Erosion prediction in ungauged glacierized basins

JIM BOGEN & TRULS E. BØNSNES

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

jbo@nve.no

Abstract Methods to estimate sediment yields in ungauged glacierized areas are discussed and the sediment load in ungauged parts of the Svartisen hydropower scheme in northern Norway is estimated as an example. Long-term measurements of sediment yields of various glaciers in Norway revealed that erosion rates to a large extent are controlled by bedrock geology, glacial variables and large scale morphology of each individual glacier. Measurements of bed load G_b and suspended load G_s of two glaciers gave a relation $G_b = k\ G_s$. Long-term values of the parameter k were found to vary between 0.67 and 1.0. The existence of such a relationship is due to the fact that suspended load is derived from abrasion and crushing of the coarser glacially quarried material. In the Svartisen hydropower scheme, direct measurements of sediment fluxes were carried out at selected locations. The sediment yields of the remaining ungauged catchments were then estimated from an evaluation of each individual glacier and the underlying bedrock. This gave as a result a suspended load and a bed load of 7100 t year^{-1} and 4760 t year^{-1}, respectively, for the eastern tunnel, and of 20 300 and 13 600 t year^{-1}, respectively, for the southern tunnel complex. The amount of sediment delivered by the glaciers draining directly into the reservoir was calculated as 103 000 t year^{-1}, using sedimentation rates in dated sediment cores from the reservoir bed. The sediment yield of other glacier areas is discussed.

Key words bed load; glacial erosion rate; hydropower planning; sediment yield; suspended load; ungauged glacierized basins

INTRODUCTION

The meltwater from glaciers often carries large amounts of sediment, with a variety of particle types ranging from clay to large boulders. In order to prevent damage to the waterways and turbines of hydropower schemes, it is necessary to separate these sediments from the operational water by the construction of sand traps, sedimentation chambers or settling basins. Information about sediment volumes supplied by the glaciers is needed in order to plan the underground excavations in such a way as to minimize costs. Planning for hydropower development in glacierized areas thus needs sediment data as one of the criteria for power plant construction. Secondly, adequate planning may reduce turbine wear and environmental impacts on downstream reaches. Norwegian power schemes often include a large number of intakes to divert water. As examples, the Breheimen–Stryn and the Svartisen schemes involved diversion of water at 32 and 46 intakes, respectively. It is not possible to measure sediment transport at every intake. It may be dangerous to conduct field measurements in front of some glaciers, and elsewhere the access may be difficult. Not all glaciers have meltwater streams that can be monitored in a conventional manner, because the glacier may be calving into a lake or the meltwater may infiltrate into a block field rather than drain through an open channel. The bed load of meltwater streams is often virtually impossible to measure. Furthermore, the application of standard fluvial bed load equations is not generally valid in front of glaciers, rendering theoretical computations unreliable. Sediment yield must thus be estimated for some localities, even though numerous sediment transport monitoring stations may have been included in a hydropower scheme. Large variability of sediment transport has been observed both at short-term (hours and days) and long-term (seasonal and year to year) scales. It is thus also necessary to try to predict maximum rates of sediment load within a longer time frame.

During the recent decades, several large hydropower schemes have been completed in Norwegian glacierized basins (Wold & Østrem, 1979; Bogen, 1989; Bogen & Olsen, 1986; Bogen & Bønsnes, 2000). The objective of this paper is to discuss erosion prediction in ungauged glacierized basins on the basis of experience from these schemes and related measurements.

SEDIMENT YIELDS OF NORWEGIAN GLACIERS

Sediment transport in glacial meltwater streams has been studied for many years. Sediment concentrations in such rivers are often subject to large fluctuations within short time intervals. There is some dependence on water discharge, but no obvious direct correlation. This complex pattern may be explained by the seasonal development of the subglacial drainage system. When water pressure increases during a melt period, the melting ice delivers sediment directly into the drainage system through the expansion of subglacial cavities and tunnels. The sediment load measured in the meltwater streams is the amount that is removed from the glacier sole. The concentration of sediments in the ice at the glacier sole, however, is determined by glacial quarrying and abrasion processes. Thus, the supply of sediments over a scale of centuries is determined by glaciological parameters, whereas the actual sediment export each year is dependant on meteorological parameters controlling the rate of melting in the subglacial conduits.

One of the best studied glaciers in Norway is Nigardsbreen. Long-term measurements from this glacier cover both suspended sediments and indirect data of bed load calculated from the annual growth of the delta in the proglacial lake. The highest suspended sediment transport rates occurred during years with several flash flood events in the meltwater river (Fig. 1). Annual suspended load thus depends on the number of flash floods rather than on the total water discharge. The rate of bed load transport, however, has been highest during years characterized by large runoff volumes, i.e. 1970, 1972, 1973, 1975, 1996, 1997 and 1998. During these years, water discharge exceeded 1 800 000 m^3 day^{-1} for more than 30 days of the melt season.

The measurements of bed load and suspended load in the meltwater river from Nigardsbreen Glacier showed that the two modes of transport are related:

$$G_b = k\, G_s \tag{1}$$

There is some year-to-year variation, but $k = 1.0$ when observations for all the years on record are averaged. The same type of measurements at Bondhusbreen Glacier confirmed a similar value of $k = 1.0$, although these covered only 2 years. Measurements during the years 1976–1981 at Engabreen gave a somewhat different value of

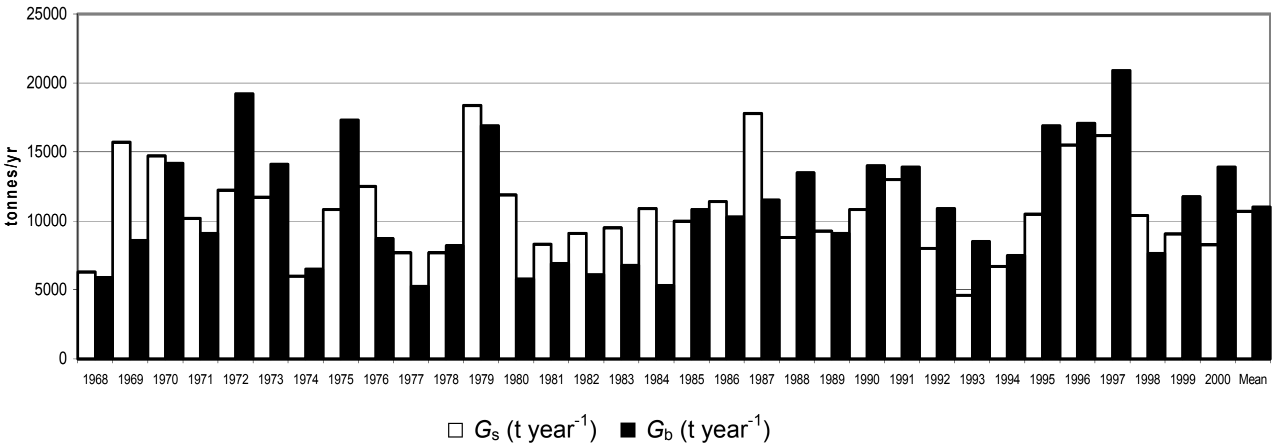

Fig. 1 Suspended sediment load and bed load in the meltwater river from Nigardsbreen during 1968–2000.

$k = 0.67$. In lowland rivers without glacial input, by contrast, the bed load is often only a small fraction of the volume of the suspended load and there is not necessarily a clear relation between the origin of the sediments carried by the two modes of transport.

The reason for the existence of the relationship between bed load and suspended load in glacial meltwater streams is that the suspended load is derived by the abrasion and crushing of coarse, glacially-quarried material. In weak bedrock, the abrasion and crushing take place at a more rapid rate. The low ratio that was observed at Engabreen is probably explained by more rapid comminution of weaker bedrock. From equation (1) it is possible to compute bed load from measurements or estimates of suspended load. As the parameter k of the sediment load from Nigardsbreen Glacier is fairly constant through time, application of this value for k is considered sufficiently reliable for the calculation of the bed load of other glaciers of the same type.

Suspended sediment yields for various Norwegian glaciers are compared in Fig. 2. The variability in suspended sediment yield between the different glaciers is large,

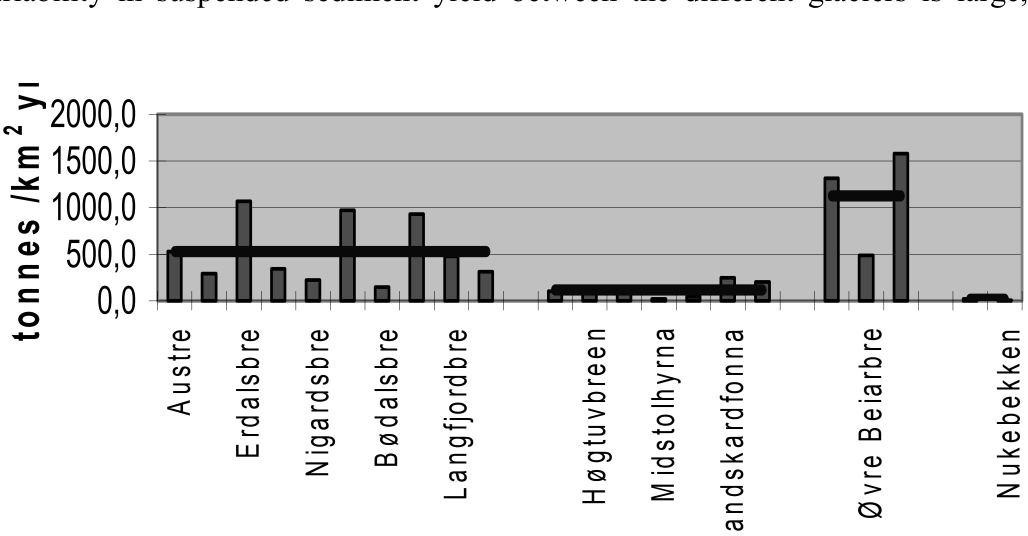

Fig. 2 Suspended sediment yield of various glaciers in Norway. Mean sediment yield of different types of glaciers are indicated.

ranging from 22 to 1577 t km^{-2} year^{-1}. This range is subdivided into three distinct groups of glaciers: (a) valley glaciers and outlet glaciers from ice caps; (b) plateau glaciers, cirques and cirque-like glaciers; and (c) glaciers in schistose rocks in the Svartisen area. Glacier type and characteristics are important factors controlling the intensity of erosion, but they are not the only ones. On igneous and metamorphic rocks of Precambrian age, erosion is particularly intense beneath large valley glaciers with several tributaries like Erdalsbreen and Tunsbergdalsbreen. Fissure zones and lines of weaknesses in the bedrock may also be of importance; this is most probably the reason why some of the valley glaciers like Nigardsbreen, Bødalsbre and Engabreen yield less than the others. The mean sediment yield of all the glaciers in this group is 528 t km^{-2} year. The yield of smaller cirque or plateau glaciers, like Stolhyrna and Tindfjellsbre, is somewhat lower than the valley glaciers, with a mean of 116 t km^{-2} year^{-1}. However, erosion by the small, cirque-like Trollbergdalsbre and Øvre Beiarbre and the glaciers in the Blakkåga drainage basin yields 1126 t km^{-2} year^{-1}. This is the highest measured sediment yield from glaciers in mainland Norway. These glaciers are located in the same rock formation where schistose and very loose rocks often occur. Trollbergdalsbreen is a relatively thin and slow-moving glacier. High erosion rates would not be expected from its glaciological characteristics.

Bedrock susceptibility to erosion thus seems to be decisive for the erosion rates of glaciers. A significant year-to-year variability of each glacier was observed. However, within the same climatic region, the ranking of erosion rates between each individual glacier remained the same from one year to another. The mean sediment yields of two glacier-free catchments in the mountain areas near the glaciers were measured to just 13 t km^{-2} year^{-1} and are included in Fig. 2 for comparison.

LONG TERM YIELDS FROM SEDIMENT CORES

Sediment cores from lakes have been used to compute sediment yields from glaciers. In proglacial lakes, the bed sediment typically accumulates as varves, reflecting changes in seasonal and annual sedimentation. Østrem (1975), Østrem & Olsen (1987) and Bogen (1979, 1995) investigated varves in several Norwegian glacial lakes in order to study sediment fluxes. In addition to the overall finer grain sizes in the winter layers, they found these layers also contained a higher proportion of fine-grained biotite than was present in the summer layers. Within some varves, thinner layers, so-called pseudovarves, were present. These laminae reflect discharge variations during the summer. In some lakes it has been possible to correlate the thickness of annual deposits with discharge (Gilbert, 1975). A summer with high discharge will show a thicker sediment layer, because more material is carried by the glacier stream into the lake. In the proglacial lake Tunsbergdalsvatn, Bogen (1979, 1995) demonstrated a degree of correspondence between varve thickness and water discharge. However, during some years there were large deviations. Varve thicknesses were larger or, in some cases, much smaller than expected from the water discharge record. Flood events of unusual character were found to have occurred during those years. The varves corresponding to the years of direct measurements of sediment supply to the lake were identified. The measurements for these years indicated that the flux of suspended sediment varied between 37 600 and 44 000 t year^{-1}. The 11-year record of varve thicknesses gave a larger range of 34 200 to 83 000 t $year^{-1}$, and a mean of 46 000 t $year^{-1}$ for the period.

In a similar study, a sediment flux of 1100 t $year^{-1}$ was measured in the meltwater river from Bødalsbre Glacier in 1986 (Bogen, 1989). Bødalsbre is an outlet glacier from the western side of the Jostedalsbre ice cap. From a study of varves in sediment cores in the proglacial lake Sætrevatn, the range of suspended sediment yield during the period 1970–1986 was estimated to range between 400 and 3600 t $year^{-1}$ (Fig. 3). The largest transport indicated by the core took place in 1979 when a flood of 100-year recurrence interval occurred in the nearby river Jostedøla (Gjessing & Wold, 1980). The mean sediment yield for the 17 years covered by the sediment core was calculated as 1200 t km^{-2} $year^{-1}$, which is not far from the value obtained in the year of direct measurements.

In the proglacial lake Bondhusvatn, Østrem & Olsen (1987) used the thickest varves from a long sedimentary record to estimate the size of extreme sediment transport events. Lake Bondhusvatn receives sediments from the Bondhusbreen Glacier, an outlet glacier of the Folgefonna ice cap. As a part of the Mauranger hydropower scheme, water was to be collected in a subglacial intake beneath the glacier. It was thus necessary to estimate the dimensions of a sedimentation chamber to collect the

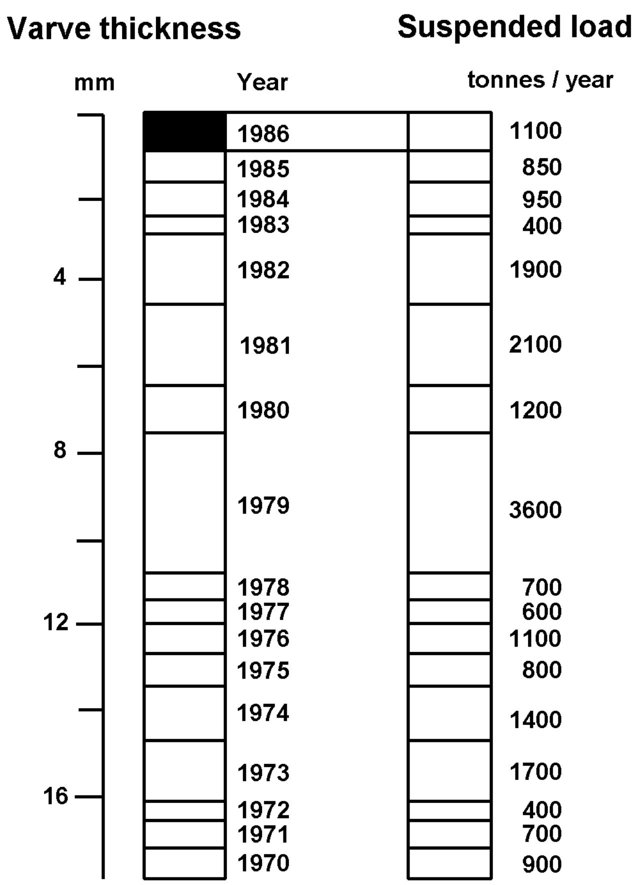

Fig. 3 Suspended sediment yield of Bødalsbreen Glacier, 1986–1970, estimated from a sediment core in lake Sætrevatn. Black infill indicates sedimentation during years of direct measurements of sediment transport in the meltwater river from the glacier.

sediment load before the water is diverted to the power station. The longest of the cores covered a varve sequence of 200–300 years. It was dated by identification of deposits related to high discharges described in the historical record. At least six of the thickest varves from each core were regarded as being the result of exceptional hydro-meteorological events in the past. The volume of the corresponding deposits on the lake bottom was calculated and it was shown that a mean annual total of 9100 m^3 of suspended sediments would be delivered by the glacier in events happening about twice a century.

THE SVARTISEN POWER PLANT

At the Svartisen power plant, water is collected through 45 intakes in a complex tunnel system with a total length of 100 km (Fig. 4). Water is then transferred from the

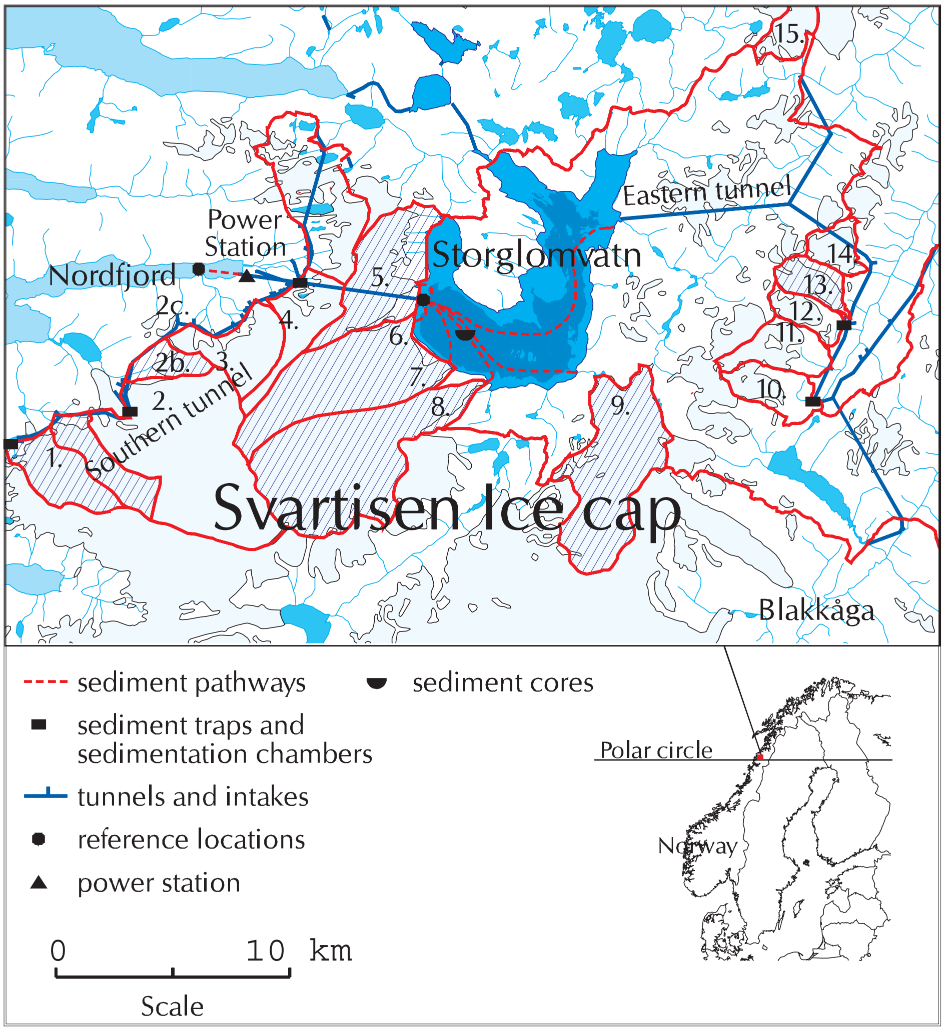

Fig. 4 Diversion tunnels and intakes of the Svartisen power plant. The sediment yield for some glaciers (cross-hatched) had to be estimated. The other numbered glaciers have been subject to direct measurements of sediment yield. Names of glaciers in Table 1. The sediment pathways refer to those used in the routing model.

reservoir or directly from the tunnels to the power station. The station is situated at sea level, thus utilizing a hydraulic head of 585 m at maximum reservoir level.

During the planning phase it was necessary to estimate or measure the sediment supply to the various parts of the system. A long-term programme was carried out on one of the glaciers, Engabreen, during 1970–1981. During the same decade, the sediment yield of a number of Norwegian glaciers in other areas was measured. A large year-to-year variability for each glacier was observed. However, within the same climatic region, the ranking of sediment yield between each individual glacier seemed to remain fairly constant from one year to another. Thus, it was assumed that the annual variability of the Engabreen Glacier gave an indication of the scale of the variations to be expected at other glaciers in the area. This means that the ratio (r) of the sediment yield of Engabreen during a certain year (G_{yr}), and the mean sediment yield of the whole period of measurement (G_{mean}), is assumed to be the same for all the glaciers in the region. In 1989, the sediment yield of Engabreen and a number of other glaciers were measured. The mean sediment yield of each of these glaciers were thus calculated from the relation $r = G_{1989}/G_{mean}$. The reason that such a relation exists is that the sediment transport is related to the effect of a number of hydrometeorological events, which in turn determine the development of the subglacial drainage system and hence the sediment availability. These events tend to vary in the same manner within the same climatic region. An example of such hydrometeorological events is the number of flash floods during the melting season rather than the total annual runoff. In addition, the sediment transport during flash floods resulting from a combination of glacier melt and rain also tends to be higher than during an event arising from a rainstorm alone.

The Øvre Beiarbre and Trollbergdalsbreen glaciers drain to the eastern tunnel of the Svartisen power plant. These glaciers did not follow the year-to-year variations of Engabreen, but vary in a more unpredictable manner. During some years their yields are very high, but they are fairly low in the intermediate years. These glaciers are characterized by very high sediment yields, even though they are small in size and move very slowly. Bogen (1996) suggested that the irregular pattern of year-to-year variations was due to shifts in the position of the subglacial drainage system. In the years following a shift in position, the availability of sediments increased. As sediments are washed away, the sediment delivery decreases.

The sediment yield of glaciers 1, 2b and 13 was estimated from the yields given in Fig. 2. Fonndalsbre (no. 1) and Lillebre (no. 2b) in Table 1 were assumed to have the same yield as Engabreen (342 t km^{-2} year^{-1}). Skjelåtindbre (no. 13) was assessed to have a yield of 450 t km^{-2} year^{-1}, which is the same as the nearby Hanspolsabre (no. 14). The bed load of all the glaciers was computed from relation (1). This gave a total suspended load and bed load of 7100 and 4760 t year^{-1}, respectively, for the eastern tunnel, and of 20 300 and 13 600 t year^{-1}, respectively, for the southern tunnel complex. Four sand traps and one sedimentation basin were constructed along the tunnels.

When the Svartisen power plant was put into operation, extensive sediment pollution was observed in the downstream fjord area. To analyse the contribution from different types of sources, it was necessary to determine the sediment supply from the glaciers draining into the Storglomvatn Reservoir. This was done by means of

Table 1 Measured and predicted sediment yield of glaciers draining to the Svartisen power plant.

Glacier/Catchment	No.	Area of glacier (km^2)	Suspended transport (t $year^{-1}$) 1987	Suspended transport (t $year^{-1}$)	Bed load (t $year^{-1}$)	Suspended yield (t km^{-2} $year^{-1}$)
Fonndalsbre	1	7		2400	2400	342
Engabre	2	36.2	9300	12400	8270	342
Lillebre	2b	1.84		630	420	342
Botteløyra/bre	2c	0.31	28	28	30	90
Dimdalen	3	7.5	2000	4000	3100	533
Frokostind bre	4	8.73	600	800	550	92
Storglomvatn	5–9	95		103000		1084
Øvre Beiarbre	10	2.4	1500	1160	773	488
Lappflyttar elv	11	5.3	80	125	83	24
Trollbergdalsbre	12	2.02	950	2345	1560	1173
Skjelåtindbre	13	1.28		576	384	450
Hanspolsabre	14	2.67	800	1200	850	449
Vegdalen	15	3.21	1150	1700	1130	530

Note: The sediment pathways refer to those used in the routing model.

sediment cores from the reservoir (Bogen *et al.*, 1996). A total of 22 cores were recovered from the bed sediments in various parts of the lake. Dating of the sediment cores was based on varve counts. The bathymetry of the reservoir is complex, exhibiting several basins. For the studies, the reservoir was divided into a number of zones and a sedimentation rate was calculated for each zone. The longest core was 1.8 m and covered a time span of several hundred years.

Large variations in sedimentation rates were found. The mean varve thickness during each decade of the period 1695–1845 is shown in Fig. 5. During this period, the mean sedimentation rate was around 1.6 mm $year^{-1}$. After 1850 it increased slowly to about 2.5 mm $year^{-1}$ by 1920. From that time, there was an abrupt increase to nearly 7 mm $year^{-1}$ in the last decade (1985–1995). The general increase in runoff after the "Little Ice Age" of the 17th century increased the sediment supply to the lake. When reservoir regulations first started in 1920, a period of heavy erosion of sediments during low drawdown was initiated. The general increase in sedimentation rate shown in Fig. 5 is thus due to the combined effect of these two factors.

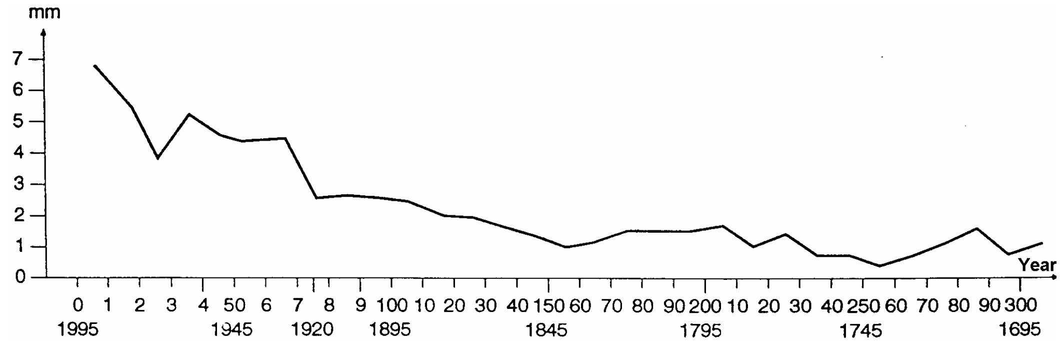

Fig. 5 Sedimentation rates in lake Storglomvatn during 1695–1995.

The period 1850–1920 was selected as a reference period not affected by reservoir erosion. The sedimentation rates of the various zones of the lake and the corresponding sediment supply during this reference period are given in Table 1. The sedimentation rates within the various sectors range from 1.3 to 3.4 mm year^{-1}. Applying a sediment density of 2.0, the sum of all sectors adds up to 103 000 t year^{-1}. Five large glaciers and a number of smaller ones drain to the Storglomvatn Reservoir. The total glacier area of 95 km^2 gives a mean sediment yield of all these glaciers of 1084 t km^{-2} year^{-1}. This is above the yield of the glaciers draining to the southern tunnel, but well within the range of the eastern glaciers in Blakkådalen and Beiardalen. A routing model was applied to calculate the amount of sediments remaining in suspension in downstream water bodies. This indicated that the contribution from the reservoir glaciers accounted for 55% in the downstream fjord area in 1995. It was predicted that the operation of the power station and the water level in the reservoir would affect the flow of sediment-laden water from the different sources.

DISCUSSIONS AND CONCLUSIONS

There is a large variability in the sediment yield of different Norwegian glaciers. In a global context, however, the variability is even larger (Fig. 6). The glaciers on the southern coast of Alaska yield in the order of 100 000 t km^{-2} year^{-1}. This is approximately two orders of magnitude higher than the typical rates of between 100 and 1000 t km^{-2} year^{-1} reported for Norwegian glaciers. Sediment yields of 12 000 t km^{-2} year^{-1} have been measured beneath the large glacier Vatnajøkull in Iceland (Tomasson, 1987). In the Swiss Alps, yields range from 3000 to 6000 t km^{-2} year^{-1} (Bezinge, 1987; Small, 1987). Chernova (1981) reports 8000–13 500 t km^{-2} year^{-1} for basins in Central Asia. The variability between the different regions reflects the combined effect

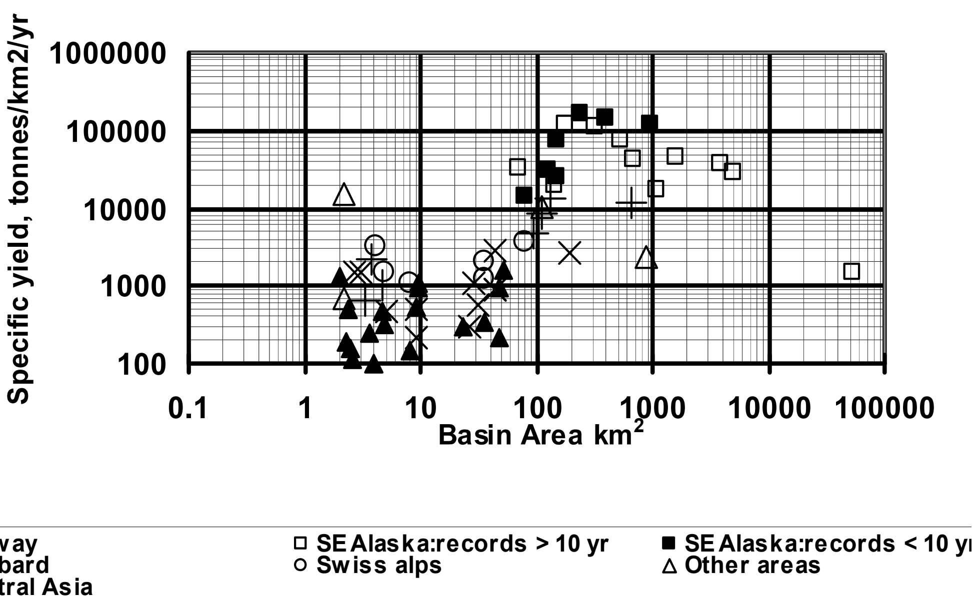

Fig. 6 Sediment yield of various glacierized basins. Modified after Hallet *et al.* (1996).

of glacier dynamics, glacier temperature regime, and bedrock susceptibility to erosion. Thus, in an area where little information exists, predictions should be based on long-term sediment monitoring programmes at selected stations. Such measurements will indicate the level of sediment yield within the area and the range of year-to-year variation.

Sediment cores may be helpful for obtaining long-term data where sediment monitoring programmes are lacking. However, this requires suitably located proglacial lakes or fjords, preferably with varved bottom sediments. Such core data, however, often reflect sediment flux from a larger area rather than from a single glacier. To relate the sediment supply to individual intakes, more detailed estimates are necessary. The dynamic state of glaciers may also be subject to changes within the lifetime of a power plant. Glacier advances may push up moraines and thus bring more sediment into positions where it may be exposed to fluvial erosion. However, the very thin varves in the sediment core from the Storglomvatn Reservoir during the large glacier advances in the 17th century show that a large proportion of the precipitation will be stored in the glacier as snow and ice, and so dampen rather than enhance meltwater transport and sediment flux.

The relation between bed load and suspended load is most probably variable because of bedrock type, but there is little data available. Gurnell (1987) found the percentage of total load to vary between 33 and 40% (k = 0.49–0.67) in a 2-year study in front of Tsidjiore Nove in Switzerland. Hammer & Smith (1983) reported a variation of between 55 and 59% (k = 1.21–1.43) at Hilda Glacier in Canada. In regions with softer rock, one would expect the increased crushability of the glacier substrate to result in a smaller bedload contribution.

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