Erosion and sediment transport in High Arctic rivers, Svalbard

Jim Bogen & Truls E. Bønsnes

This paper discusses sediment yield, sediment delivery and processes of erosion in rivers subject to High Arctic conditions in Svalbard. Long-term measurements reveal large variations between rivers and from year to year in each individual river. In the unglacierized catchment of Londonelva, annual sediment transport varied between 28 and 93 t/yr, with a mean sediment yield of 82.5 t/km^2/yr. In the glacier-fed rivers Bayelva and Endalselva, the suspended sediment transport varied in the range of 5126 t/yr to 22 797 t/yr during a 12-year period. A mean of 11 104 t/yr gave rise to a mean sediment yield of 359 t/km^2/yr for the whole Bayelva catchment area. The sediment yield of the glacier and the moraine area was estimated at 586 t/km^2/yr. A conceptual model used to interpret the long- and short-term patterns of sediment concentration in the meltwater from the glacier and erosion of the neoglacial moraines is proposed. Evidence is found that a proportion of the sediments are delivered by a network of englacial and subglacial channels that exist even in cold ice. Regression analyses of water discharge versus suspended sediment concentration gave significant correlations found to be associated with the stability of ice tunnels in cold ice. Large floods have been found to flush the waterways and exhaust the sediment sources. A long-term change in the exponent of regression lines is attributed to changes in sediment availability caused by flushing and expansion of tunnels and waterways by large floods and a subsequent slow deformation of them caused by the ice overburden and the glacier movement. A comparison of sediment yields from a number of polythermal and temperate glaciers in various areas showed large differences that were attributed primarily to bedrock susceptibility to erosion and, secondarily, to glaciological parameters.

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The aim of this paper is to discuss the sediment yield, sediment delivery and the processes of erosion in rivers subject to High Arctic conditions in Svalbard, an archipelago which (excluding the southern outlier Bjørnøya) spans from 77 to 80 °N (Fig. 1). The processes of erosion and sediment transport in High Arctic rivers in Svalbard differ in many ways from those of middle latitudes. The scant vegetation and the presence of permafrost in the ground affects runoff conditions and slope erosion processes. A large part of the land is covered by glaciers. Due to the cold climate, some of the glaciers are polythermal (Blatter & Hutter 1991) and some are cold. Some of the thicker glaciers have proved to be temperate at the base. The thermal regime affects the processes of subglacial erosion since cold ice is frozen to the bed. Subglacial meltwater flow may also be lim-

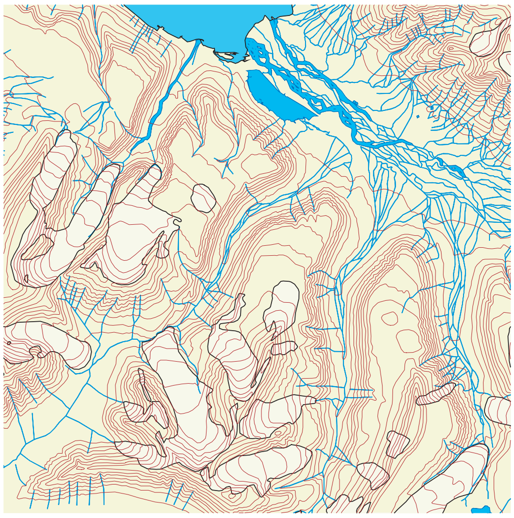
Fig. 1. Svalbard (Bjørnøya, to the south, not shown), indicating the locations of the main study areas, (a) Endalselva, (b) Bayelva and (c) Londonelva, which are shown in detail in Fig. 2.

ited in cold areas, with less sediment carried out from the glaciers.

Studies in Norway and elsewhere have shown that sediment concentrations in glacial meltwater rivers are subject to large temporal fluctuations. This pattern of long- and short-term variations in sediment concentrations reflects the activity of the processes of erosion and sediment delivery of the glaciers in each catchment.

Most previous studies have concerned measurements over relatively short periods. It is therefore of interest to study the sediment transport within a longer time frame. Sediment yields and seasonal and interannual variations in sediment concentrations in the glacier-fed rivers Bayelva and Endalselva and in the unglacierized river Londonelva (Fig. 2)—all on the archipelago's largest island, Spitsbergen—are examined in this paper with respect to annual and seasonal patterns, in an attempt to elucidate the different processes responsible.

Earlier work in Bayelva has been conducted by Repp (1979, 1988), Bogen (1991, 1993) and Husebye (1994). Gurnell et al. (1994) discussed the sediment discharge variability of the Bayelva glaciers in comparison to Alpine glaciers, while Bogen (1996) compareded their erosion rates to temperate glaciers in mainland Norway. Krawczyk & Opolka-Gadek (1994) reported measurements of suspended sediment concentrations in the drainage basin of the glacier Werenskioldbreen, southern Spitsbergen. Vatne et al. (1995) undertook a study of the glaciofluvial sediment transfer of Erikbreen, in inner Liefdefjorden, northern Spitsbergen. Sollid et al. (1994) studied the glacial dynamics and material transport of Erikbreen and Hannabreen, in Liefdefjorden (Fig. 1). Hodson et al. (1997) compared the thermal regime and the suspended sediment yield of the polythermal glacier Austre Brøggerbreen (Fig. 2) and the temperate Finsterwalderbreen, southern Spitsbergen. Hodson & Ferguson (1999) and Hodson (1999) analysed the temporal variability in proglacial sediment and solute time series of the same glaciers and included the polythermal glacier Erdmannbreen, southern Spits-



bergen. Hodgkins (1997) reviewed studies of glacier hydrology, solutes and suspended sediments in Svalbard in a comprehensive paper. Etzelmuller et al. (2000) studied glacier characteristics and sediment transfer systems of the glaciers Longyearbreen and Larsbreen, two essentially cold-based glaciers with temperate patches, in the vicinity of Longyearbyen. Studies of sediment yields that include measurements of non-glacial catchments are Kostrzewski et al. (1989) and Barsch et al. (1994), who studied recent fluvial sediment budgets in glacial and periglacial environments in Svalbard. Bogen (1996, 1997) included the river Bayelva and the unglacierized Londonelva in a study of the sediment yield of various types of Norwegian rivers. Bogen & Bønsnes (1999a) reported on the sediment transport in the river Endalselva, which drains into the lake Isdammen, the Longyearbyen reservoir.

Due to scant vegetation and the special runoff conditions caused by permafrost, the High Arctic environment of Svalbard is very sensitive to disturbance from human activity (Husebye et al. 1993) so it is important for management purposes to find out more about erosion activity and sediment yields in Svalbard rivers. In 1989 the Norwegian Water Resource and Energy Directorate (NVE) therefore initiated a long-term monitoring programme of water discharge and sediment transport in the glacier-fed river Bayelva, near Ny-Ålesund. The non-glacial river Londonelva was also studied from 1992. The river Endalselva was monitored during the years 1994–98.

Methods

Sampling strategy and laboratory methods followed the procedures established by the NVE as described by Bogen (1988, 1992). Automatic ISCO-type pumping samplers have been used to obtain water samples with suspended sediment. Normal sampling frequency was 2 - 4 samples a day. In accordance with European standards for determining suspended solids, the water samples were filtered through Whatman GF/C glass fibre filters (CEN 1996). These filters have a nominal retention diameter of particles of 0.7 micron. The concentrations of organic and inorganic particulate matter were determined by repeated weighing and by ignition at 500 °C for 2 hours. Sediment transport (G_s) was calculated for hourly intervals from the equation:

$$G_s = \int_{t_1}^{t_2} QC dt \tag{1}$$

Water stage discharge curves were established at the three monitoring stations included in the study. Water discharge (Q) was calculated from the continuous record of water stage. It was shown by Repp (1979) that the relation between water discharge and water stage is subject to a change throughout the season. This change is attributed to the degradation of the river channel caused by seasonal melting of the upper permafrost layer. A compound Crump weir was built in Bayelva to meet this problem (Skretteberg 1991). In Endalselva a culvert beneath the road served the same purpose.

Hourly sediment concentrations (C) were obtained by linear interpolation between the known concentrations of collected samples. Tests have shown that linear interpolation between four samples a day will reproduce very well the diurnal variations in sediment concentration in meltwater rivers. However, events of short duration related to slides, the collapse of river banks or similar processes may in some cases fail to be recorded with this sampling frequency. Suspended sediment concentration rating curves were only used to analyse processes. However, if samples are missing, concentrations have been estimated by rating curves to compute sediment fluxes. Seasonal measurements were initiated when the snowmelt started and ceased when the temperature fell below 0 °C in September. The grain size distribution of water samples were determined by Laser coulter analysis. Samples for grain size analyses were filtered through HA 0.45 micron Millipore membrane filters. It was necessary to use membrane filters as the filtrate had to be scraped off the filter prior to the Coulter analysis.

Suspended sediment concentrations and transport—Londonelva

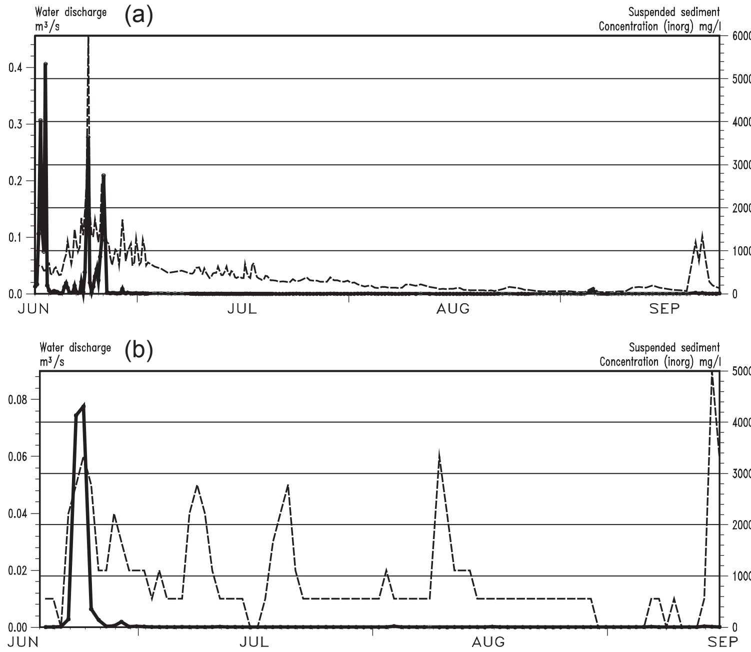
Londonelva drains a small unglacierized catchment (0.7 km^2) on the small island of Blomstrandhalvøya near Ny-Ålesund (Fig. 2), with maximum elevation of 300 m a.s.l. A major part of the catchment consists of carbonate bedrock exposures patchily covered by till and frost-weathered bedrock material. Frost weathering processes are very active on bedrock slopes in the tributary areas.

The monitoring station is situated downstream from a 500 m long and 200 m wide floodplain. This plain is almost devoid of fine-grained overbank deposits, presumably because of very powerful erosion during the bigger floods. Channels are not well-defined and the surface is covered by cobbles and boulders, with fine material present only in patches. Streamflow is restricted to a short period from the end of June to the beginning of September. Most of the runoff is a response to snowmelt. Concentrations tend to be very high during the low discharges at the start of the snowmelt. During early season low water discharge in 1992, concentrations exceeded 5000 mg/l; they exceeded 4200 mg/l in 2000 (Fig. 3). Later in the season concentrations were low. Sediment concentrations are in general poorly correlated to water discharge.

The reason for this irregular pattern may be attributed to the lack of stable channels. In High Arctic streams and rivers there is a layer of ice at the bed early in the melt season. This layer has accreted during the preceding autumn and winter and is subject to progressive melting during the summer. Thus, during the early snowmelt, a large part of the runoff may be located outside the channels. Frost in the ground limits the infiltration of runoff. As the flow may sweep over large areas, patches of otherwise unavailable sediments may be exposed to erosion during this early period. At this time sediments that melt out from the snowcover may be soaked with meltwater and easily eroded. The general lack of fine fractions on the floodplain is most probably due to their removal by this early flow washing over large areas.

During 1992–96 the measured suspended sediment load in Londonelva varied between 28 and 93 t/yr. This gives a mean erosion rate of 82.5 t/km^2/yr (Table 1). Published measurements recorded during shorter periods in other nonglacial rivers in Svalbard give similar or somewhat lower yields but of the same order of magnitude (Table 1). Kostrzewski et al. (1989) report a sediment yield of 27.7 t/km^2 in Dynamiskbekken in 1985. This stream drains into Petuniabukta, in the central part of western Spitsbergen, in an area dominated by Cambro-Silurian sedimentary rocks. The catchment covers 1.42 km^2 and

Fig. 3. Suspended sediment concentration in the river Londonelva in (a) 1992 and (b) 2000. The dashed lines represent water discharge. The thick solid lines represent sediment concentration.



its highest altitude is about 650 m a.s.l. Barsch et al. (1994) measured the sediment yield in Beinbekken, near Liefdefjorden, northern Spitsbergen, in 1990 and 1991 as 30 t/km^2 and 46 t/km^2, respectively. Svendsen et al. (1989) estimated denudation rates from a sediment core in the lake Linnévatnet, central Spitsbergen, and found 15 mm/1000 yrs, corresponding to 30 t/km^2/yr in the non-glacial part of the catchment. The bedrock of this catchment area is composed of metamorphosed quartzites and micaschists and sedimentary rocks. In non-glacierized areas in Greenland, Hasholt (1996) found values in the range of 1 - 56 t/km^2/yr. These figures are minimum values since on Greenland it has not yet been possible to monitor the transport during the early spring, late autumn and winter. Measurements from Iceland give substantially larger suspended sediment delivery values. Thomasson (1990, 1991) gives values of 10 - 200 t/km^2/yr for ice-free areas in Iceland. It is possible that erosion rates in unmeasured non-glacial areas of very loose bedrock in Svalbard may be of the same order of magnitude.

Table 1. Annual suspended sediment yield in non-glacial catchments. Data compiled from various authors (see references in the text).

River	Area (km^2)	Sediment yield Total t/yr	Sediment yield t/km^2/yr
Londonelva	0.7	57.8	82.5
Dynamiskbekken	1.42	39.6	27.7
Beinbekken	5.0	190	38
Greenland			1 - 56
Iceland			10 - 200
Foksåi, Norway	10 [a]	261	26
Upper Atna, Norway	30 [a]	361	12

[a] "Contributing catchment area", according to Bogen (1996).

Sediment concentrations and transport—Bayelva

The sediment monitoring station in Bayelva is situated about 2.5 km downstream from the glaciers Austre Brøggerbreen and Vestre Brøggerbreen (Fig. 2). The catchment draining to the monitoring station covers an area of 30.9 km^2, where 55 % is covered by glaciers. The meltwater rivers from the glaciers flow through a gap in the proglacial moraines and onto the constrained sandurs downstream. These sandurs are composed of boulders and gravel with only patchy accumulations of sand and silt. Sediment data from the years 1989–2000 revealed that the largest concentrations often occur late in the season. Values for the years 1990, 1995, 1996 and 1999 are given

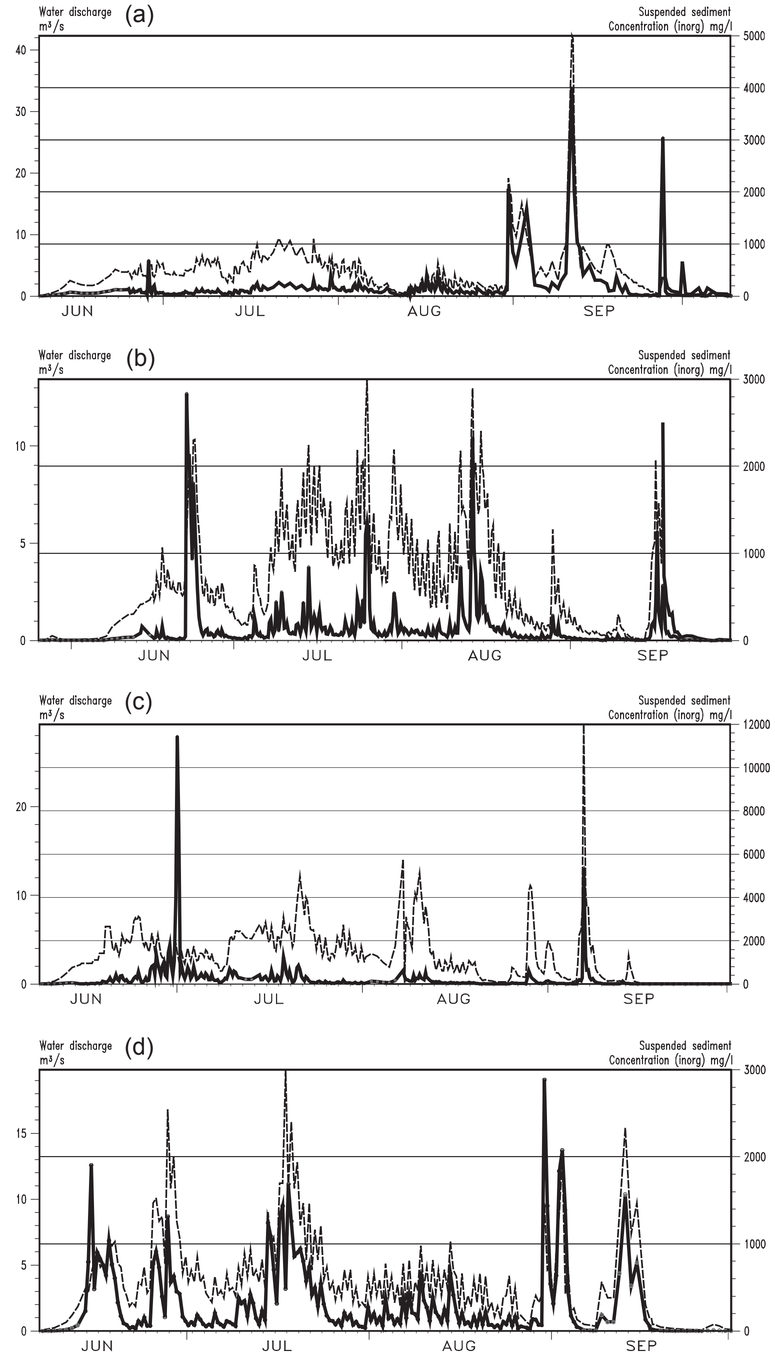
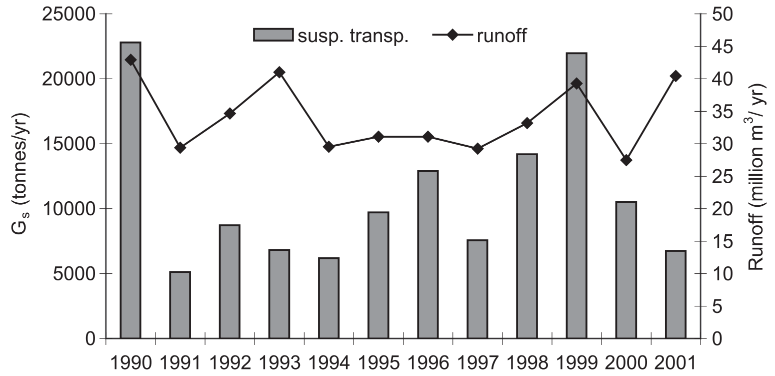


Fig. 4. Suspended sediment concentration in the river Bayelva in (a) 1990, (b) 1995, (c) 1996 and (d) 1999. The dashed lines represent water discharge. The thick solid lines represent sediment concentration.

as examples in Fig. 4. During July and August 1990, when the runoff originated from meltwater, the mean suspended sediment concentrations varied in the range of about 100 - 300 mg/l. After 28 August, frequent rain caused high water discharges. A first peak culminated on 1 August at 19 m^3/s. During this event the sediment concentration reached 2000 mg/l. On 12 September a much greater discharge of 42 m^3/s gave rise to a concentration of 4000 mg/l. This is the highest

Fig. 5. Annual suspended load in the river Bayelva 1990–2001.



discharge on record for Bayelva. A similar pattern was recorded during the following years.

Concentrations during snowmelt events rarely exceed 500 mg/l; it is rain floods, or flood events due to a combination of snowmelt and rain, that generally produce the high concentrations. During 1996–2000, the maximum concentrations associated with rain floods were in the range of 2500 - 5500 mg/l. In 1995 and 1999, concentrations in the range of 1500 - 2200 mg/l occurred during floods arising from a combination of snowmelt and rain in June and July. Anomalously high concentrations that have been measured during meltwater periods are 11 000 mg/l (1 July 1996) and 3200 mg/l (18 July 1994); they occurred during water discharges of less than 5 m^3/s.

Annual sediment yield was subject to large variations during the 11 years of measurement. 1990 recorded the largest annual sediment transport, 23 000 t, which was associated with the large flood event in September that year. However, the annual loads during the following years were low even though the total annual runoff stayed at the same high level (Fig. 5). A slow increase in sediment transport took place over the period, and in 1999 the sediment load of 21 948 t approached the 1990 level. Since there were no increases in total runoff throughout the period, it is probable that sediment availability had increased. Repp (1988) measured sediment transport varying from 15 851 t (1974) and 16 558 t (1975) to 13 599 t (1976) and 6646 t (1977).

Subglacial and englacial drainage

Austre Brøggerbreen is an almost entirely non-temperate glacier except for a shallow layer near its bed at depths greater than 90 m (Hagen et al. 1991). For this reason it has been assumed that the percolation of meltwater to the glacier bed is restricted, and that there is no subglacial drainage system. Hodson et al. (1997) and Hodson (1997) conclude that sediment supply delivered from supraglacial sediment sources and erosion of lateral moraines dominated the transported suspended sediment. Hagen et al. (1991) describe englacial and subglacial channels connected to moulins. These moulins may have originated from old crevasses; they are visible on aerial photographs of Austre Brøggerbre from 1934. A relict subglacial or englacial drainage system may therefore exist even in the cold part of the glacier. Observations carried out by Wold (1976) also indicate the presence of a system of

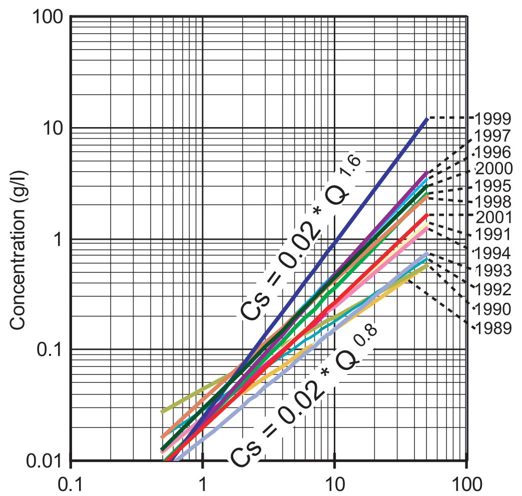


Fig. 6. Sediment rating curves in the river Bayelva, 1989–2001.

subglacial channels. On a day of intense melting, sediment-laden water suddenly debouched under pressure from tunnels and fissures in the debris-covered part of the glacier. Vatne (2001) studied the geometry of englacial water conduits on Austre Brøggerbreen and found that some of them had been formed by gradual downcutting of supraglacial meltwater channels. Sandbars were observed in one of these channels. The initiation of glacier melt has often been observed associated with sediment-laden water that has been seen debouching from subglacial tunnels. In 1998 a special programme of sediment concentration measurements was carried out along the main channel of Bayelva upstream to the point where it emerged from a subglacial tunnel.

Regression analyses of water discharge versus suspended sediment samples gave significant correlations. The best fitted curves are, however, different in each individual year of the period of observation. The curves are potential relations of the type $Gs = a\,Q^b$, where the exponent b indicates the curve slope. The exponent was subject to change throughout the period, from low values of 0.83 (1989) and 0.65 (1990) to higher values of 1.58 (1999), 1.19 (2000) and 1.12 (2001) (Table 2a, Fig. 6). A regression analysis of the b values as a function of time indicates a trend with 99 % confidence. The data were normalized with regard to the square root of the estimated variance. The T-value of the test (ratio of slope of regression line to standard deviation) was found to be 3.58 and the maximum confidence reflected by the p value was 0.6 %.

Regression analyses were also applied to different parts of the season. It was found that suspended sediment concentrations sometimes increased more rapidly with discharge during rain flood

Table 2. (a) Sediment rating curves and statistics based on water discharge in the interval 1.0 - 10.0 m^3/s in the river Bayelva and for all discharges in the river Endalselva.

	Year	Dependent variable	Simple lagged rating curve	R^2	Standard deviation	Standard dev. residuals	degree of freedom	Significance 0.995 level
Bayelva	1989	Cs	$0.02262 * Q^{0.8264}$	0.16	0.4344	0.3968	164	yes
	1990	Cs	$0.04375 * Q^{0.6539}$	0.22	0.3331	0.2940	259	yes
	1991	Cs	$0.02410 * Q^{1.0240}$	0.37	0.3310	0.2624	210	yes
	1992	Cs	$0.02872 * Q^{0.8001}$	0.39	0.3215	0.2511	307	yes
	1993	Cs	$0.01574 * Q^{0.9838}$	0.40	0.3387	0.2615	275	yes
	1994	Cs	$0.02414 * Q^{1.0069}$	0.51	0.3629	0.2530	161	yes
	1995	Cs	$0.02181 * Q^{1.2155}$	0.58	0.4052	0.2622	292	yes
	1996	Cs	$0.02929 * Q^{1.2119}$	0.27	0.5150	0.4394	257	yes
	1997	Cs	$0.02181 * Q^{1.3277}$	0.54	0.3604	0.2432	125	yes
	1998	Cs	$0.03507 * Q^{1.0799}$	0.29	0.4386	0.3676	211	yes
	1999	Cs	$0.02407 * Q^{1.5793}$	0.60	0.4234	0.2667	149	yes
	2000	Cs	$0.02886 * Q^{1.1864}$	0.72	0.3404	0.1811	165	yes
	2001	Cs	$0.01987 * Q^{1.1245}$	0.48	0.3003	0.2150	187	yes
Endalselva	1994	Cs	$0.12218 * Q^{1.4789}$	0.69	0.7160	0.3968	321	yes
	1995	Cs	$0.17125 * Q^{0.3755}$	0.40	0.4499	0.3462	151	yes
	1996	Cs	$0.13407 * Q^{0.4216}$	0.29	0.4096	0.3449	180	yes
	1997	Cs	$0.31493 * Q^{0.1658}$	0.10	0.3466	0.3268	142	yes
	1998	Cs	$0.40081 * Q^{0.1845}$	0.04	0.2813	0.2743	154	no

(b) Sediment rating curves and statistics based on situations with (1) meltwater and (2) high precipitation with moderate melting.

	Year	Dependent variable	Simple lagged rating curve	R^2	Standard deviation	Standard dev. residuals	degree of freedom	Significance 0.995 level
Bayelva	1990 (1)	Cs	$0.04699 * Q^{0.56305}$ June 23–Aug. 30	0.31	0.2819	0.2329	234	yes
	1990 (2)	Cs	$0.02350 * Q^{1.3582}$ Aug. 31–Oct. 10	0.75	0.2407	0.4407	56	yes
	2000 (1)	Cs	$0.03683 * Q^{0.9530}$ June 28–Sept. 5	0.84	0.5491	0.2207	191	yes
	2000 (2)	Cs	$0.03188 * Q^{1.3839}$ Sept. 6–Sept. 16	0.89	0.2293	0.2563	27	yes

events than during glacier meltwater events (Table 2b). In 1990 the b values of the meltwater events and the rain flood events were 0.6 and 1.31, respectively; in 2000 they were 0.95 and 1.4. These changes in the exponent b probably express changes in sediment availability and/or processes of erosion during large runoff events. It is likely that this increased availability of sediments is located in the glacier and moraine area. Floods will flush and expand the subglacial and englacial tunnels and also flush the surface of the glaciers. The frontal part of the glaciers is laden with sediment. At the end of the ablation season sediments have melted out from the glacier surface and from the ice-cored moraines. Sediment flux from erosion by subaerial channels in proglacial areas does not necessarily correlate with water discharge. Strong correlations between suspended sediment concentration and water discharge implies that sufficient amounts of sediment were available for erosion when the discharge rose. The channels also needed to be relatively stable since channel changes may move the river away from slopes and isolate it from sediment sources available for erosion. Measurements of sediment transport in the river Atna, in a glacier-free, mountainous area of mainland Norway, did not give any significant correlation with discharge (Bogen & Bønsnes 1999b). The main source area in this river system has many features in common with proglacial areas. A number of slopes are unvegetated and exposed to active erosion while sediment availability may change throughout the season as a result of channel migration. In the same way, the erosion of sediment inside the proglacial area of the Svalbard rivers would not be expected to correlate with discharge. The moraines of Austre and Vestre Brøggerbreen are, however, ice-cored and erosion of sediments from the moraine area involves the melting of sediment-laden ice. Channel erosion and sedimentation on the sandur downstream from the glacier may even out erratic fluctuations in meltwater sediment concentrations, which would improve the correlation. Erosion and sedimentation do take place on the Bayelva sandurs. However, a rating curve between water discharge and sediment concentration may exist upstream from the sandur. Repp (1988) attributed a significant correlation between sediment transport and water discharge to the existence of a stable system of subglacial tunnels beneath Austre and Vestre Brøggerbreen.

Significant correlations between sediment concentration and water discharge are rare in meltwater rivers of temperate glaciers in mainland Norway. They display some dependence on discharge, but no obvious direct correlation. The relationship between water and sediment discharge is subject to continuous change both through the season and from year to year (Østrem 1975; Bogen 1980). This complex pattern may be explained by the seasonal development of the subglacial drainage system of a glacier resting on bedrock. When the water pressure increases during a melt period, sediments are supplied to the drainage system by expansion of subglacial cavities and tunnels. Sediments may be entrained from the glacier bed or released by the melting of ice that is laden with debris. When glacial melting slows down in response to a drop in air temperature, subglacial tunnels are deformed by glacier movement and the weight of overlying ice so that after a time they may actually close (Bogen 1995, 1996). In cold ice, tunnel responses may proceed more slowly.

According to Nye (1953) and Röthlisberger (1972), the contraction rate of a subglacial tunnel is in a steady state:

$$\frac{\acute{r}}{r} = A\left(\frac{P-p}{n}\right)^{n} \qquad (2)$$

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 $\acute{r}$. A and n are the flow parameters of Glen's Law (Glen 1958), P is the ice overburden pressure and p is the water pressure. A decreases with temperature. Paterson (1994) gave a value of 6.8×10^{-15} (s^{-1} [kPa]$^{-3}$) for temperate ice, decreasing to 1.7×10^{-17} (s^{-1} [kPa]$^{-3}$) for cold ice at –20 °C. Thus, from Eq. (2) it is evident that the deformation of the tunnel slows down as the temperature drops. As an example, the deformation of a 3 m diameter tunnel in cold ice at –20 °C, subject to ice thickness of 150 m, was calculated to ca. 0.2 m/yr. In temperate ice, a tunnel of corresponding dimensions was completely closed in less than 6 months. According to Paterson (1994) the value of the flow parameter A is subject to considerable variations in different laboratory tests and borehole measurements. It is therefore difficult to give an exact value for the closure rates for the Brøggerbreen glaciers, but it is assumed to be somewhere in between the calculated values.

The subglacial or englacial tunnels in the Brøg-

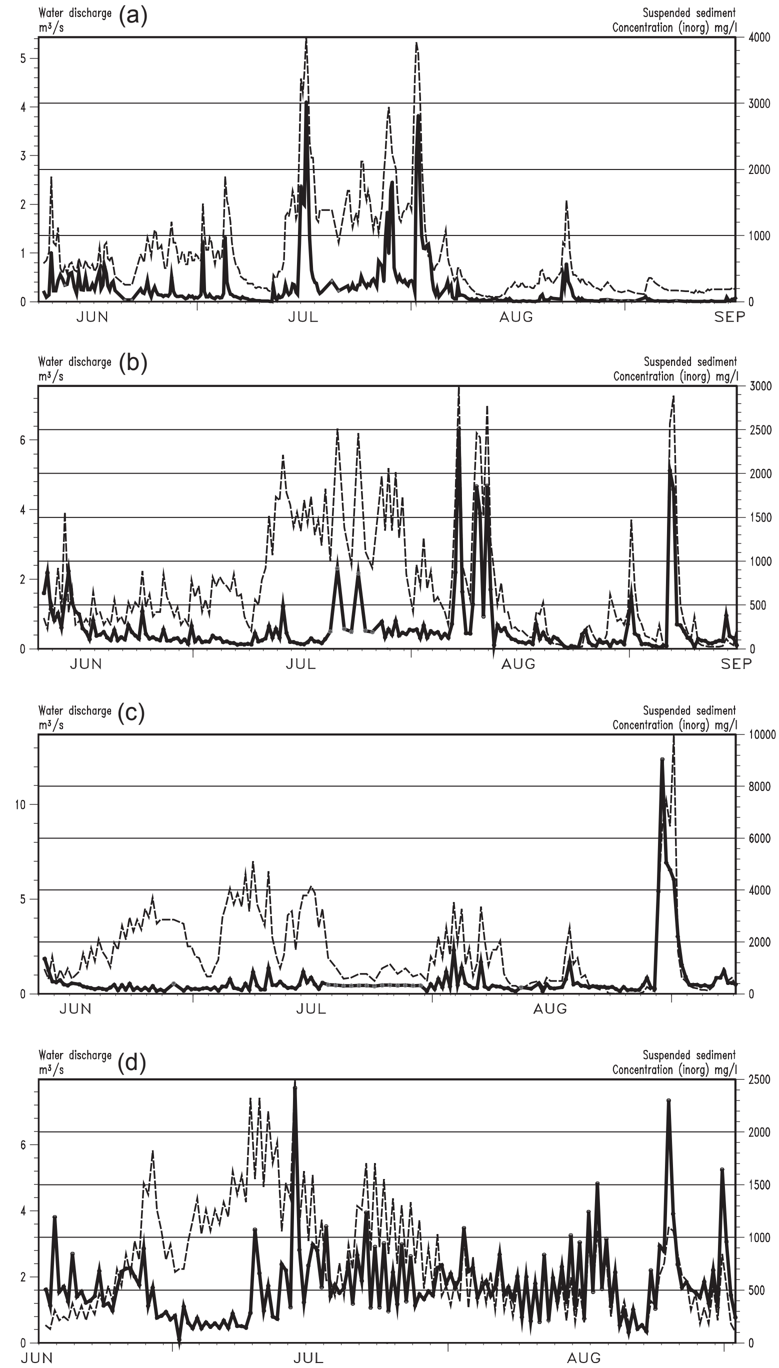


Fig. 7. Suspended sediment concentration in the river Endalselva in (a) 1994, (b) 1996, (c) 1997 and (d) 1998. The dashed lines represent water discharge. The thick solid lines represent sediment concentration.

gerbreen glacier are assumed to be stable throughout the season since the ice is not temperate. The cross-section may nevertheless expand due to the heat generated by turbulence during high water discharge. The pattern of long-term variations in sediment yield from Austre and Vestre Brøggerbreen may be explained in terms of a model involving deformation of subglacial or englacial tunnel systems that pass through debris-rich parts of the glacier. The large flood in 1990 may have increased the volume of the system of conduits and enlarged the cross-sectional area of the tunnels by melting. The water discharge exceeded 30 m^3/s during a 24-hour period. Water in subglacial conduits is heated through loss of potential energy. A rough estimate of the ice volume melted by the 1990 flood may be obtained by assuming that all the potential energy was converted to heat. On a reach where the height difference is 50 m, the power (P) was calculated as $147*10^5$ J/s. The latent heat of the melting ice $l=333.5*10^5$ J/kg. In the course of 24 hours this heat may melt an ice volume of $P*t/l$ = 4231.5 m^3. Along a 300 m long tunnel, this volume will correspond to a widening of an initial diameter of 3 m to 9 m. This calculation neglects the heating of the ice and that some of the heat disappears with the water out of the tunnel, so the actual tunnel widening will be somewhat less.

During the years following the large flood, it is likely that the water discharges was unable to fill the tunnel. Thus, the volume of sediment-laden ice in contact with meltwater at a lower water discharge was reduced. As the overburden pressure or the movement of the glacier deform the tunnels more sediment may be melted out from the ice after some time. This could explain why the b value of the sediment rating curves increases after several years have passed. The same pattern seems to have been repeated after the large flood in 2000.

The mean sediment transport of the river Bayelva at the monitoring station during the period 1990–2001 amounts to 11 104 t/yr (Table 3a). It is difficult to distinguish between sediments derived from melting and erosion of ice- cored moraines and sediments delivered from the subglacial or englacial drainage system. From visual inspections, the erosional activity in the non-glacial areas of Bayelva does not differ much from that of Londonelva. Erosion and deposition of suspended sediments may take place on the Bayelva sandurs. According to measurements reported by Bogen (1995) for a similar sandur system, no net erosion is to be expected on an annual basis. If the sediment supply from the non-glacierized area outside the moraines is estimated with this in mind, this gives 1150 t. The sediment yield for the glaciers Austre and Vestre Brøggerbreen and their moraines is therefore around 586 $t/km^2/yr$.

Endalselva

The catchment of the river Endalselva (28.8 km^2) constitutes the major part of the area draining into the lake Isdammen (34.2 km^2), the Longyearbyen reservoir (Fig. 2). Glaciers cover 22.5 % of the Endalen valley catchment. The largest glacier is Bogerbreen (6.6 km^2). The areas of the other glaciers are 2.3 km^2 and 0.3 km^2. Sediment transport was measured during 1994–98 at a monitoring station where the river flows into Isdammen.

Seasonal variation in suspended sediment concentration is given for selected years in Fig. 7. During 1994–97 the concentrations were below 200 - 300 mg/l for large parts of the season, but during floods sometimes exceeded 2000 mg/l. The maximum concentration measured during a rain flood event was 9000 mg/l in August 1997

Table 3. (a) Suspended sediment transport in three High Arctic rivers in Svalbard.

Monitoring station	Area (km^2)	Glac. %	Suspended transport (tonnes) 1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	mean (t/yr)	Spec/ (km^2/ yr)
Bayelva	30.9	55	22 797	5126	8716	6829	6200	9718	12 881	7566	14 194	21 960	10 522	6746	11 104	359
Londonelva	0.7	0			80	93	30		28						57.8	82.5
Endalselva	28.8	20					3873	3864	6625	16 359	9792				8102	281

(b) Specific annual sediment yield and mean grain size (md), maximum concentration (cmax) and mean concentration (cmid) of all samples.

Monitoring station	Area (km^2)	Glac. %	Specific annual sediment yield: Mean annual yield (t/yr)	Spec yield ($t/km^2/yr$)	Spec yield glacier ($t/km^2/yr$)	Spec yield non-glacier ($t/km^2/yr$)	Grain size /concentration: md (mm)	cmax (mg)	cmid (mg)
Bayelva	30.9	55	11 104	359	586	82.5	0.014	11 446	305.1
Londonelva	0.7	0	57.8	82.5	0		0.040	5343	161.5
Endalselva	28.8	20	8102	281	1077	82.5	0.021	9043	554.1

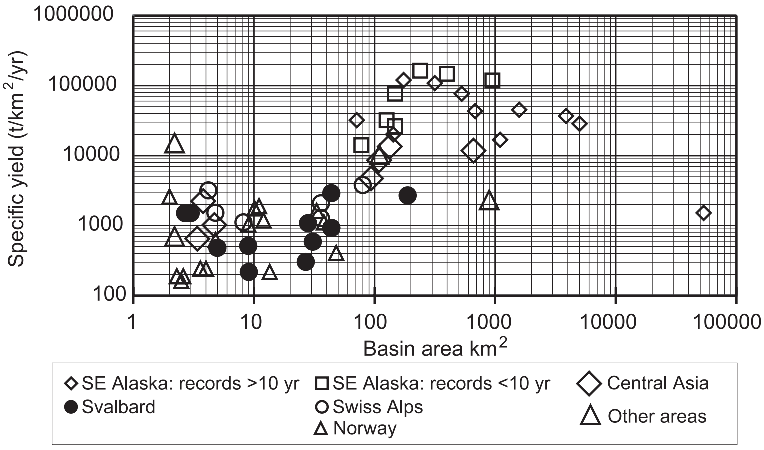


Fig. 8. Specific suspended sediment yield of glaciers from Svalbard, mainland Norway, Alaska, the Swiss Alps, Central Asia and other areas plotted against basin area (data from Hallet 1996).

and occurred during the rising water stage. Flood culmination concentrations of between 4000 and 5000 mg/l were observed. In 1998 the pattern deviated from the preceding years, with concentrations remaining high throughout the summer (Fig. 7). The rain flood in 1997 may be characterized as an extreme erosional event that may have delivered much sediment to the central part of the river system. The sediment yield during the years 1994–96 varied from 3873 to 6625 t/yr, rising to 16359 t/yr in 1997 (Table 3a). In 1998, the transport rate remained at a high level, 9792 t/yr, when compared to the years preceding the large flood. This is probably due to suspended sediments having previously been stored in or near active subaerial channels. The lower part of Endalselva differs from Bayelva because fine sediment is deposited on the river bed in the lower part. As with the Bayelva catchment, the sediment yields of the 23 km^2 non-glacierized area were estimated by applying the Londonelva sediment yield. This gave a contribution from the glaciers of 6205 t and a specific sediment yield of the glacier-covered area of 1077 t/km^2/yr. This may seem high, but it is of the same order of magnitude as the values given by Etzelmüller et al. (2000) for the nearby glaciers Longyearbreen and Larsbreen.

Discussion

The specific sediment yield (586 t/km^2) determined for the glaciers Austre Brøggerbreen and Vestre Brøggerbreen in the Bayelva catchment area is higher that (160 t/km^2/yr) given by Hodson (1997) which was based on measurements in 1992 at a monitoring station 100 m downstream from the terminus of Austre Brøggerbreen. Runoff in this location was from a 7 km^2 portion of the glacier. The reason for the discrepancy is presumably the difference in sampling locations and the longer period of observation reported in the present paper. The found yields of Austre Brøggerbreen, Vestre Brøggerbreen and Bogerbreen are nevertheless well within the range for other polythermal or cold-based glaciers studied in Svalbard. The sediment yields of these are: Ebbabreen (central Spitsbergen) 303 t/km^{2}yr (Kostrzewski et al. 1989); Glopbreen (northern Spitsbergen) 480 t/km^{2}yr (Barsch et al. 1994); Werenskioldbreen (southern Spitsbergen) 919 t/km^{2}yr (Krawczyk & Opolka-Gadek 1994); and Longyearbreen and Larsbreen (central Spitsbergen, near Longyearbyen) 1500 t/km^{2}yr (Etzelmuller et al. 2000).

Estimates for warm-based glaciers are much higher. For example, Hodson et al. (1997) reported a sediment yield of 710 - 2900 t/km^2/yr for Finsterwalderbreen, in southern Spitsbergen. A seismic survey of fjord sediments in front of the large warm-based glacier Kongsvegen, east of Ny-Ålesund, indicated 2700 t/km^2/yr (Elverhøy et al. 1983). In Fig. 8, the sediment yields from these Svalbard glaciers are compared with known yields from various glacier basins in mainland Norway, the Swiss Alps, Iceland and Alaska, given by Hallet et al. (1996). Sediment yields of similar magnitude to the two temperate-based Svalbard glaciers are not observed in mainland Norway. Most of the polythermal or cold-based Svalbard glaciers, however, do plot within the range of the temperate mainland glaciers. It is apparent that glacial sediment production is not only dependent on thermal regimes and other glacier variables, but also on the character of the bedrock, especially its degree of consolidation. The lowest erosion rates recorded are from glaciers underlain by ancient crystalline bedrock in Fennoscandia, whereas the highest rates are found in young mountain areas in Alaska, central Asia and Iceland.

Sediment yield measurements in glacier meltwater rivers primarily reflect the amount of evacuation of sediments from the glaciers. As pointed out by Hodgkins (1996: 151), "the suspended load of the proglacial stream is not indicative of glacial erosion since the glacier is currently frozen to its bed, but is derived from the sediment stored following glacial erosion in an earlier time period."

The existence of tunnels in cold ice is also described in other studies. Hodgkins (1997) reports turbid plumes observed at the marine margins of polythermal ice caps, indicating that meltwater can be routed subglacially through non-temperate ice.

To keep a subglacial tunnel open requires turbulent water flow. If the upstream part of a tunnel is clogged for some reason, deformation by overlying ice and the glacier movement will close it after some years. As there is no percolation of water through cold ice, a re-opening of a closed tunnel is unlikely. Thus, the existence of subglacial tunnels in cold ice is most probably due to a change in temperature regime as the glacier has become thinner. Changes in glacier thickness and dynamics are driven primarily by changes in mass balance. According to Lefauconnier & Hagen (1990), the mass balance of Vestre Brøggerbreen has been negative since 1918. The corresponding reduction in thickness is about 40 m, which will have led to a reduction in the volume of temperate ice.

The 82.5 t/km^2 sediment yield of the non-glacierized river Londonelva was higher than other rivers of this type but of the same order of magnitude. Conditions in Svalbard—permafrost and scant vegetation—seem to favour a higher yield than in mainland Norway, where sediment yields of 12 t/km^2/yr (river Atna) and 26 t/km^2/yr (river Foksåi) have been measured (Bogen 1996). The sediment yield in Atna increased by one order of magnitude during a large flood in 1995. Debris flows occurring during extreme flood events will probably increase the sediment yield estimates of non-glacial areas in Svalbard. André (1995) estimated a recurrence interval of 80 - 500 years for debris flows and ca. 500 years for slush avalanches. During such events, the sediment yield will be subject to a considerable increase. Because of the low recurrence interval, their contribution to the sediment budget will be of less importance.

Conclusion

Long-term measurements of suspended sediment yield of High Arctic rivers in Svalbard have been examined in this paper. Sediment transport of the non-glacial river Londonelva has varied in the range of 28 - 93 t/yr, giving rise to a mean transport of 59 t/yr and a corresponding sediment yield of 82.5 t/km^2/yr. This is of the same order of magnitude as measured in other non-glacial rivers in Svalbard.

The large year-to-year differences in sediment yield in Londonelva are attributed to early snowmelt conditions when channels are ice-filled and frozen ground prevents surface infiltration. This unstable drainage results in a haphazard pattern of exposure of sediment to erosion.

In the glacier-fed rivers Bayelva and Endalselva, the suspended sediment transport varied in the range of 5126 t/yr to 22 797 t/yr during a 12-year period. A mean of 11 104 t/yr was calculated for the period, giving rise to a mean sediment yield of 359 t/km^2/yr for the whole catchment of Bayelva.

It was found that a major part of the sediment load is delivered from the glaciers Austre Brøggerbreen and Vestre Brøggerbreen and by erosion of the neoglacial moraines in their vicinity. An assessment of the contribution from various sediment sources resulted in an estimate of the sediment yield of the glacier and the moraine area to 586 t/km^2/yr.

We propose a conceptual model used to interpret the long- and short-term patterns of sediment delivery from the glacier and the neoglacial moraines. The observed short-term, seasonal and interannual pattern of variations in sediment concentration at the monitoring station is related to erosion of material delivered by melt-out processes of sediment from the ice, and erosion of material from the non-glacial areas.

Evidence is found that a proportion of the sediments are delivered by a network of englacial and subglacial channels that exist even in cold ice. Contrary to observed patterns in glacial meltwater rivers in mainland Norway, regression analyses of water discharge versus suspended sediment concentration give significant correlations. It is suggested that this is due to the stability of ice tunnels in cold ice. Large floods will flush the waterways and exhaust the sediment sources. The year-to-year change in the exponent of regression lines is attributed to changes in sediment availability caused by the slow deformation of tunnels and waterways that take place in cold ice. At the end of the ablation season rain floods will flush sediments that have melted out from the glacier surface and from the ice-cored moraines.

A comparison of sediment yields from a number of polythermal and temperate glaciers indicate differences of several orders of magnitude. It is concluded that the size of the long-term sediment yield is to a large extent controlled by bedrock susceptibility to erosion and, secondarily, by glaciological parameters.

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References

André, N. F. 1995: Holocene climate fluctuations and geomorphic impact of extreme events in Svalbard. *Geogr. Ann 77A*, 241–250.

Barsch, D., Gude, M., Mausbacker, R., Schukraft, G. & Schulte, A. 1994: Recent fluvial sediment budgets in glacial and periglacial environments, NW Spitsbergen. *Z. Geomorphol. Suppl.bd. 97,* 111–122.

Blatter, H. & Hutter, K. 1991: Polythermal conditions in Arctic glaciers. *J. Glaciol. 37,* 261–269.

Bogen, J. 1980: The hysteresis effect of sediment transport systems. *Nor. Geogr. Tidsskr. 34*, 45–54.

Bogen, J. 1988: *A monitoring programme of sediment transport in Norwegian rivers. IAHS Publ. 174.* Wallingford, UK: International Association of Hydrological Sciences.

Bogen, J. 1991: Erosion and sediment transport in Svalbard. In Y. Gjessing et al. (eds.): *Arctic hydrology, present and future tasks. Norwegian National Committee for Hydrology Rep. 23/91*, 147–158.

Bogen, J. 1992: Monitoring grain size of suspended sediments in rivers. In J. Bogen et al. (eds.): *Erosion and sediment transport programmes in river basins. IAHS Publ. 210*, 183–190. Wallingford, UK: International Association of Hydrological Sciences.

Bogen, J. 1993: Erosjon og sedimenttransport i Bayelva og Londonelv. (Erosion and sediment transport in Bayelva and Londonelva.) In K. Sand (ed.): *Polar hydrologi. Rapport fra forskermøte i Trondheim 29–30 mars 1993. (Report from research meeting in Trondheim 29–30 March 1993.) SINTEF Rep. STF60 A93081.* Pp. 45–54. Trondheim: Norwegian Institute of Technology.

Bogen, J. 1995: Sediment transport and deposition in mountain rivers. In I. D. L. Foster et al. (eds.): *Sediment and water quality in river catchments.* Pp. 437–451. New York: Wiley & Sons.

Bogen, J. 1996: Erosion and sediment yield in Norwegian rivers. In D. E. Walling & B. W. Webb (eds.): *Erosion and sediment yield: global and regional perspectives. IAHS Publ. 236.* Pp 73–84. Wallingford, UK: International Association of Hydrological Sciences.

Bogen, J. 1997: Sedimenttransport i høyfjell og arktis. (Sediment transport in mountain and Arctic rivers.) In A. Haugum (ed.): *Hydrologisk forskning i Norge. Norsk Hydrologiråd Rapp. 1/97,* 30–38. Norwegian National Council for Hydrological Research.

Bogen, J. & Bønsnes, T. E. 1999a: *Suspensjonstransporten ved målestasjonene i Endalselva og utløpet av Isdammen. Sammensetning, volum og sesongmessig variasjon. (The suspended load at the monitoring stations in Endalselva and the outlet of Isdammen. Composition, volume and seasonal variation.) NVE Dok. 11.* Oslo: Norwegian Water Resources and Energy Directorate.

Bogen, J. & Bønsnes, T. E. 1999b: *Miljøvirkninger av erosjon og sedimenttransport under flommer. (Environmental impact of erosion and sediment transport during floods.) Hydra Rep. Mi05.* Oslo: Norwegian Water Resources and Energy Directorate.

CEN (European Committee for Standardization) 1996: *Water quality—determination of suspended solids—method by filtration through glass-fibre filters. ISO 11923: 1997, EN 872: 1996.* European Committee for Standardization.

Elverhøy, A., Lønne, Ø. & Seland, R. 1983: Glaciomarine sedimentation in a modern fjord environment, Spitsbergen. *Polar Res. 1*, 127–149.

Etzelmüller, B., Ødegaard, R. S., Vatne, G., Mysterud, R. S., Tonning, T. & Sollid, J. L. 2000: Glacier characteristics and sediment transfer system of Longyearbreen and Larsbreen, western Spitsbergen. *Nor. Geogr. Tidsskr. 34*, 157–168.

Glen, J. W. 1958: *The flow law of ice. A discussion of the assumptions made in glacier theory, their experimental foundations and consequences. IASH Publ. 47,* 171–183. Wallingford, UK: International Association of Hydrological Studies.

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 L. J. Olive et al. (eds.): *Variability in stream erosion and transport. IASH Publ. 224*, 325–334. Wallingford, UK: International Association of Hydrological Sciences.

Hagen, J. O., Korsen, O. M. & Vatne, G. 1991: Drainage pattern in a subpolar glacier, Brøggerbreen, Svalbard. In Y. Gjessing et al. (eds.): *Arctic hydrology, present and future tasks. Norwegian National Committee for Hydrology Rep. 23/91*, 121–31.

Hallet, B., Hunter, L. & Bogen, J. 1996: Rates of erosion and sediment evacuation by glaciers: a review of field data and their implications. *Glob. Planet. Change 12*, 213–235.

Hasholt, B. 1996: Sediment transport in Greenland. In D. E. Walling & B. W. Webb (eds.): Erosion and sediment yield: global and regional perspectives. *IAHS Publ. 236*, 105–114.

Wallingford, UK: International Association of Hydrological Sciences.

Hodgkins, R. 1996: Seasonal trend in suspended-sediment transport from an Arctic glacier, and implications for drainage-system structure. *Ann. Glaciol. 22*, 147–151.

Hodgkins, R. 1997: Glacier hydrology in Svalbard, Norwegian High Arctic. *Quat. Sci. Rev.16*, 957–973.

Hodson, A. J. 1999: *Glacio-fluvial sediment and solute transfer in High Arctic basins: examples from Svalbard. Glacial Geol. Geomorphol. rp10/1999.* Available on the internet at http://ggg.qub.ac.uk.

Hodson, A. J. & Fergusson, R.I. 1999: Fluvial suspended sediment transport from cold and warm-based glaciers in Svalbard. *Earth Surf. Process. Landforms 24*, 957–974.

Hodson, A. J., Tranter, M., Dowdeswell, D. A., Gurnell, A.M. & Hagen, J. O. 1997: Glacier thermal regime and suspended sediment yield: a comparison of two High-Arctic glaciers. *Ann. Glaciol. 24*, 32–37.

Husebye, S. 1994: Studies of erosion and sediment transport at Svalbard. In K. Sand & Å. Killingtveit (eds.): *Proceedings of the 10th International Northern Research Basins Symposium and Workshop, Spitsbergen, Norway.* Pp. 47–76. *SINTEF Rep. 22 A96415.* Pp. 232–250. Trondheim: Norwegian Institute of Technology.

Husebye, S., Bogen, J., Helgestad, A. K. & Petterson, L. E. 1993: *Miljøkonsekvenser av veiutbygging mellom Longyearbyen og Svea. Avrenning, erosjon og landskap. (Environmental impacts of road construction between Longyearbyen and Svea. Runoff, erosion and landscape.* (In Norwegian with English summary.) *NVE Rapp. 7/92.* Oslo: Norwegian Water Resources and Energy Directorate.

Kostrzewski, A., Kanecki, A., Kapuschinski, J., Klimczak, R., Stach, A. & Zwolinski, Z. 1989: The dynamics and rate of denudation of glaciated and non-glaciated catchments in central Spitsbergen. *Pol.Polar Res. 10*, 317–367.

Krawczyk, W. E. & Opolka-Gadek, J. 1994: Suspended sediment concentrations in the Werenskiold glacier drainage basin in 1986. In S. Maciej Zalewski (ed.): *XXI Polar Symposium, Warzawa*. Pp. 215–224. Warsaw: Institute of Geophysics, Polish Academy of Sciences.

Lefauconnier, B. & Hagen, J. O. 1990: Glaciers and climate in Svalbard, statistical analysis and reconstruction of the Brøgger glacier mass balance for the last 77 years. *Ann. Glaciol. 14*, 148–152.

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.

Østrem, G. 1975: Sediment transport in glacial meltwater streams. In A. V. Jopling & B. C. McDonald (eds.): *Glaciofluvial and glaciolacustrine sedimentation. SEPM Spec. Publ. 23*, 101–122. Society for Sedimentary Geology.

Paterson, W. S. B. 1994: *The physics of glaciers.* New York: Pergamon / Elsevier.

Repp, K. 1979: *Breerosjon, glaci- hydrologi og materialtransport i et høyarktisk miljø, Brøggerbreen, Vest-Spitsbergen. (Glacial erosion, glacier hydrology and sediment transport in a High Arctic environment, Brøggerbreen glacier, west Spitsbergen.)* Thesis, Dept. of Geography, University of Oslo.

Repp, K. 1988: The hydrology of Bayelva, Spitsbergen. *Nord. Hydrol. 19*, 259–268.

Röthlisberger, H. 1972: Water pressure in intra and subglacial channels. *J. Glaciol. 11*, 177–203.

Skretteberg, R. 1991: Discharge measurement structures under Arctic conditions. Design and construction considerations. In Y. Gjessing et al. (eds.): *Arctic hydrology, present and future tasks. Norwegian National Committee for Hydrology Rep. 23/91*, 167–174.

Sollid, J. L., Etzelmuller, B., Vatne, G. & Ødegaard, R. S. 1994: Glacial dynamics, material transfer and sedimentation of Erikbreen and Hannabreeen, Liefdefjorden, northern Spitsbergen. *Z. Geomorphol. Suppl.bd. 97*, 23–144.

Svendsen J. I., Mangerud, J. & Miller, G. H. 1989: Denudation rates in the arctic estimated from lake sediments on Spitsbergen, Svalbard. *Paleogeogr. paleoclimatol. palaeoecol. 76*, 153–168.

Thomasson, H. 1990: Glacial and volcanic shore interaction. Part I. On land. In G. Sigbjarnarsson (ed.): *Iceland coastal and river symposium, proceedings.* Pp. 7–18. Reykjavik: National Energy Authority.

Thomasson, H. 1991: Glaciofluvial sediment transport and erosion. In Y. Gjessing et al. (eds.): *Arctic hydrology, present and future tasks. Norwegian National Committee for Hydrology Rep. 23/91*, 27–36.

Vatne, G. 2001: Geometry of englacial water conduits, Austre Brøggerbreen, Svalbard. *Nor. Geogr. Tidsskr. 55*, 85–93.

Vatne, G., Etzelmuller, B. & Sollid, J. L. 1995: Hydrology of a polythemal glacier, Erikbreen, northern Spitsbergen. *Nord. Hydrol. 26*, 169–190.

Wold, B. 1976: *En glasiologisk undersøkelse av Austre Brøggerbre, Spitsbergen. (A glaciological investigation of Austre Brøggerbreen, Spitsbergen.)* Thesis, Dept. of Geography, University of Oslo.