The impact of climate change on glacial sediment delivery to rivers

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Abstract Climate change scenarios indicate that most glaciers in Norway will have disappeared by the year 2100. As the downstream river reaches are often completely dominated by glacial sediments, large environmental changes are expected. This paper discusses and reviews sediment transport studies in order to deduce the impact of climate change on the sediment delivery of glaciers. Sediment monitoring programmes have revealed large seasonal and year-to-year changes in sediment transport that reflect the rate of melt-out and flushing of sediments in the subglacial conduits and cavity systems. Long-term changes in sediment delivery were revealed by sedimentation rates in proglacial lakes. It was found that the reduction in the glacier volumes during the last 300 years and the increased meltwater runoff, were accompanied by an increase in suspended sediment supply. A doubling of the sediment yield is estimated for the Nigardsbreen Glacier during the period 2070–2100, due to predicted temperature rise.

Key words glacial erosion; sediment delivery; climate change; sediment transport

INTRODUCTION

Glaciers are very efficient agents of erosion. In Norway the sediments delivered from the glaciers often dominate the downstream river reaches and large environmental changes are expected when they melt away. This paper focuses on six glaciers in Norway (Fig. 1). The total glacier-covered area in mainland Norway is 2806 km^2, distributed between 1600 individual glaciers covering about 1% of the area. Sediment transport monitoring programmes have shown that the specific sediment yield of glacier-fed river basins is most often larger than in basins only exposed to fluvial erosion. Typical erosion rates in this region are observed to be in the range 100–1000 t km^{-2} year^{-1} in mainland Norway (Bogen, 1996). The variability of the erosion rates between the different regions reflects the fact that they are largely controlled by bedrock geology, glacial variables and the large-scale morphology of each individual glacier. Compared to other glacierized areas, the sediment delivery of Norwegian glaciers is of moderate magnitude (Hallet *et al*., 1996), and the sediment delivery may be characterised as availability-controlled; there are no long-lasting correlations between sediment concentration and water discharge in glacial meltwater rivers.

Climate change scenarios indicate that extensive glacier melting will take place in this region towards the year 2100. This paper will discuss and review sediment transport studies in order to deduce the impact of climate change on the sediment delivery of glaciers.

SEDIMENT MEASUREMENT METHODS

The sediment yields discussed in this paper are all based on high-frequency sampling programmes and laboratory analyses following procedures established by the Norwegian Water Resources and Energy Directorate, as described by Bogen (1996) and Bogen & Bønsnes (2003a). ISCO automatic pumping samplers are installed in very turbulent river reaches with full mixing. Before 1982, manual samples were taken in the same way. Samples have been collected 2–4 times every day throughout the runoff season and most programmes have lasted for at least 5 years, and longer at reference sites. Sediment monitoring stations have been located in the glacial meltwater rivers close to the glacier fronts. Water stage has been recorded by data loggers and calibrated to water discharge measurements by establishing stage–discharge curves in reaches with stable beds. Water discharge is most often carried out by salt dilution measurements. Water samples are filtered through Whatman GF/C filters and the concentration of organic and inorganic particulate matter is determined by repeated weighing and by ignition at 500°C for 2 h.

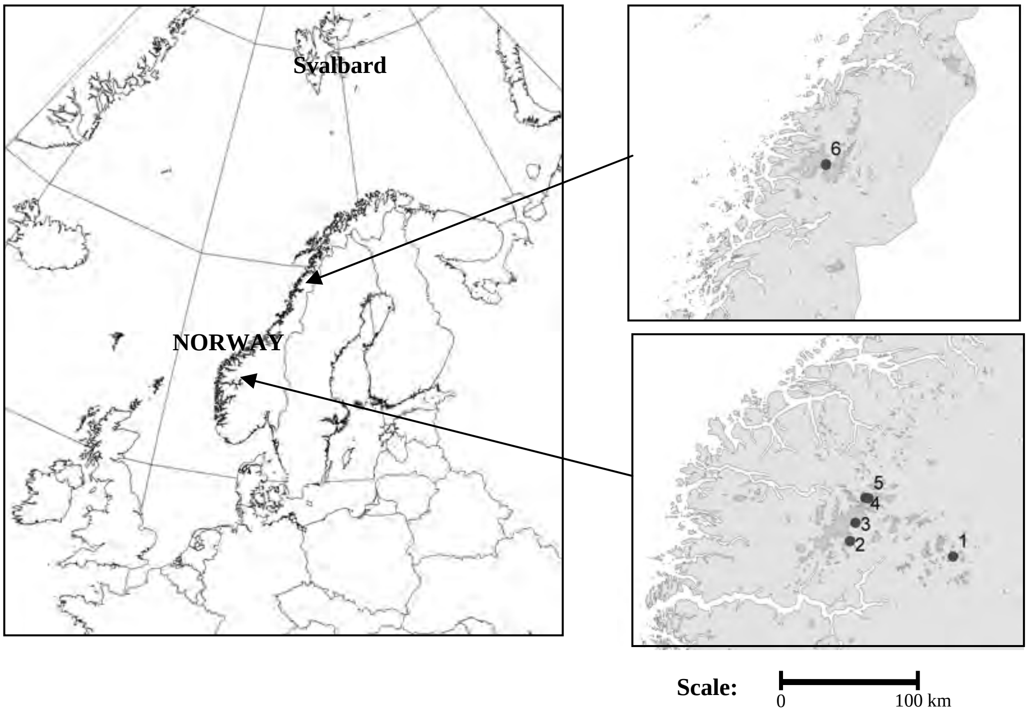

Fig. 1 Location of the studied glaciers: 1, Memurubre; 2, Tunsbergsdalsbre; 3, Nigardsbre; 4, Erdalsbre; 5, Vesledalsbre; 6, Svartisen ice cap.

Sediment transport G_s is calculated from relation (1) for hourly time steps.

$$G_s = \int_{t_1}^{t_2} QC\,dt \qquad (1)$$

water discharge *Q*, is calculated from the continuous record of water stage and hourly sediment concentrations *C*, obtained by linear interpolation between the known concentrations of collected samples.

In mainland Norway, the sediment supply from the rock walls adjacent to the glaciers is negligible when compared to the glacial erosion rates. In Svalbard, erosion rates of unglaciated parts of the catchments may be larger, but measurements have not so far revealed yields of magnitudes comparable to the glacial ones. Analyses of lake sediment cores have been used to obtain an insight into long-term sediment supply from glaciers (see Bogen & Bønsnes, 2003b).

GLACIAL EROSION AND SEDIMENT DELIVERY

Sediment derived from glacial erosion originates from plucking and abrasion processes beneath the glaciers. The mean annual sediment yields for various glaciers in mainland Norway and Svalbard are compared in Fig. 2. Sediment yields of all glaciers are derived from sediment transport measurement in glacier meltwater rivers, except for Kongsvegen. This estimate was based on a seismic survey of bed sediments of the downstream fjord (Elverhøy *et al*., 1983). The variability in suspended sediment yield between the different glaciers is large, ranging from 22 to 1577 t km^{-2} year^{-1} for the temperate glaciers and from around 300 to near 3000 t km^{-2} for polythermal glaciers in Svalbard. Three distinct types of glacier may be recognised in mainland Norway: (1) valley and outlet glaciers from ice caps; (2) plateau glaciers, cirques and cirque-like glaciers; and (3) glaciers in schistose rocks in the Svartisen area, included as a special type because of their high erosion rates.

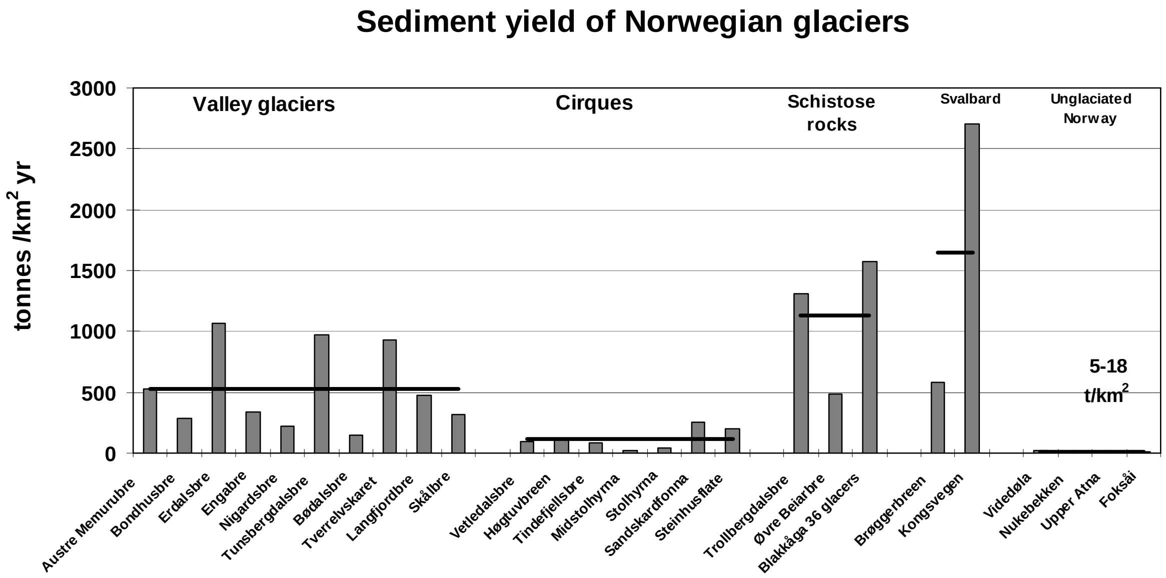

Fig. 2 Rates of erosion of Norwegian glaciers. Mean erosion rate of each group is indicated by a line. The sediment yield of unglaciated mountain rivers is shown for comparison.

The two first groups are situated on igneous and metamorphic rocks, either of Precambrian age or belonging to the Caledonian orogeny. Erosion is particularly intense beneath large valley glaciers with several tributaries, such as Erdalsbreen and Tunsbergdalsbreen. Fissure zones and lines of weakness in the bedrock may also be of importance. The lack of fissure zones is most probably the reason why some of the valley glaciers such as Nigardsbreen, Bødalsbre and Engabreen yield less. The low yields of the plateau glaciers and cirques in group 2 reflect their low velocity and modest thicknesses. The difference in erosion rates between groups 2 and 3, however, indicates that bedrock characteristics are a very important factor.

Sediment transport in glacial meltwater streams is often subject to large fluctuations within the season and from year to year. The highest concentrations often come at the beginning of the season. There is some dependence on water discharge, but with a few exceptions, observations show no obvious direct correlation that persists for more than one flood event. Bogen (1996) demonstrated that the pattern of variability in sediment yield may be interpreted in terms of a model where the sediments are introduced into the subglacial waterways by melting of debris-rich ice at the glacier sole. In periods of low water discharge, the movement of the glacier and its plastic deformation will reduce conduit cross-sections. Subsequent conduit expansion by an increase in water pressure will melt more ice and add more sediment to the subglacial system. Thick and fast-moving glaciers such as Engabreen and Nigardsbreen will deform their empty subglacial conduits more rapidly than thin, slow-moving ones. The highest suspended sediment transport rates of these glaciers occurred during years with several flash-flood events in the meltwater rivers. Annual suspended load thus depends not only on the total water discharge but also on the availability of sediment created by the opening of new conduits beneath the glaciers.

In order to predict the impact of climate change on the sediment delivery from glaciers it is important to recognise the different nature of the two components that constitute the glacial erosion / sediment delivery system. One of the two subsystems is the glacial erosion that is determined by glacial plucking and abrasion processes related to bedrock properties and glaciological variables. These are variables that regulate the concentration of sediment in the ice at the glacier sole over a scale of centuries. The way that climate change will affect these processes is that they will be intensified by a large long-term increase in glacier net balance. The second subsystem is the rate of melting in the subglacial conduits, which control the annual sediment delivery to the glacier meltwater rivers each year. This meltout of sediments is controlled by meteorological parameters. This is graphically illustrated by the fact that, despite the large

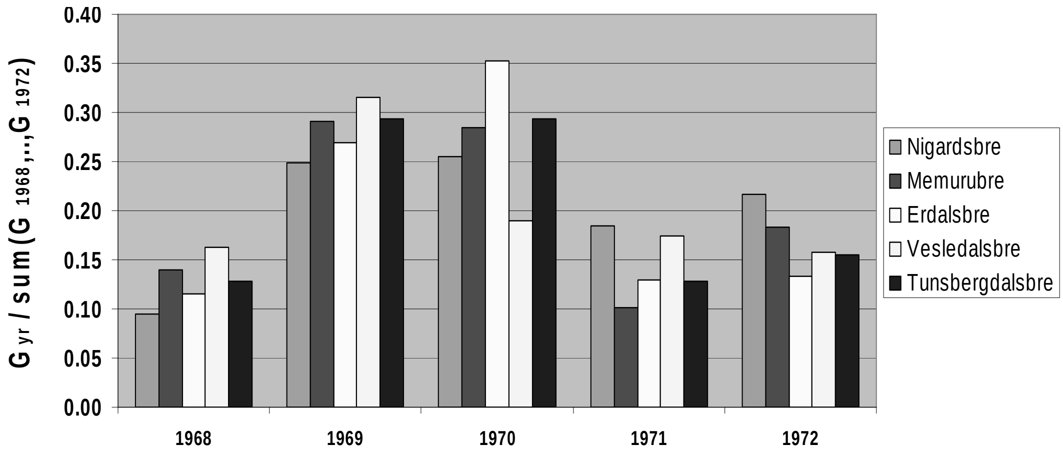

Fig. 3 Year-to-year variations of sediment transport of glaciers within the same climatic region. Data are normalized as the observed rate of each individual glacier is divided by the sum of the rates of each series.

variability between mean erosion rates shown in Fig. 2, the ranking of sediment yield between each individual glacier seems to remain fairly constant from one year to another within the same climatic region (Fig. 3). When the effect of erosion rates is removed by normalisation, the sediment yields of selected glaciers in southern Norway show a similar variation.

LONG-TERM SEDIMENT DELIVERY

Lake sediment cores have been used to compute glacier sediment yields. In proglacial lakes, the bed sediment typically accumulates as varves, reflecting changes in seasonal and annual sediment flux. In Norway, proglacial lakes have been studied by, among others, Østrem & Olsen (1987), who used the thickest varves from a long sedimentary record to estimate the size of extreme sediment transport events. Bogen *et al*. (1996) investigated varves in several Norwegian glacial lakes in order to study sediment fluxes. To obtain a long-term record of sediment flux it is necessary to analyse a core from a lake close to the glacier front. Two lakes are discussed here, Storglomvatn and Bondhusvatn in northern Norway.

Storglomvatn Lake forms the reservoir for the Svartisen hydroelectric power plant. Three outlet glaciers from the Svartisen ice cap are calving into the lake and two others drain directly into it. Their combined glacier area is 95 km^2. A total of 22 cores were recovered from the lakebed sediments in various parts of the lake (Bogen *et al*., 1996). Sediment core dating was based on varve counts. The varve thickness variations from a selected core covering the period 1695–1995 are shown in Fig. 4. Annual sedimentation was subject to substantial variations during this period. There are very thin varves around 1695. The summer that year is said to have been so cold that in parts of the Norwegian mountain areas the grass never became green. From official documents it is known that the nearby Engabreen, another outlet glacier from the Svartisen ice cap, had its greatest extension in the early part of the 18th century (the glacier destroyed one farm and damaged another in 1723). During this period the varves are very thin. After 1850 the glacier receded and the sedimentation rate slowly increased 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 reduced sedimentation rate around 1970 is due to a glacier advance at that time (Kjøllmoen, 2005). The mass balance expresses the year-to-year volume change due to winter snow accumulation and summer melting. A negative net balance causes a surplus of glacial meltwater that is added to the runoff, whereas a positive net balance and increase in glacier volume involves less glacial meltwater. It is apparent from the Storglomvatn record that the large positive net balance and glacier advances during the “Little Ace Age” were associated with low sediment yields. The negative net balance during the following centuries increased the runoff and the sediment supply to the lake.

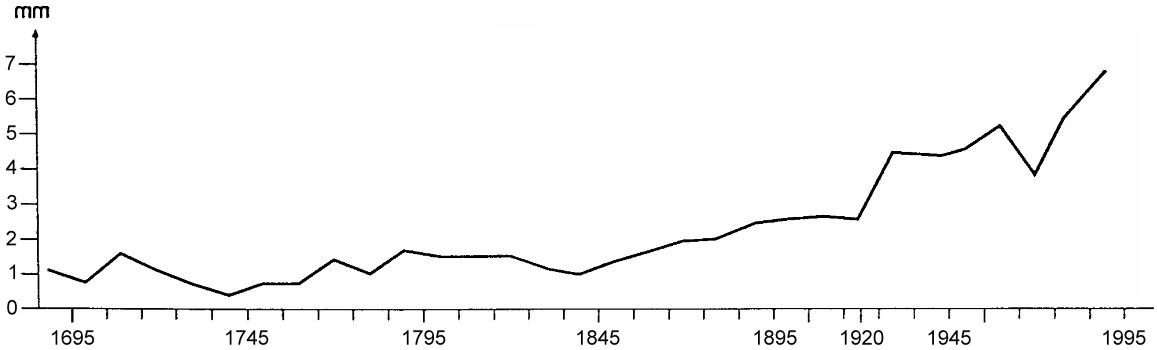

Fig. 4 Mean sedimentation rates in proglacial Lake Storglomvatn during each decade of the years 1695–1995.

Lake Bondhusvatn receives sediments from Bondhusbreen (12 km^2), which is a west facing outlet glacier from the Folgefonna ice cap in southwestern Norway. It is apparent from the varve count that the time span of the sediment cores is the same as in Storglomvatn, but the variations in sedimentation rate are smaller (Olsen, 2006). The glacier seems to have had its maximum historic extension in 1875 (Bogen *et al.*, 1989). This event is associated with a small decrease in the sedimentation rate. A similar decrease is also recorded for the glacier advance that took place in 1930. According to Tvede & Liestøl (1977), the glacier mass increased significantly between 1918 and 1925, followed by a very rapid retreat between 1930 and the late 1950s. The sedimentation rate was also high during these two decades. As in Lake Storglomvatn, the increased sediment supply to the lake was most probably caused by the increase in runoff corresponding to the reduction in glacier volume. The smaller increase is most probably related to the fact that the rise in summer temperatures from the 18th century is only moderate in this area. The rapid glacier advance in the early 18th century was mainly due to higher winter precipitation rather than lower summer temperatures (Nesje *et al.*, 2008).

CLIMATE CHANGE AND GLACIAL SEDIMENT DELIVERY

The globally-averaged surface temperature is projected to increase by 1.4 to 5.8°C over the period 1990–2100. Water vapour concentration and precipitation are also projected to increase (WMO 2001; IPCC, 2007). RegClim (Regional Climate Development) is a research project that converts the results from global circulation models into scenarios for regional climate change in northern Europe. According to the latest scenario given by RegClim (2005), the summer maximum temperatures in Norway towards 2100 will be 2.5–4°C higher, depending on location. There will be an increase in total annual precipitation, varying between 5 and 20% in different parts of the country. The prediction for the largest increase is in the western part, with precipitation expected to exceed 20 mm on at least 15 more days per year. Extreme rainstorm frequency will increase throughout the country. These scenarios have been converted into runoff predictions by model simulations (see among others Roald *et al.*, 2002; Tveito & Roald, 2005).

Winter precipitation and summer temperature are the most important factors controlling glacier mass balance and runoff in the glacier meltwater rivers. As the winters become warmer, snow storage will probably decline at low altitudes, but increase at the higher altitudes as a result of greater precipitation. Model runs indicate that this will increase the net balance for glaciers with high-altitude accumulation areas during the period 2030–2050 (Roald *et al.*, 2002). This implies that glaciers like Nigardsbreen will tend to advance, whereas glaciers with a low-lying accumulation area will recede. After 2050 the predicted continued increase in temperatures will cause ubiquitous negative net balances and a general glacier recession. Oerlemans (1997) predicted a slight advance of Nigardsbreen up to 2020, after which a rapid retreat would reduce it to 10% of its 1950 volume by 2100.

Nigardsbreen may be used as a representative glacier to discuss future sediment delivery. It is an east-facing outlet glacier from the Jostedalsbre ice cap in southwestern Norway. Its snout is situated at 285 m a.s.l. and the highest elevation is 1946 m a.s.l. The sediment load in the glacier meltwater river has been monitored from 1968 to 2007. The mean sediment yield during 1968–1995 was 10 520 t $year^{-1}$ increasing to 14 073 t $year^{-1}$ during 1996–2007. The increase is partly due to greater meltwater runoff. The mean annual runoff during the two periods was 178 and 210×10^6 m^3 $year^{-1}$, respectively. However, a significant glacier advance occurred during the last period as a response to several years with positive net balance during the early 1990s. In addition, a major change in the subglacial channel system is believed to have increased sediment availability.

Lappegård *et al*. (2007) have developed streamflow scenarios for the period 2071–2100 for several heavily glaciated catchments. These indicate that catchments containing glaciers will produce 10–70% more water during summer. In the meltwater river from Nigardsbreen, various scenarios predicted 20–40% increases in the magnitudes of the mean annual floods and also the 5- and 10-year floods, while the 50-year flood increased by up to 60%. The highest annual sediment load on record before 1995 was 18 000 t $year^{-1}$, associated with the 100-year flood in 1979.

As the opening of subglacial tunnels by melting processes is a gradual process, the large-magnitude floods may drain on the surface of the glacier rather than through the subglacial system. An increase in the size of the large-magnitude floods will thus not necessarily deliver excessively large quantities of sediment. It is the more frequent meltwater floods of more moderate size that will be important. In a warmer climate they will also have longer duration, and thus carry more sediment. Such a situation occurred during the warm summer of 2002 when a transport of 20 000 t $year^{-1}$ was measured. This figure is approximate, but represents a minimum value. This is about twice the recorded mean during the period 1968–2005. As pointed out by Nesje *et al*. (2008), the mean temperature during the ablation season was 2.1°C warmer than the 1961–1990 mean. This summer may thus be regarded as an analogy for the future climate scenario and suggests that the sediment yield during the period 2071–2100 may be in the order of 400 t km^{-2}, double that of the 1968–1995 mean.

The fast temperature rise in the RegClim scenario is likely to cause a faster increase in sediment flux than is indicated by the Storglomvatn and Bondhusvatn lake sediment cores. The long-term peak in the sediment delivery rate of Nigardsbreen will probably occur when thinning of the ice allows cavities to exist at the glacier bed. In this situation the subglacial drainage may access the sediment at the bed more readily.

According to Nesje *et al*. (2008), this climate scenario may cause an equilibrium line rise of 260 m and the disappearance of about 98% of the glaciers. This is consistent with reconstructions of past glacier fluctuations in Norway, which strongly indicate that all the investigated glaciers melted completely at least once during the Early/Mid Holocene due to summer temperatures up to 0.7–1°C higher and precipitation at only 50–80% of present levels. The specific sediment yields of unglaciated mountain areas are found to be in the order of 5–18 t km^{-2} (Fig. 2), dependent on the extent of erodible deposits in the catchments. Lappegård *et al*. (2007) also found a decrease in the mean annual and the 5- to 10-year floods of the glacier-free neighbouring catchment to Nigardsbreen. The sediment yield of the glacier-free Nigardsbreen catchment will thus decrease considerably.

DISCUSSION AND CONCLUSIONS

The impact of climate change on the sediment delivery from glaciers is assessed from a conceptual model of the subglacial processes. This model is composed of two interacting subsystems. The glacial erosion subsystem is determined by glacial plucking and abrasion processes related to bedrock properties and glaciological variables. These processes regulate the concentration of sediment in the ice at the glacier sole over the scale of centuries. Climate change will affect these processes in the way that an increase in glacier net balance will increase erosion rates. The glacial meltwater and the subglacial waterways constitute the sediment delivery subsystem. It is the rate of melting and the water discharge in the subglacial conduits which controls the annual sediment delivery to the glacier meltwater rivers. This meltout of sediments is controlled by meteorological parameters and the sediment flux may vary during short time intervals and from year to year. A long-term decrease in glacier net balance may thus increase the meltwater and sediment discharge as illustrated by the Lake Storglomvatn sediment core, and a period of very cold summers may result in very low sediment delivery rates. Within the same climatic region the annual sediment delivery of various glaciers was thus found to vary concurrently, even if the ranking of sediment yield between the each individual glacier is different due to bedrock or glaciological characteristics.

River streamflow scenarios worked out for the period 2071–2100 for the heavily glaciated catchment of Nigardsbreen indicated 10–70% more summer runoff and a substantial increase in the magnitude of summer floods. On the basis of existing data from very warm summers a minimum value of the future sediment load in this river was estimated to be 20 000 t year^{-1} corresponding to a specific sediment yield of 400 t km^{-2} year^{-1}. This is the double of the mean of the period 1968–1995. It is expected that the yield will increase even more when the character of the subglacial drainage system is changed by glacial thinning.

River streamflow scenarios for the period 2071–2100 for the heavily glaciated catchment of Nigardsbreen (Lappegård *et al*., 2007) indicated 10–70% more summer runoff and a substantial increase in the magnitude of summer floods. On the basis of existing data from very warm summers, a minimum value of the future sediment load in this river was estimated at 20 000 t year^{-1}, corresponding to a specific sediment yield of 400 t km^{-2} year^{-1}. This is double the mean of the period 1968–1995. It is expected that the yield will increase even more when the character of the subglacial drainage system is changed by glacial thinning. However, Roald *et al*. (2002) predicted an increase in net balance in the period 2030–2050 due to the increase in precipitation. A period of sediment transport rates near the present (1995–2007) level may thus be expected for glaciers with high-altitude accumulation areas such as Nigardsbreen.

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