux in Norwegian glacier-fed rivers is to a large extent controlled by sediment availability, which varies with the type of glacier and the temperature regime.

Sediment delivery from glaciers by meltwater is one component of the glacial sediment delivery system. The glacial erosion subsystem is controlled by glacial quarrying and abrasion processes, which are in turn influenced by bedrock properties and glaciological variables. These processes regulate the amount of sediment contained in the ice at the glacier sole over the scale of centuries. The glacier meltwater and the subglacial waterways constitute the second component of the sediment delivery subsystem. The rate of melting and the water discharge in the sub-glacial conduits control the annual sediment delivery to the glacier meltwater rivers. The subglacial drainage system is dynamic and will adjust to the amount of meltwater being produced. The melt-out of sediment is thus controlled by meteorological parameters and the sediment flux may vary during short time intervals and from year to year (Bogen, 1996).

THE STUDY

Sediment transport processes in various parts of Norway have been studied by sediment monitoring programmes operated by the Norwegian Water Resources and Energy Directorate. These programmes are based on high frequency sampling and laboratory analyses as described by Bogen (1996) and Bogen & Bønsnes (2003). ISCO automatic pumping samplers were installed in highly turbulent river reaches to ensure full mixing at the sampler intake. Samples were collected 2–4 times a day, throughout the runoff season. Water stage was recorded by data loggers and converted to water discharge by establishing stage–discharge rating curves for reaches with stable beds. Water discharge measurements were most often carried out by salt dilution techniques. The record of water discharge is derived using the stage–discharge relationship and the continuous record of water stage. Water samples are filtered through Whatman GF/C filters and the concentration of organic and inorganic particulate matter is determined by repeated weighing and by ignition at 500°C for 2 h.

The data selected for this study were collected in the meltwater streams draining from the Nigardsbreen glacier in southwestern Norway and from the Bayelva River, which drains from the Brøggerbreen glaciers in Svalbard in the high Arctic. The Nigardsbreen is a temperate glacier in southwestern Norway covering an area of 48 km^2 and is an outlet from the Jostedalsbre icecap. (Fig. 1). The Brøggerbreen glaciers cover an area of 22 km^2. They are classified as polythermal glaciers as large parts of the ice have a temperature below 0°C and the frontal parts are frozen to the bed. The mean annual sediment yields of the Nigardsbreen and Brøggerbreen glaciers are estimated to be 210 t km^{-2} year and 486 t km^{-2} year, respectively.

The data sets available for glacier meltwater rivers are often limited to short periods. The glaciers discussed in this paper have, however, been monitored over several decades, although only selected years have been included in this analysis.

SEASONAL VARIATION IN SEDIMENT TRANSPORT

Runoff and sediment concentrations in the study rivers are subject to large fluctuations throughout the year. Some selected years may be used as examples to illustrate the pattern of variation shown by the meltwater draining from the Nigardsbreen glacier. Seasonal variations in air temperature and precipitation are plotted along with those of suspended sediment concentration and water discharge for the year 2007 in Fig. 2(a) and (b). On the basis of the meteorological record, several periods with different runoff conditions may be recognised; these comprise the early snowmelt period in May, the glacier melt from May–June to early September, and the period of autumn rain. During the snowmelt period, sediment concentrations are low, often less than 20 mg L^{-1}. During the period extending from 29 May to 14 June in 2007 the sediment concentrations varied in a somewhat irregular manner and concentrations were high, even during low water discharges. The highest concentration of the whole ablation season in 2007 was recorded during this period. On 11 June a sediment concentration of 569 mg L^{-1} was observed. The water discharge during this event culminated at 19 m^3 s^{-1}, a relatively moderate magnitude. The discharge rise was due to snow and glacier melt only, and no rain was recorded.

During the following period, extending from the end of June until mid-August, the high air temperature caused the rate of snowmelt to increase. The peak water discharge of 40 m^3 s^{-1} that occurred on the 8 July was caused by a combination of snowmelt and rain. Diurnal water discharge fluctuations were seen during the whole period. Sediment concentrations fluctuated around a mean value of 80–100 mg L^{-1}. From the middle of August several rain flood events occurred. The

Fig. 1 The Nigardsbreen glacier front with the sediment transport monitoring stations. During the glacier advance of 1999–2006 the glacier meltwater channels split up into several channels and two monitoring stations were established (black circles). Photograph by H. Elvehøy.

sediment concentrations of these rain flood events were relatively high, ranging from 330 mg L^{-1} on the 7 September to 510 mg L^{-1} on the 25 September. The highest water discharge during the melt season in 2007 (62 m^3 s^{-1}) occurred on the 15 August and originated from a combination of snow-melt and rain. The maximum concentration recorded during this flood was 481 mg L^{-1}. In September, the air temperature fell and the rain floods were smaller, because of the reduced contribution from melting. A pronounced hysteresis effect was seen during the rain floods, as the sediment concentrations were considerably higher on the rising limb of the flood than on the falling limb.

In 1990, the early period of high concentrations was less pronounced (Fig. 3). Suspended sediment concentrations did not rise above 200 mg L^{-1} before the end of June. During the remainder of the summer season, the concentrations remained low for most of the time and stayed below 100 mg L^{-1}, even for relatively high water discharges exceeding 30 m^3 s^{-1}. However, the highest water discharge occurred on the 31 August and this flood event caused the sediment concentration to rise to 846 mg L^{-1}. After the culmination of this flood, the sediment concentration decreased to a low level. The water discharge also decreased as the air temperature reduced during the remaining part of September.

Sediment concentrations in the Bayelva River are much higher than those recorded in Nigardsbreelv. During the melt season of 1999, concentrations above 1000 mg L^{-1} occurred during several flood events and values in excess of 2000 mg L^{-1} were measured during flood events occurring between the end of August and the beginning of September (Fig. 4). Sediment concentrations in the Bayelva River are also better correlated to water discharge than in the Nigardsbreelv, although a high concentration was recorded during the first melt period in June, without a corresponding rise in water discharge. However, such situations do not occur frequently during the period of record for the Bayelva River.

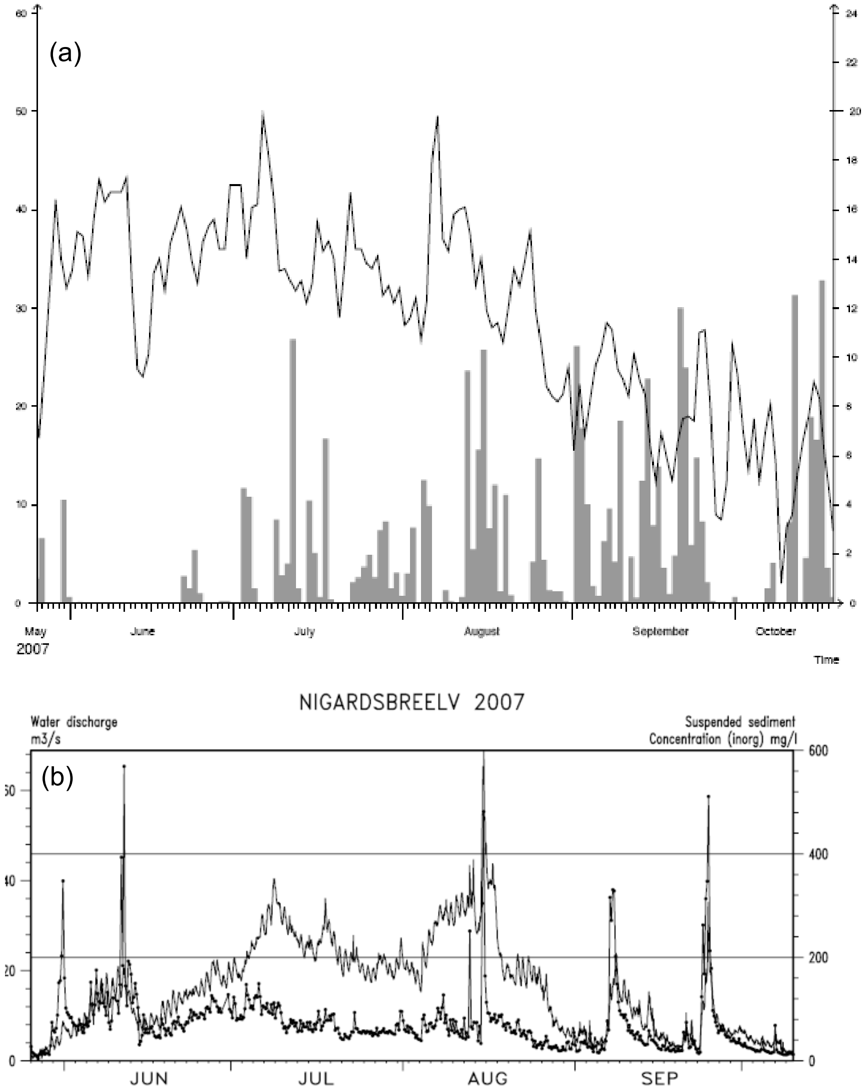

Fig. 2 (a) Air temperature (line) and precipitation (columns) measured at a meterological station (Fjærland) near the Nigardsbreen glacier. (b) Sediment transport and water discharge in the meltwater river from the Nigardsbreen during 2007.

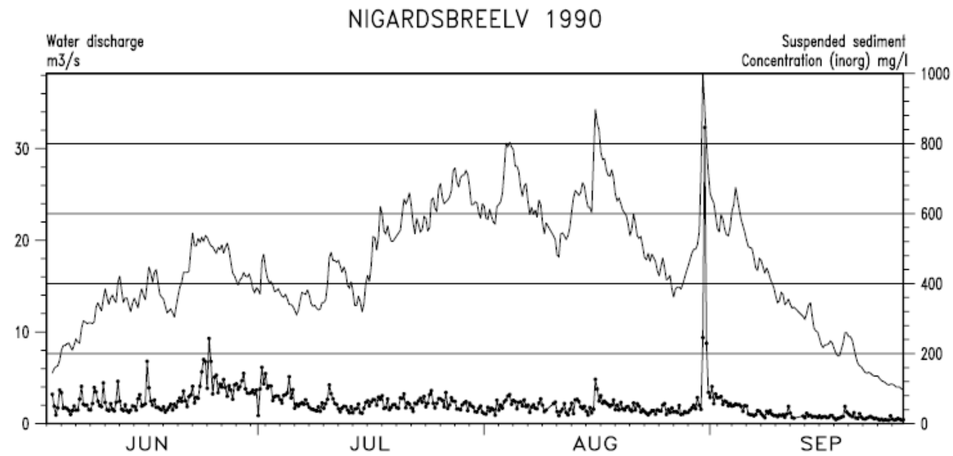

Fig. 3 Sediment transport and water discharge in the meltwater river from the Nigardsbreen during 1990.

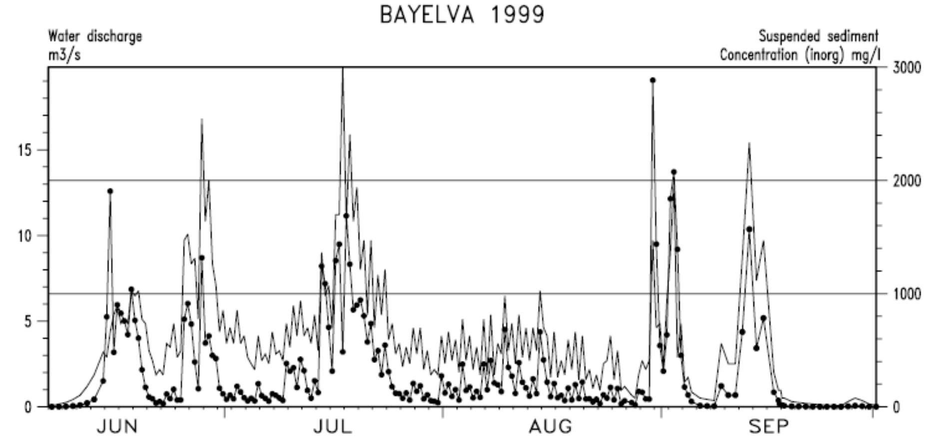

Fig. 4 Sediment transport and water discharge in the Bayelva, the meltwater river draining from the Brøggerbreen glaciers, during 1999.

THE DRAINAGE SYSTEM IN TEMPERATE AND POLYTHERMAL GLACIERS

Rainwater and meltwater from the surface of the glacier may percolate into the glacier through the snow and firn in an arborescent network of passages leading down through the glacier ice (Hooke, 1989). In temperate glaciers, a fraction of this water flows through pores that form at the intersection of ice grains and the rest flows to the bed as concentrated flow through moulins. Water at the bed can flow in tunnels or linked cavities. The subglacial drainage is likely to comprise a tortuous system of linked cavities intersected by larger and comparatively straight conduits. The average flow direction in the combined system is controlled by a combination of ice overburden pressure and bed topography (Røthlisberger, 1972; Lafountain, 1998). The drainage system is dynamic and will adjust to the amount of meltwater being produced.

The pattern of temporal variability of sediment transport in glacier fed rivers may be explained in terms of a model where sediment is supplied to the subglacial waterways by the melting of debris-rich ice at the glacier sole (Bogen, 1996). The rate of deformation of the conduits depends on the difference between the ice overburden pressure and the internal water pressure. Due to variations in glacier melting and precipitation, water discharge in the subglacial conduits is subject to changes throughout the season. During periods of low water discharge, the movement of the glacier and the plastic deformation will deform the conduits. Any subsequent expansion due to an increase in water pressure will melt more ice and add more sediment to the subglacial system.

The irregular fluctuations in sediment concentration observed in the meltwater draining from the Nigardsbreen glacier in the early period of 2007 probably reflect the establishment of a new subglacial drainage system. When the air temperature rises above zero degrees in the firn layers of the glacier, water will start to percolate down and open up the subglacial drainage system. During the winter, the conduits and cavities are closed or nearly closed. The deformation process may make more sediment available, and when the water seeps through the cavities at the glacier bed, substantial amounts of sediment may be exposed to erosion. The movement of the glacier during the winter may have brought new sediment into the area of the subglacial drainage system. Thus, during the early season, a large amount of sediment is available for mobilisation.

In some years the period characterized by irregular fluctuations in sediment concentration is short or missing as illustrated by the data from the ablation season in 1990. It is very likely that the reason for this is that water has been draining beneath the glacier over the whole winter and has kept a conduit open. The cavities and conduits of the subglacial drainage system may have remained open during the winter in such years. A large flood occurred late in the season of the preceding year. Such a flood may have expanded the subglacial drainage system and possibly re-opened conduits that had not closed completely.

The highest floods of the season are most often associated with a high sediment concentration, because the expanding tunnels are able to access more sediment. In 1990 it is apparent that the water discharge had to exceed that associated with preceding discharge events, in order to access more material. As illustrated by the late floods in 2007, the glacier movement caused new material to be exposed to erosion. As the cavities are open, the rainwater may drain down into open tunnels and access sediment. If the cavities are closed, water may drain across the surface of the glacier and not make contact with sediment.

The surface meltwater of polythermal glaciers may freeze when it reaches the cold layers in the firn. In these glaciers there may therefore not always be a connection between the meltwater on the surface and the subglacial drainage system. On the other hand, cavities and channels that exist in the ice may persist for a longer time due to the limited movement of this type of glacier.

DEFORMATION RATE OF THE DRAINAGE SYSTEM

A calculation of the deformation rate of the subglacial conduits was carried out by Bogen & Bønsnes (2003). The calculation was based on the version of Glen's flow law given by Nye (1953) and Rothlisberger (1972). The contraction rate of a subglacial tunnel in a steady state is:

$$\frac{\dot{r}}{r} = A\left(\frac{P-p}{n}\right)^{n} \tag{1}$$

For simplicity the subglacial tunnel is assumed to be straight and have a circular cross section of radius r. The change in radius per time unit is denoted as $\dot{r}$; A and n are the flow parameters of Glens law, P is the ice overburden pressure, and p is the water pressure. It is evident from this equation that the closure rate increases with glacier thickness. Paterson (1994) gave a value of 6.8 $\times 10^{-15}$ for temperate ice. As an example of closure rates of temperate glaciers, a tunnel with a diameter of 3 m beneath a glacier with a thickness of 150 m will close completely in 6 months. This means that when the water pressure falls at the end of the season the subglacial drainage system will close during the winter months and be re-established the following year. Often there is also a seasonal change in the subglacial drainage system due to deformation of tunnels. The relationship between sediment transport and water discharge may thus be subject to continuous change through the season and from year to year, as described for the Erdalsbreen glacier by Bogen (1995). As with the Nigardsbreen glacier, there were significant correlations between sediment concentration and discharge only during some years. It is very probable that these were years when there were moderate seasonal changes in the subglacial drainage system.

In the meltwater river draining from Øvre Beiarbre, significant correlations were found for two individual years, but an analysis of the combined data for both years resulted in a lower coefficient of correlation, indicating two different populations. This phenomenon was probably due to a shift in sediment sources, possibly caused by a change in the position of the subglacial conduits (Bogen, 1996).

To examine the properties of the subglacial drainage systems in polythermal glaciers it is important to note that the constant A in equation (1) decreases with temperature. Paterson (1994) gives a value of 1.7×10^{-17} for cold ice at –20°C. Subject to the same glacier thickness of 150 m, a closure rate of 0.2 m year^{-1} for the same type of tunnel was calculated by Bogen & Bønsnes (2003). This means that tunnels in cold ice are more stable and may stay open throughout several years. In the Bayelva, the meltwater river from the polythermal Brøggerbreen on Svalbard, significant correlations between water discharge and sediment concentration were found. This was attributed to the existence of a stable system of subglacial tunnels (Repp, 1988; Bogen & Bønsnes, 2003).

A comparison of the sediment rating curve for the Bayelva River in 1999 with the same type of relation for the Nigardsbreen in 1989 is given in Fig. 5(a) and (b). There is a significant correlation between concentration and discharge for the Bayelva River, but apparently no correlation for the Nigardsbreelva during that year.

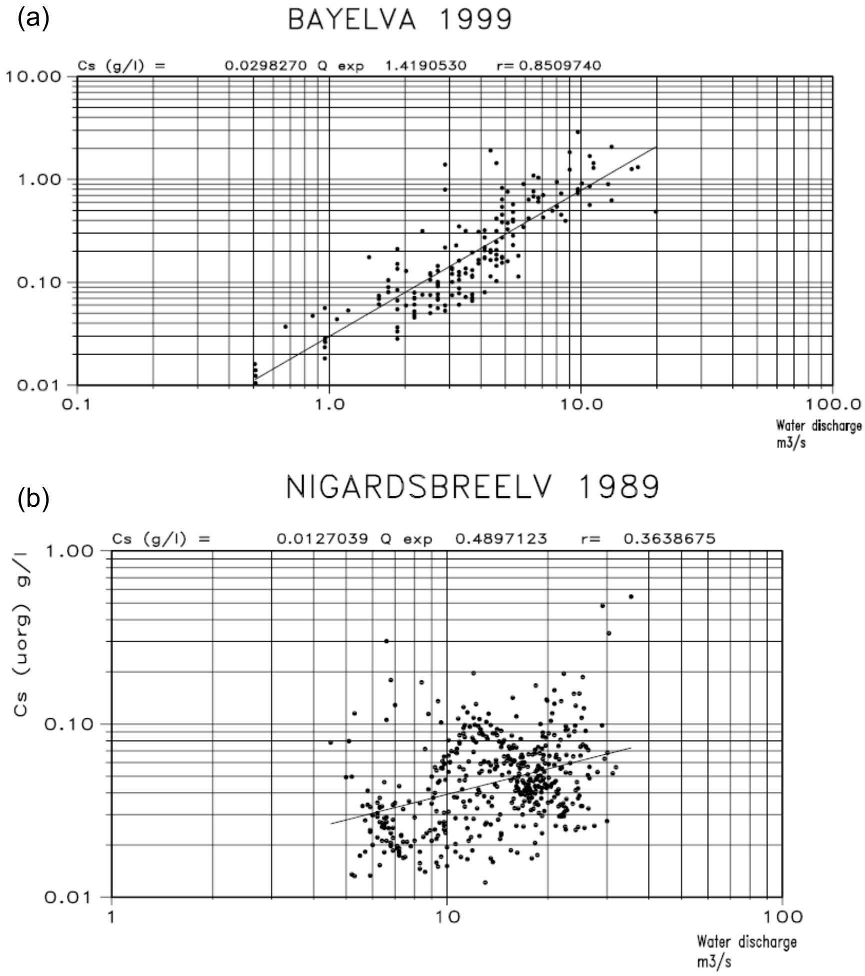

Fig. 5 (a) The relationship between sediment transport and water discharge for the Bayelva in 1999. (b) The same type of relationship for the Nigardsbreelva in 1989.

CONCLUSIONS

The dynamics of sediment transport in glacier fed rivers are to a large extent controlled by the establishment and seasonal development of subglacial drainage systems. Sediment is introduced into the subglacial waterways by melting of debris-rich ice at the base of the glacier during flash flood events. During periods of low water discharge, less sediment is added but movement of the glacier and its plastic deformation will eventually expose more sediment to melt-out processes. Three different periods of sediment transport may be recognised. During the early season extending from late May to the end of July, the subglacial drainage system is established. This period is characterised by high sediment concentrations fluctuating in an irregular manner, most often during relatively low water discharges. The second period extends from July to around mid-August. During this period, water is supplied by primarily by glacier melt and to some extent by a combination of rain and glacier melt. The highest sediment concentrations are associated with such flood events. During the third period, glacier melt contributes an increasingly smaller component of the water discharge. When the water pressure falls because of falling air temperature, the conduits tend to close. Runoff is dominated by rain floods and the magnitude of sediment concentrations is determined by its access to the subglacial drainage system. If the subglacial drainage system has been kept open during the winter, the period of high sediment concentrations may be less pronounced. The continuous deformation of the subglacial conduits in temperate ice limits the establishment of sediment rating curves valid for periods longer than individual events.

Because of the low deformation rates in cold ice, the subglacial drainage beneath polythermal glaciers is more stable and sediment rating curves may remain stable on an annual basis.

REFERENCES

Bogen, J. (1995) Sediment transport and deposition in mountain rivers. In: *Sediment and Water Quality in River Catchments* (ed. by I. D. L. Foster, A. M. Gurnell & B. W. Webb), 437–451. John Wiley & Sons, Chichester, UK.

Bogen, J. (1996) Erosion rates and sediment yield of glaciers. *Annals of Glaciol*. **22**, 48–52.

Bogen, J. (1996) Erosion and sediment yield in Norwegian rivers. In: *Erosion and Sediment Yield: Global and Regional Perspectives* (ed. by D. E. Walling & B. W. Webb) (Proc. Exeter Symp.), 73–84. IAHS Publ. 236. IAHS Press, Wallingford, UK.

Bogen, J. & Bønsnes, T. E. (2003) Erosion and sediment transport in high Arctic rivers, Svalbard. *Polar Res.* **22**, 175–189.

Fountain, A. & Walder, J. S. (1998) Water flow through glaciers. *Rev. Geophys*. **36**, 299–328.

Gurnell, A. M., Hodson, A. Clark, M. J., Bogen, J., Hagen, J. O. & Tranter, M. (1994) Water and sediment discharge from glacier basins: an Arctic and Alpine comparison. In: *Variability in Stream Erosion and Transport* (ed. by L. J. Olive *et al.*) (Proc. Canberra Symp.), 325–334. IAHS Publ. 224. IAHS Press, Wallingford, UK.

Hooke, R. LeB (1989) Englacial and subglacial hydrology: a qualitative review. *Arctic Alpine Res.* **21**, 221–223.

Nye, J. F. (1953) The flow law of ice from measurements in glacier tunnels, laboratory experiments and the Jungfrauhof borehole experiment. *Proc. R. Soc. Lond.*, Ser A **219**, 477–489.

Paterson, W. S. B. (1994) *The Physics of Glaciers*. Pergamon/Elsevier, New York, USA.

Repp, K. (1988) The hydrology of Bayelva, Spitsbergen. *Nordic Hydrol.* **19**, 259–268.

Røthlisberger, H. (1972) Water pressure in intra and subglacial channels. *J. Glaciol.* **11**, 177–203.

Singh, P., Ramasatri, K. S., Kumar,N. & Bhatnagar, N. K. (2003) Suspended sediment transport from the Dokriani Glacier in the Garhwal Himalayas. *Nordic Hydrol.* **34**, 221–244.