Annals of Glaciology 13 1989
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GLACIAL SEDIMENT PRODUCTION AND DEVELOPMENT OF HYDRO-ELECTRIC POWER IN GLACIERIZED AREAS

by

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ABSTRACT

This paper discusses the results of a sediment-monitoring programme carried out in connection with hydro-electric power development plans in the river basins surrounding the Jostedalsbreen ice cap in Norway. Whereas the highest suspended-sediment transport rates occur during years with several flash-flood events, the bed load is more dependent upon the duration of large magnitude flood events. Bed-load transport has been obtained from annual measurements of deltaic growth in small lakes at the front of glaciers. During the years 1968–86, the mean ratio of bed load to total load amounted to 0.30–0.50% of the total load, but in years with large magnitude floods this ratio decreased. The mean annual suspended sediment yield of Norwegian glaciers ranges from 100 tonnes km^2 a^{-1} to 1300 tonnes km^2 a^{-1}. Valley glaciers cause the highest erosion rates, with the exception of the small cirque glacier, Trollbergdalsbreen, which is thought to be a soft bed glacier. The investigation programme undertaken involved monitoring the volume of suspended sediments, together with the size distribution, mineralogy and shape of grains. In general, the valley glaciers supply more sand than the smaller cirque glaciers, whereas particles in the fine sand and silt-size ranges in almost all of the glaciers are angular in shape. Methods of comparing the abrasive capacity of the sediment load at various intakes in a power plant are discussed. Long-term sediment supply from the glaciers was investigated by studies of varves and rythmites in sediment cores from glacier-fed lakes.

INTRODUCTION

During the last few years, several glacier areas in Norway have been developed for hydro-electric power. In this paper the results of a sediment-monitoring programme carried out in connection with hydro-electric power plans in the river basins surrounding the Jostedalsbreen ice cap are discussed. The hydro-electric power plans on the western side, the Breheimen–Stryn Project, involve diversions of water at 32 intakes (Fig. 1). Of these, 14 intakes were selected for sediment transport measurements, together with a further station for reference. In the Jostedal project, several stations have been set up in order to monitor the future changes caused by river regulation. Of these, however, only Nigardsbreen station has been operational for a significant period. The water 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 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 from the glaciers is necessary in order to plan the excavation of underground space in a manner which will make possible the location of sedimentation chambers where turbine wear will be minimized. Even if all the bed load is removed, turbine wear due to abrasion by suspended load will still take place.

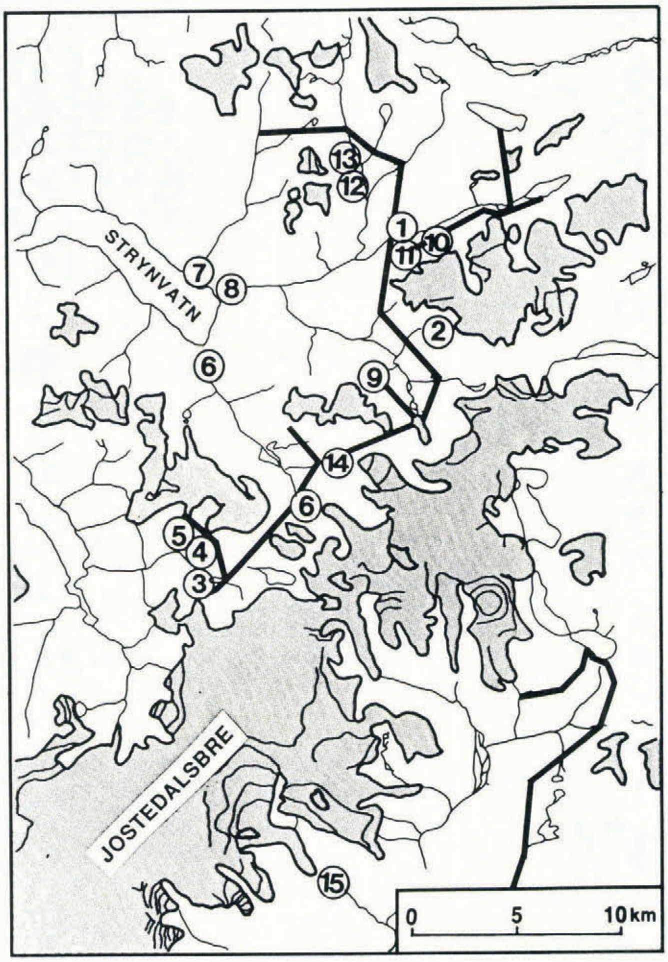

Fig. 1. Sediment-monitoring stations, Breheimen–Stryn project. Stations 1–14 are part of the project, and station 15 is included as a reference station.

It is not possible to construct settling basins to separate the suspended load at all intakes, but examination of sediment load, mineral composition and grain-size at the various intakes in a power plant offers an opportunity for comparing the abrasive capacity of various glaciers. If glaciers of large abrasive capacity are identified during the initial stages of plant planning, financial resources may be concentrated on constructing settling basins and sand traps on selected intakes, and costs may thus be reduced.

Suspended sediments influence river conditions with respect to the content of nutrients, metals, bacteria or pesticides, and also modify light conditions and hence influence photosynthesis. Coarse sediments supplied from glaciers form the river beds and provide substrates for living organisms, and for this reason sediment load affects the ecological conditions in river basins. The significance of sediment load monitoring programmes for the management of Norwegian rivers has been discussed by Bogen (1986a). In this paper, data from the monitoring programme of selected glaciers are discussed.

METHODS

In the monitoring programmes carried out by the Norwegian Water Resources and Energy Administration (NVE) up until 1980, samples of suspended sediments were collected manually four times a day, and hourly during flood events throughout the months of June to September. The procedures used have been described by Østrem (1975). Since 1980 automatic sampling has been carried out, ISCO model 1680 or 2700 samplers which are installed in the manner described by Bogen (1986b), and are programmed to collect samples four times a day. Analysis of the grain-size distribution of large volume samples collected each week is also carried out. Samples are filtered through Whatman GF/C filters and the sediments are ignited at 500°C. Weights are determined using a balance to 0.1 mg precision.

The size distribution of material larger than 0.063 mm in diameter is determined by wet sieving, and that of finer material is analysed with a Shimadzu centrifugal analyser. A bulk sample composed of the filtrates of a number of water samples is selected for mineral analyses by microscopy and X-ray diffraction.

NIGARDSBREEN GLACIER

The monitoring programme of sediment transport in the melt-water river from Nigardsbreen has continued since 1968. The transport of suspended load is subject to large variations from year to year (Fig. 2), mean transport is about 12×10^6 kg a^{-1}. The annual transport of suspended load seems to be dependent upon the number of flash-floods. The largest rates occur during years with several flash-flood events. There is an apparently poor correlation between annual water discharge and annual sediment transport.

The largest recorded transport rate of suspended load occurred in 1979, a year in which a large magnitude flood occurred. Estimates of bed load have been obtained by annual measurements of deltaic growth in Lake Nigardsvatn down-valley from the glacier. During the years with large run-off volumes the magnitude of the bed load was low. The largest transport rate of bed load occurred during the years 1970, 1972, 1973 and 1975. These years differ from the others in that the discharge exceeded 1.8×10^6 m^3 d^{-1} for more than 30 d of the melt season. The year 1969 was exceptional in that bed-load transport rate was relatively low despite a long-lasting high discharge. This indicates that the availability of sediments is also an important factor controlling the transport rate. It is thought that the movement of bed load through subglacial tunnels is slow when compared with that of the suspended load. The bedload that is melted out from the ice moves through the tunnels over the course of several days or weeks, whereas the suspended load may be carried away in some hours. The production of suspended load takes place by abrasion and crushing of larger blocks beneath the glacier, and bed load and suspended load are therefore related. In the melt-water river from Nigardsbreen the ratio of bed load to total load is approximately 0.5 : 1.0 (Fig. 3). The spread of data points is probably due to differences in the transfer mechanisms of the two transport modes. At Engabreen, comparable measurements have shown a ratio of bed load to total load of about 0.4 : 1.0. The difference between the two ratios is probably due to differences in rock type.

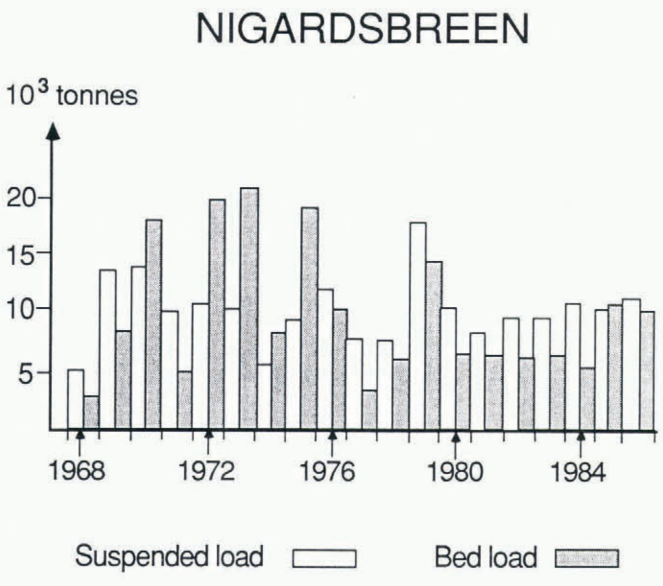

Fig. 2. Measurements of bed load and suspended load, 1968–86, in the melt-water river from Nigardsbreen.

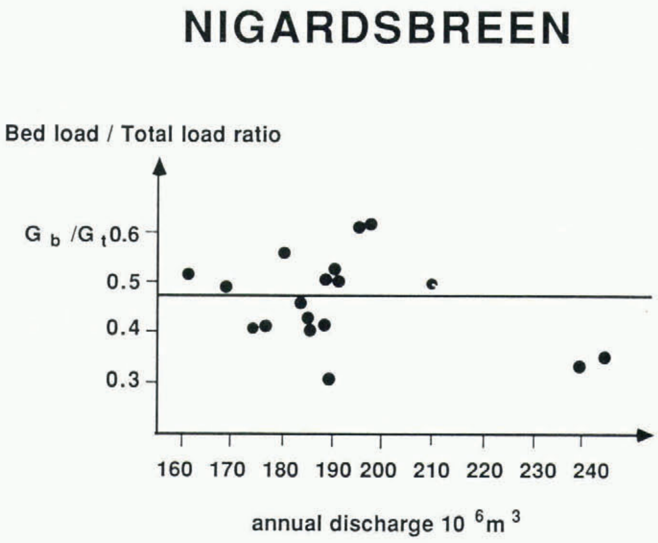

Fig. 3. Ratio of bed load to total load in melt-water river from Nigardsbreen.

BREHEIMEN–STRYN GLACIERS

The results from the 14 stations of Breheimen–Stryn power plant are given in Table I. Erdalsbreen supplies the

TABLE I. ANNUAL SEDIMENT LOAD, SIZE, SHAPE, AND MINERALOGY OF GRAINS IN SAMPLES FROM VARIOUS GLACIER INTAKES OF BREHEIMEN–STRYN POWER PLANT

	Monitoring station	*a*	G_S	*r*	*q*	*d*	*S*
1	Videdøla	2	850	4.8	0.6	0.3	734
2	Tverrelvskardet	72	8 800	5.0	0.6	0.39	10 296
3	Bødalsbre	69	1 400	4.8	0.3	0.3	604
4	Skålbre	66	1 500	5.0	0.53	0.48	1 908
5	Tindefjellsbre	49	200	4.8	0.4	0.2	76
6a	Erdalselv	38	4 700	5.0	0.5	0.36	4 230
6b	Erdalsbre	82	10 400	5.0	0.4	0.38	7 904
7	Glomsdøla	19	700	5.0	0.5	0.51	892
8	Hjelledøla	18	9 700	5.0	0.56	0.25	6 790
9	Sandsvora	50	450	4.5	0.50	0.45	455
10	Steinhusflate	50	230	4.0	0.45	0.1	41
11	Nukebekken	24	3	5.0	0.5	0.47	4
12	Midstolhyrna	30	20	4.5	0.5	0.18	8
13	Stolhyrna	22	33	4.8	0.4	0.26	16
14a	Vetledalsbre	60	394	5.0	0.58	0.14	159
14b	Vetledalsvatn	38	250	5.0	0.5	0.04	25

a: per cent glacier area; G_S: suspended load (tonnes a^{-1}); *r*: grain shape; *q*: proportion of quartz in 0.063–0.125 mm range; *d*: proportion of sand; *S*: abrasion capacity.

largest amount of sediment load, the outlet glacier from Tystigbreen in Tverrelvskardet is also a high sediment-producing glacier and the large outlet glacier, Bødalsbreen, was found to be a low-producing glacier. There is no obvious reason for the high sediment yield of the irregular and plateau-like Tverrelvskardet glacier unless these high rates are explained as being due to properties of the bedrock. An analysis of the seasonal variation shows that sediments are more easily flushed out of Bødalsbreen. During floods occurring late in the summer the subglacial drainage system of the high-lying Tverrelvskardet glacier is almost completely closed, and precipitation falls as snow. At this site there was no sediment transport during the flood of 31 September 1986 (Fig. 4), although at Bødalsbreen this flood carried the largest amounts of sediment of that year.

The forecasting of glacier advance or retreat is important to the operation of the power plant. The large sediment load of Erdalsbreen must be separated from the operational water before this water is taken into the tunnel and for this reason a relatively large sedimentation chamber had to be constructed above the intake. However, during recent years the glacier has receded and a lake has appeared. The bed load is at present trapped in this lake. A comparison of station 6A, below the present lake, in Table I, and measurement of the load of Erdalsbreen (station 6B) before the lake appeared, shows that a large part of the suspended load is also trapped in this lake (Table I). If the glacier were to re-advance, it is predicted that the trap efficiency of the lake would be less.

Sediment cores from lakes may be used to obtain information about the long-term sediment supply from glaciers. Knowledge of the volume of the sediment supply during floods of extreme magnitudes is essential when the dimensions of sedimentation chambers or sand traps are to be evaluated. The sedimentary deposits in lakes in front of glaciers often contain layered sequences, depicting the seasonal changes in sedimentation. If the year with direct measurements of sediment transport based on water samples can be identified in the sediment core sequence, the transport during a number of years may be evaluated. This was achieved for Lake Sætrevatnet which lies in front of Bødalsbreen in Stryn (Fig. 5). The information contained in the sediment core shows that the direct measurements in 1986 are close to the mean for the last 17 years of 1.2×10^6 kg a^{-1}. However, several of the years included in this period show a suspended load considerably above the mean.

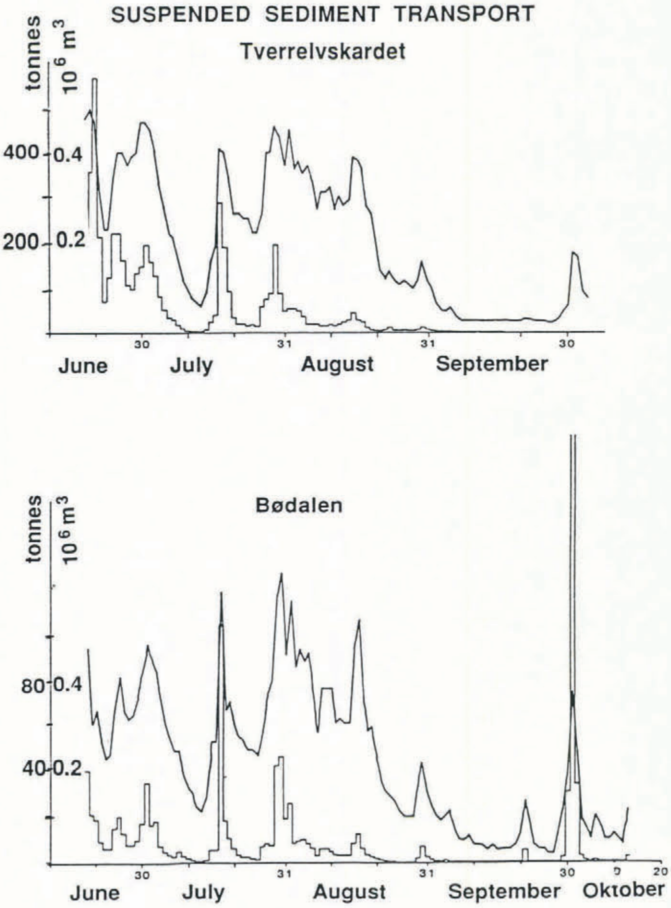

Fig. 4. Water discharge (curves) and suspended-sediment transport (columns) in melt-water rivers from Tverrelvskardet glacier and Bødalsbreen. Note difference in sediment-load scales.

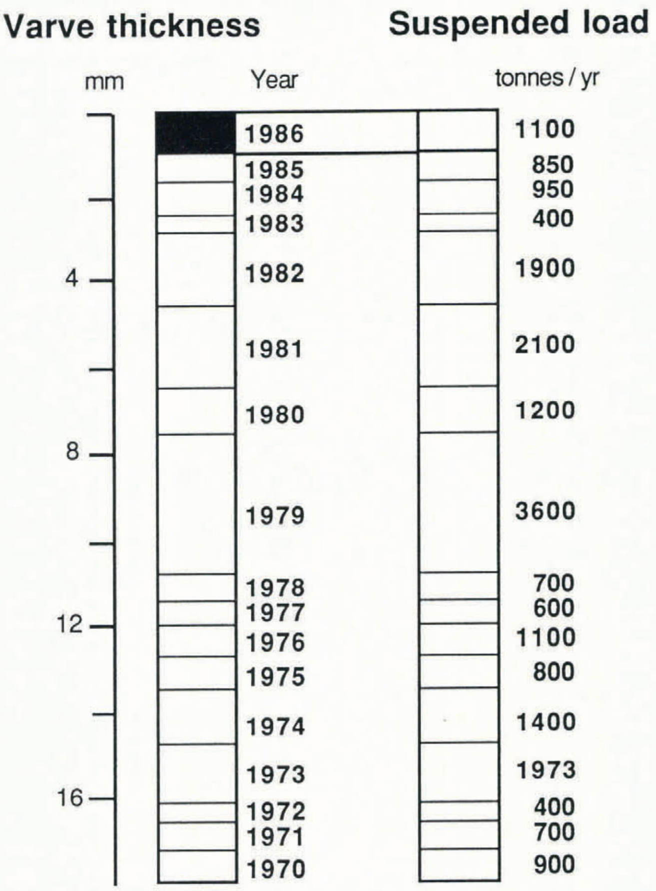

Fig. 5. Suspended-sediment yield from Bødalsbreen, 1986–70, estimated from a sediment core in Lake Sætrevatn.

The deposits from large-magnitude floods may be seen as larger layers of coarse sand and sometimes organic material embedded in a sequence of silty material. This is the case in Bondhusvatn, where a number of large-magnitude floods from the last 200 years could be identified (Østrem and Olsen, 1987). The required sedimentation-chamber volume of the subglacial intake beneath Bondhusbreen was then estimated from the sediment core information.

SIZE DISTRIBUTION OF SUSPENDED SEDIMENTS

The grain-size distribution within the sediments suspended in the melt-water rivers was analysed in samples from different discharges throughout the summer. A selection of samples indicates a large variability between sediments produced by different glaciers; the large valley glaciers contain large amounts of sand and silt and less clay (Fig. 6), while some of the smaller cirques supply sediments containing more of the finer fractions. Steinhusflatebreen contains more fine particles than any other measured Norwegian glacier; the mean of ten samples taken at different water discharges showed that only 10% of the particles are larger than 0.063 mm diameter, and as much as 33% of the sediment is composed of particle sizes less than 0.002 mm. In the melt-water river from Tverrelvskaret, there is an increase of grain-size with increasing discharge, but the first flood of the season carries less sand than floods

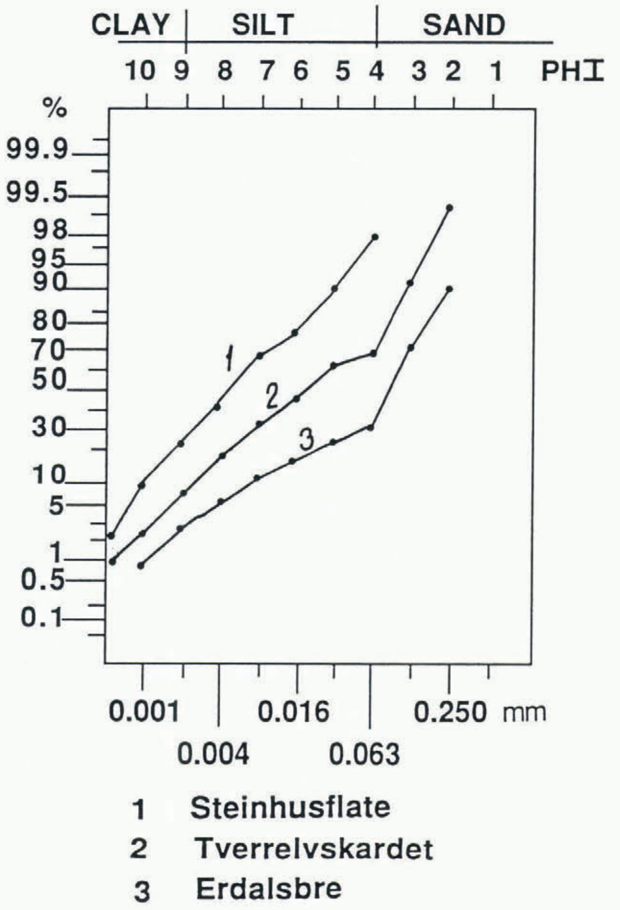

Fig. 6. Grain-size distribution curves for selected glaciers in Breheimen–Stryn project. (1) Steinhusflategrovi, (2) Tverrelvskaret, (3) Erdalsbreen.

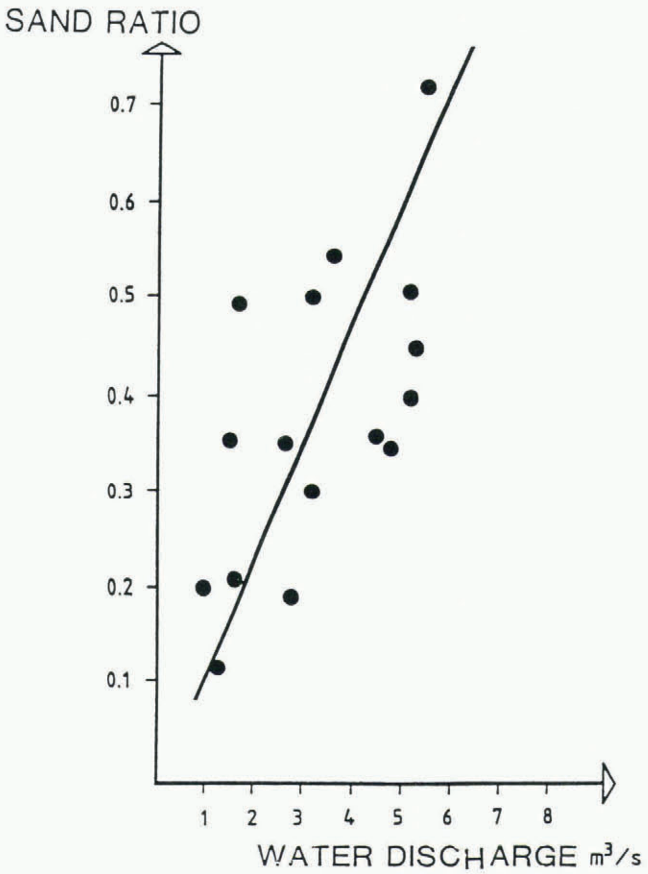

Fig. 7. Sand fraction size in melt-water river from Tverrelvskardet glacier.

occurring later on (Fig. 7). During low discharges of less than 1 m^3/s, sand content is less than 20%. A typical sand content is between 45 and 50%, and values may reach 70% during the greatest water discharges. Grain-size is an important variable influencing the turbine wear and environmental effects.

The data from Tverrelvskardet show that grain-size distribution may vary in the same complicated manner as does sediment concentration. Calculations carried out by Bogen (1980) predict hysteresis effects in size distribution during variable water discharge conditions.

TURBINE WEAR

Turbine wear increases with the total amount of suspended sediment passing the sand traps, but the grain size and mineralogy of the sediment particles are also of importance. For example, sand abrades more than silt, and quartz causes more wear than the softer feldspar minerals. Thus, during the plant design stage, it is important to investigate the mineral composition of the suspended sediment. The mineral composition of two glaciers in the drainage area of Breheimen–Stryn power plant is shown in Figure 8.

The suspended load from Skålbreen contains a considerable amount of quartz — more than 50% of the total. The sediments of Bødalsbreen contain less quartz, and the increase in proportion of quartz with decreasing grain size in the range 0.5–0.125 mm is much less pronounced. This implies that a settling basin in front of Bødalsbreen will have little effect on turbine wear. The Breheimen–Stryn power plant involves diversion of at least 14 streams carrying sediment-laden water. In order to evaluate the abrasive capacity of the water supplied to each individual intake the total suspended load, particle-size distribution, grain shape, and mineralogy have to be investigated.

Bouvet (1958), in a study of abrasion, gave the following formula for the erosive power of sand particles moving along a concave surface:

$$P = \mu v \frac{\rho_s - \rho_w}{R} V^3 \qquad (1)$$

where P is the abrasive power in kW, μ is the friction coefficient between particles and surface, v is the volume of particles in m^3, ρ_s is the density of particles in kg/m^3, ρ_w is the density of water in kg/m^3, R is the radius of curvature of the surface in m, V is the velocity of particles in m/s.

This formula shows the importance of the volume and mass of particles and of their velocity, which appears to the third power. When comparing various intakes at the same altitude abrading the same machinery velocity and radius of curvature are not important. Thus, the following formula is postulated to take into account the variables in Bouvet's formula to obtain variables that are more easily measured in a sediment transport survey:

$$S = G_s r q d \qquad (2)$$

where S is the measure of abrasive capacity of the sediment load, G_s is the annual suspended load in tonnes, r is the grain shape classified according to a scale ranging from 1 (well rounded) to 5 (sharp edged), q is the proportion of quartz in the range 0.063–0.125 mm to the proportion of other minerals in the same range, d is the proportion of sand grain-sizes (in the range 0.063–0.5 mm) expressed as a fraction of the weight of the suspended sediment sample.

The S value of each individual intake in the Breheimen–Stryn power plant was evaluated by substituting in Equation (2); the results are shown in Table I. As expected, the high-producing glaciers, in particular Tverrelvskaret and Erdalsbreen, also possess high abrasive capacity. However, Skålbreen also has a high S value due to the large sand fraction composed of sharp-edged quartz.

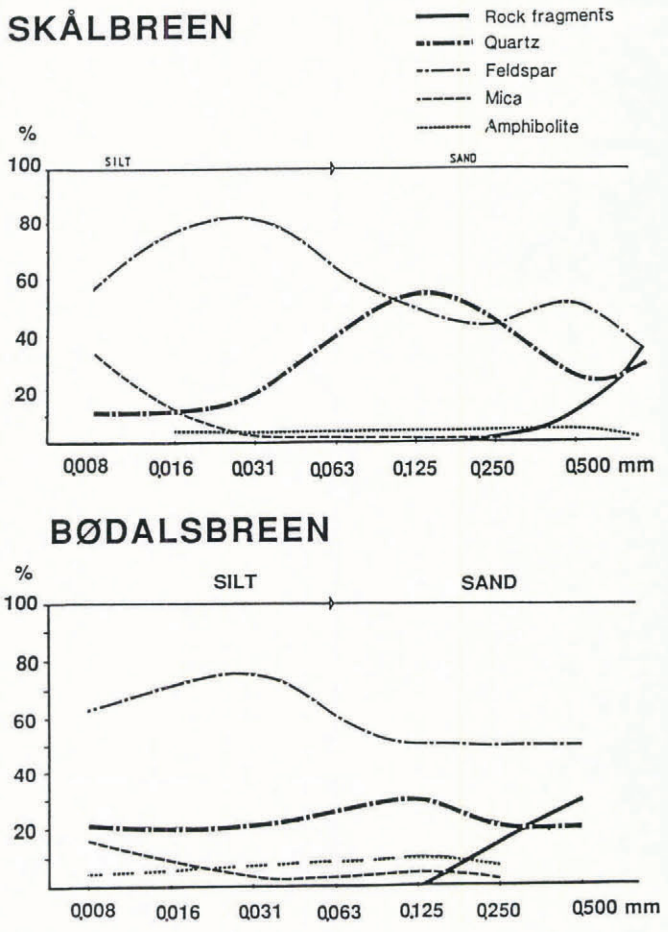

Fig. 8. Mineral composition of Bødalsbreen and Skålbreen.

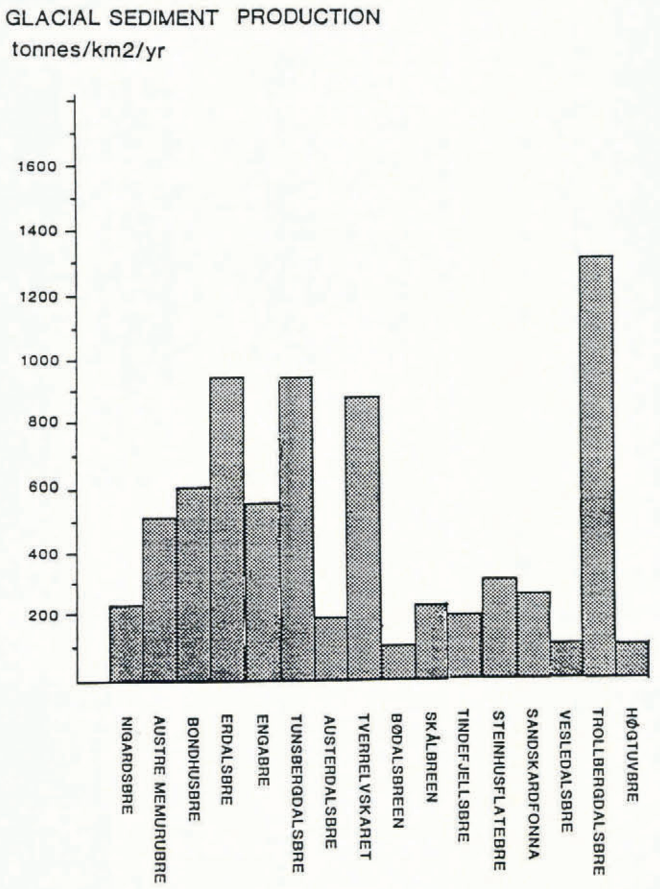

Fig. 9. Mean annual sediment yield of measured glaciers in Norway.

DISCUSSION AND CONCLUSIONS

Two types of process have to be taken into account in a sediment survey. The long-term sediment supply is controlled by the glacial erosion whereas sediment-transport rates during single floods are more dependent on the availability of sediments during a particular situation. The highest suspended-sediment transport rates occur during years with several flash flood events, whereas the bed load is more dependent upon the duration of large magnitude flood events. At Nigardsbreen, the ratio of bed load to total load amounts to 0.3–0.5 : 1.0 for the years 1968–86. Grain-size distribution of suspended sediments is subject to large variations throughout the season. There is an increase in grain-size with increasing discharge, but the first flood of the season normally contains less sand than do later floods. In general, the large valley glaciers contain large amounts of sand and silt and smaller amounts of clay. Sediment cores from lakes may be used to obtain information about the long-term sediment supply from glaciers and large-magnitude floods may be identified from larger layers of coarse sand, and sometimes organic material, embedded in a sequence of silty material.

The mean annual sediment yield of the glaciers from the Jostedal–Stryn area is compared with other measured glaciers in Norway in Figure 9. The variability in sediment yield between different types of glaciers is large and ranges between 100 tonnes km^{-2} and 1300 tonnes km^{-2}. On igneous and metamorphic rocks of Precambrian age the greatest intensity of erosion occurs beneath large valley glaciers with several tributaries, like Engabreen, Erdalsbreen, and Tunsbergdalsbreen. The yield of smaller cirque or plateau glaciers, like Vesledalsbreen and Høgtuvbreen, is an order of magnitude lower. However, erosion by the small cirque-like Trollbergdalsbreen in the schistose rocks of the Svartisen area provides the highest measured sediment yield from a Norwegian glacier. Trollbergdalsbreen is possibly a soft-bed glacier, whereas the other observed glaciers in Norway are resting on hard bedrock. The sediment yield of even the high-producing Trollbergdalsbreen is small when compared with that of certain glaciers outside Norway. In Switzerland, where large abrasion rates in power plants have been experienced, sediment yield has been estimated as 6×10^6 kg a^{-1} km^{-2} (Fig. 10) (Bezinge, 1978). In Iceland, erosion rates are as high as 12×10^6 kg a^{-1} km^{-2} beneath Vatnajøkull (Thomasson, 1987), although despite these extremely high erosion rates turbine wear has not been noted as a problem. This is most probably due to the softness of minerals in the dominant volcanic rocks, and to the relatively low hydraulic heads in use.

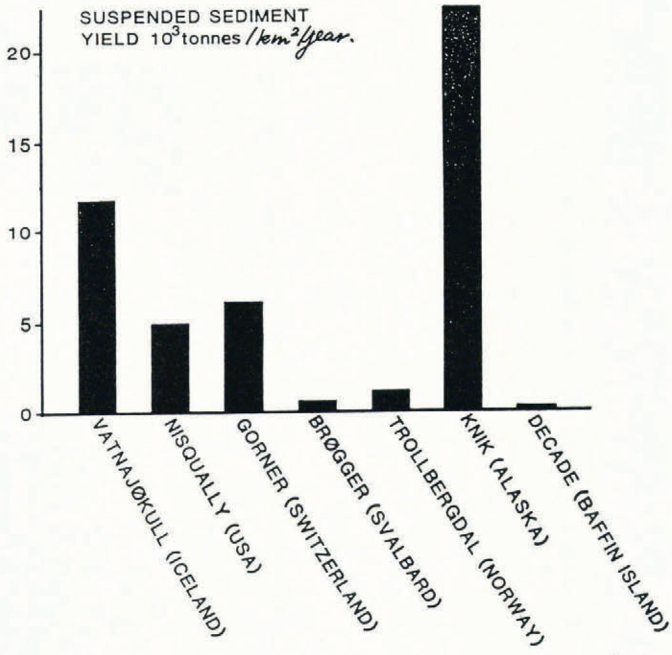

Fig. 10. Comparison of maximum suspended-sediment yield from various areas. (Data from Østrem, 1967; Guymon, 1974; Bezinge, 1978; Metcalf, 1979; Tomasson, 1987.)

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