210 *Erosion and Sediment Yields in the Changing Environment* (Proceedings of a symposium held at the Institute of Mountain Hazards and Environment, CAS-Chengdu, China, 11–15 October 2012) (IAHS Publ. 356, 2012).

Impact of climate change on glacial sediment delivery to Norwegian rivers and consequences for hydropower operations

JIM BOGEN, TRULS BØNSNES & GALINA RAGULINA

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

jbo@nve.no

Abstract The possible effects of climate change on sediment delivery from glaciers and the consequences for hydropower operations are discussed in this paper. Present climate change scenarios predict a rise in summer temperature of 2.5–4.0°C in Norway towards 2100, an increase in precipitation of 5–20% in the southwestern part of the country, and a general increase in the frequency of extreme rainfall events. Most of the glaciers will melt and sediment transport is likely to increase as a result of the melting. During the last decade, high summer temperatures and high precipitation have caused the highest volume of runoff and sediment load in the meltwater river flowing from the Nigardsbreen Glacier, since measurements began in 1968. A study of the subglacial morphology obtained from low frequency radio-echo soundings revealed that a number of depressions beneath the glaciers will form lakes when the glaciers disappear and act as sedimentation basins in the future rivers. The increased sediment delivery from the glaciers will thus not always increase the sediment input to downstream reaches. Changes in sediment delivery to hydropower stations will depend on the local conditions and the operation rules.

Key words bed load; climate change; glacial erosion rate; hydropower planning; sediment yield; suspended load; ungauged glacierised basins

INTRODUCTION

Measurements have shown that glacial erosion delivers the largest sediment volumes to Norwegian rivers. Sediment transport in these rivers is often dominated by glacially-derived material and hydropower development has to take this into account. Sediment handling measures are thus necessary during both construction and operation of power plants. Turbine wear and reduced reservoir capacity due to sedimentation are challenges that need to be addressed. Environmental problems may also arise during operation of power plants. Sediment pollution due to abnormally high sediment concentrations generated by diversions of sediment-laden water or accelerated erosion associated with the drawdown of reservoirs have already been observed (Bogen & Bønsnes, 2001). However, hydropower operations affect the sediment flux in different ways, depending on local conditions and regulation practice. The predicted climatic warming will also affect sediment transport by glacial meltwater rivers. According to the latest scenario given by RegClim (2005), the summer maximum temperatures in Norway towards 2100 will be 2.5–4.0°C higher, depending on location. There will be an increase in total annual precipitation of 5–20% and extreme rainstorm frequency will increase throughout the country (RegClim, 2005).

The development of two outlet glaciers, Nigardsbreen and Tunsbergdalsbreen, on the eastern side of the Jostedalsbre ice cap, and the outlet glaciers of the Svartisen ice cap is the focus in this paper (Figs 1 and 6). The meltwater river flowing from the Tunsbergdalsbreen Glacier is utilised in the Leirdøla part of the Jostedal power plant. Almost all the sediment load derived from the Tunsbergdalbreen Glacier is deposited in the hydropower reservoir downstream from this glacier, thus reducing the reservoir capacity significantly during the first 20 years. At the Svartisen ice cap, sediment from outlet glaciers may be transported all the way to the turbines. As the climate becomes warmer, there is reason to believe that more sediment will be supplied to the glacial meltwater rivers. The aim of this paper is to discuss the future development of the glaciers mentioned and the implications this will have for sediment delivery to downstream reaches.

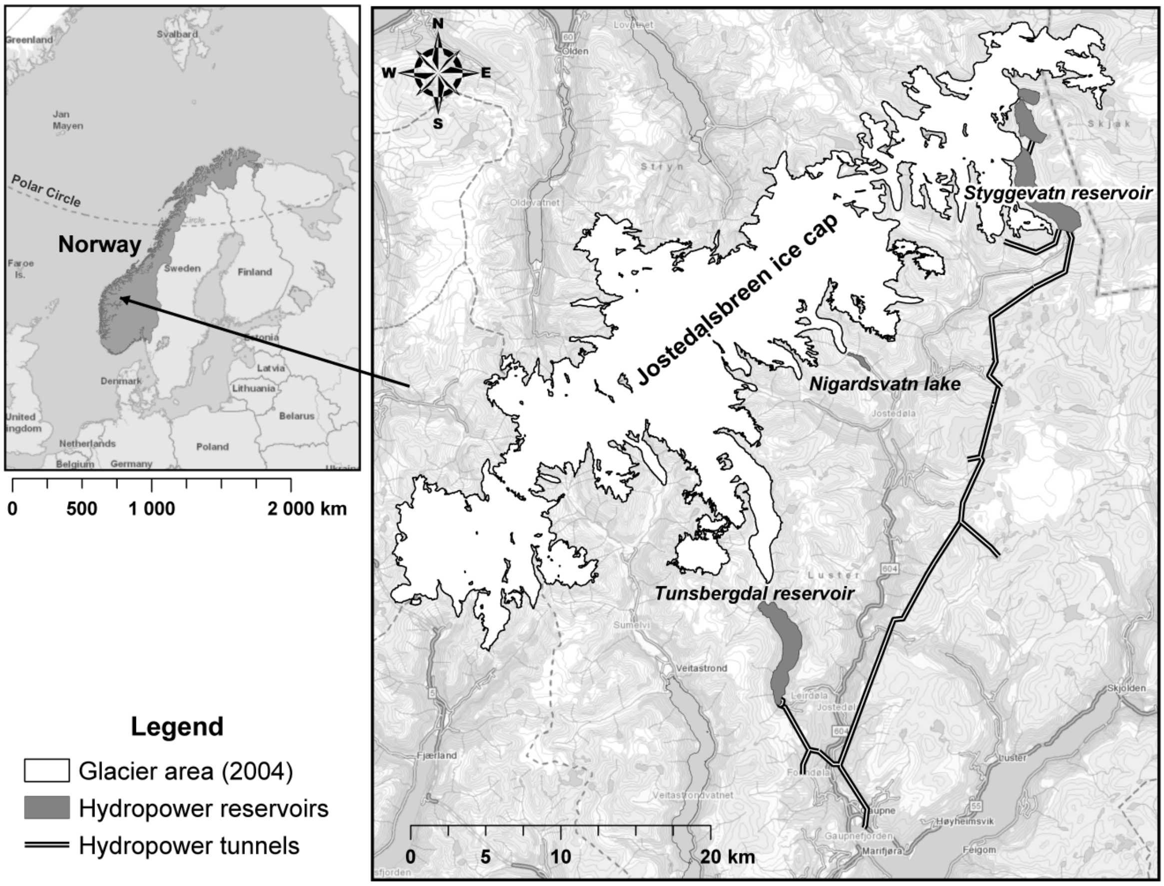

Fig. 1 The location of the study area in southern Norway.

METHODS

The sediment load in the meltwater river flowing from the Tunsbergdalsbreen Glacier has been measured both before and after hydropower development (Bogen, 1987; Stausland, 2010). A continuous record of sediment transport in the meltwater river from Nigardsbreen is available since 1968. The sediment transport measurements before 1983 were carried out in the traditional way. Sediment concentration records at that time were based on manually collected samples that were filtered through paper filters and weighed after ignition. From the 1980s, the sediment transport monitoring programmes have been based on the use of ISCO automatic pumping samplers installed in highly turbulent river reaches to ensure full mixing. Water samples are filtered through Whatman fibreglass filters and the concentration of organic and inorganic particulate matter is determined by drying, ignition and repeated weighing. Sampling procedures and laboratory methods are described by Bogen & Bønsnes (2003) and Bogen (2009).

The subglacial topography of the glaciers was mapped by radio-echo sounding, deploying a low-frequency, 8 MHz system (Sætrang & Wold, 1986; Sætrang & Holmquist, 1987). An area of 50 km^2 was mapped by 220 km of profiles and in one area the derived depths were verified by steam drilling to the glacier bed. On the basis of these data and some extrapolation, a map of the subglacial morphology was compiled. During the preparation of this paper the data were digitized and reprocessed.

GLACIAL SEDIMENT YIELD AND CLIMATE CHANGE

In order to predict the impact of climate change on sediment delivery from glaciers it is important to recognise the different nature of the two components or subsystems that constitute the glacial erosion/sediment delivery system (Bogen, 2008). One of the two subsystems is the glacial erosion caused by glacial plucking and abrasion processes which are influenced by bedrock properties and glaciological variables. These variables control the concentration of sediment in the ice at the glacier sole over a timescale of centuries. Climate change will intensify these processes through a major long-term change in glacier net balance. The second subsystem is the rate of melting in the subglacial conduits which controls the annual sediment delivery to the glacier meltwater rivers. This meltout of sediment is controlled by meteorological conditions and is dependent on total runoff volume and proportional to the glacier summer balance. For most Norwegian glaciers there is no well-defined persistent relationship between sediment concentration and water discharge, since the accessibility of subglacial sediment sources is a limiting factor.

Nigardsbreen

The sediment transport by Nigardsbreen's meltwater river has been measured since 1968. The transport of suspended sediment is subject to large variations from year to year (Fig. 2(a)). The greatest suspended sediment transport occurred during years with numerous flash flood events. In glacial meltwater rivers such events occur most often as a result of glacier melting combined with rainfall-generated floods.

There has been a tendency towards an increase in bed load during the last 17 years. All of the three years with bed-load transport in excess of 20 000 t year^{-1} occur in this recent period. During eight of these 17 years, the bed-load transport exceeded 15 000 t year^{-1}, but loads in excess of this value were recorded only four times during the preceding 28-year period (1968–1995). Most of the

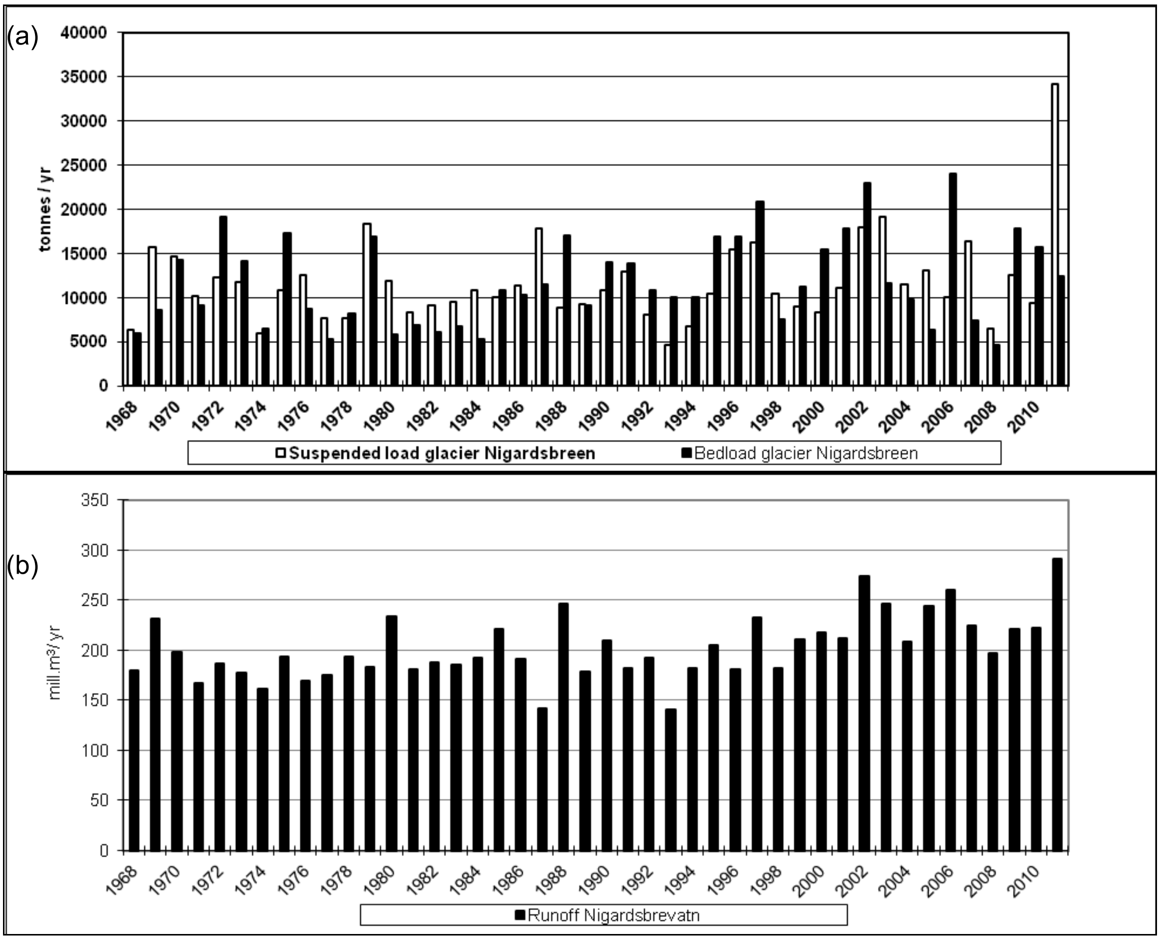

Fig. 2 (a) Suspended sediment and bed-load transport by the meltwater river flowing from Nigardsbreen Glacier during the years 1968–2011. (b) Runoff from the Nigardsbreen Glacier 1968–2012.

years with high bed-load transport were characterised by high runoff (Fig. 2(b)). There is a pronounced increase in runoff volumes after 1997 due to large negative glacier mass balances, caused by extensive summer melting. The summers of 2002, 2003 and 2006 were the warmest recorded in Norway since air temperature measurements began in 1876 (Andreassen & Oerlemans, 2009).

Considering likely future changes, Lappegård *et al*. (2007) found, on the basis of model simulations, that heavily glaciated catchments will produce 10–70% more water during summer. For the meltwater river flowing from Nigardsbreen, various scenarios predicted increases of 20–40% in the magnitude of the mean annual flood and the 5- and 10-year floods, while the 50-year flood magnitude increased by up to 60%. Bogen (2008) provided evidence for the likelihood of at least a doubling of the mean annual sediment yield from the Nigardsbreen Glacier subject to such conditions. According to Nesje *et al.* (2008), the RegClim climate scenario would cause the equilibrium line to rise 260 m, with 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 than today and precipitation at only 50–80% of present levels.

Surveys of the subglacial morphology of the Nigardsbreen have provided an indication as to how the melting of the glacier will proceed (Fig. 3). The snout of the glacier is situated in a valley that rises towards the northwest. A 500-m long overdeepening near the front will become a small

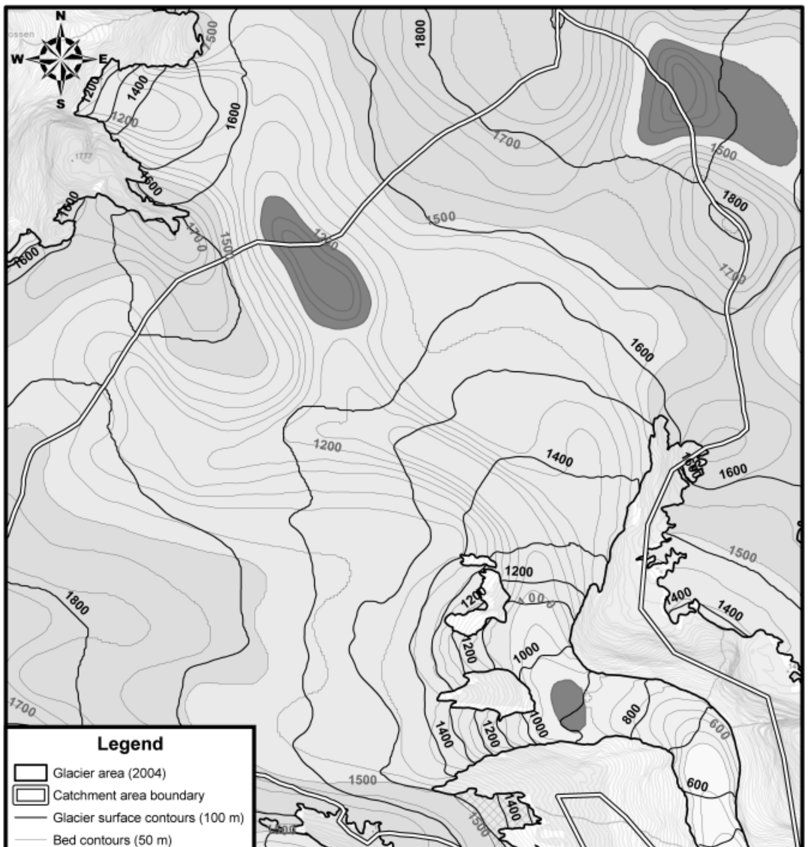

Fig. 3 The subglacial morphology of the Nigardsbreen Glacier. Both glacier bed contours and surface contours of the glacier and major depressions that will become lakes are indicated.

lake that will receive sediment during the continuing retreat. At an altitude of 1200 m the valley divides into two branches. In the northern branch there is an overdeepened section that will contain a lake more than 100 m deep when the glacier has gone. By this stage the glacier will be small and delivering only small amounts of sediment. The valley up which the western branch of the glacier will recede has no overdeepening and hence no lakes will form. Toward the end of the century it is likely that two small glaciers in the highest parts of the catchment area will be all that remains of the Nigardsbreen. The filling time of Lake Nigardsvatn, assuming the present sediment supply, was estimated to be around 900 years. Even with a substantial increase in sediment supply, this lake will persist as a sedimentation basin throughout the existence of the Nigardsbreen Glacier, trapping the greater part of the sediment load.

Tunsbergdalsbreen

The hydropower reservoir downstream from this glacier and the tunnel system associated with the hydropower plant were completed in 1978. Before that a 4-km long sandur existed in front of the

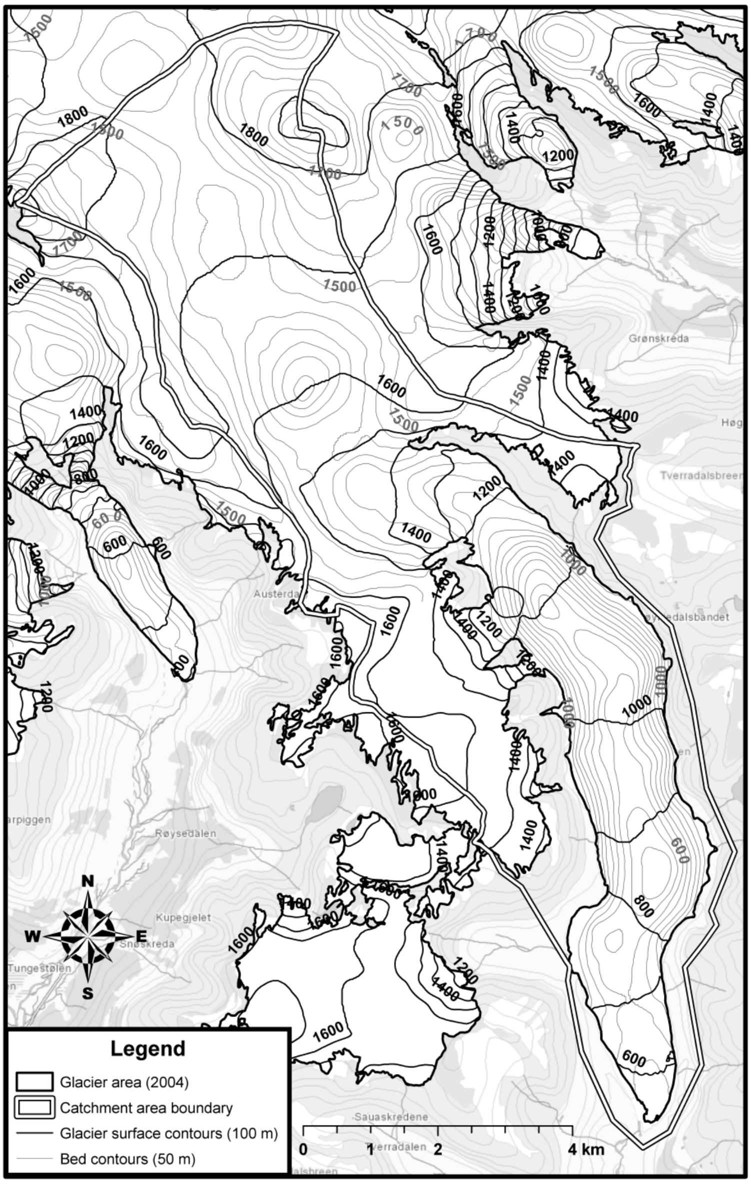

Fig. 4 The subglacial morphology of the Tunsbergdalsbreen Glacier. Both glacier bed contours and surface contours of the glacier are indicated.

glacier. This sandur ended in a lake. Before the commencement of hydropower development, the suspended sediment transport from the front of the glacier at the lake inlet was estimated to vary between 46 000 and 80 000 t year^{-1}, with no permanent deposition of suspended sediment along the sandur reach. The bed load at the inlet of the old lake, about 4 km from the glacier front, was computed to vary between 7500 and 9600 t year^{-1} before the dam was built. The transport was assessed to be considerably higher at the glacier front. After hydropower development the sediment was deposited in the reservoir and its capacity has reduced considerably as a result.

However, in the 1990s the recession of the glacier uncovered a proglacial lake. Stausland (2010) concluded that all the bed load together with most of the sand fraction of the suspended load was being deposited in this proglacial lake. The present sediment load at the glacier front at the original station was measured as 28 000 t year^{-1} in 2009. The reduction since the early 1970s was assumed to be due to sedimentation in the proglacial lake. Andreassen *et al.* (2004) found a significant correlation between the mass balance of Tunsbergdalsbreen and Nigardsbreen. It is thus reasonable to expect that the Tunsbergdalsbreen Glacier will respond to climatic change in the same way as Nigardsbreen. The sediment delivery from the two glaciers will follow a similar trend, but there is a large difference in subglacial morphology. Beneath Tunsbergdalsbreen there are several overdeepened basins (Fig. 4). As the glacier recedes, the exposed basins will become lakes that will act as sedimentation basins. The depth of the present 500-m long proglacial lake at the glacier front was estimated by Staursland (2010) to be 9 m. If the glacier continues to recede, a

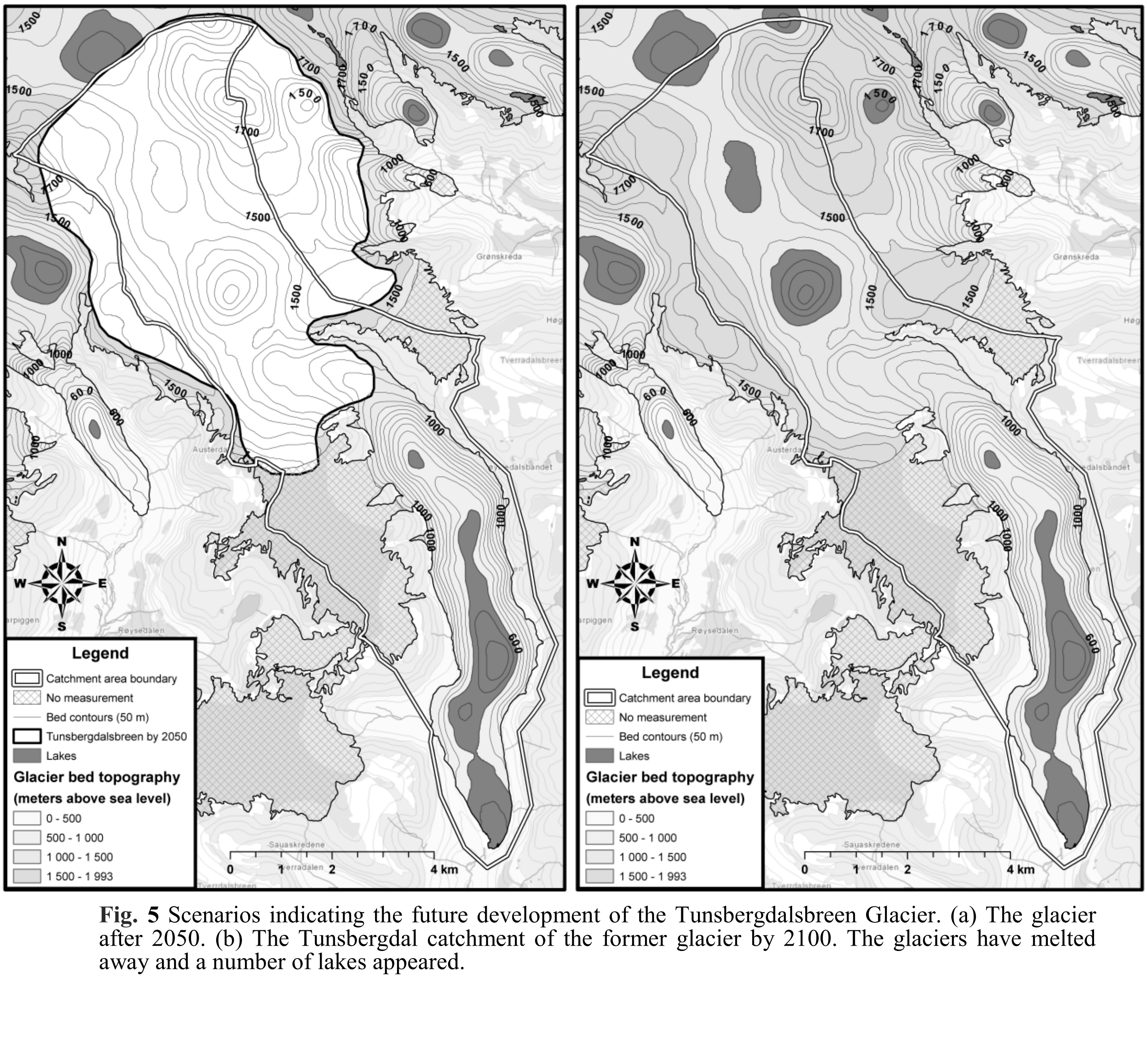

Fig. 5 Scenarios indicating the future development of the Tunsbergdalsbreen Glacier. (a) The glacier after 2050. (b) The Tunsbergdal catchment of the former glacier by 2100. The glaciers have melted away and a number of lakes appeared.

lake 1.5 km long and more than 50 m deep will develop. This will correspond to the exposure of Lake Nigardsvatn. In 1937, the glacier covered the whole lake, then in the course of 30 years the glacier calved back and by 1967 the glacier had retreated to the shore above the lake (Østrem, 1975). Upstream of the first basin beneath Tunsbergdal there is another elongated basin that will become a 4-km long lake, large parts of which will be less than 50 m deep but the deepest areas more than 100 m deep. The amount of sediment that passed through Lake Nigardsvatn during the first 10 years of its existence was shown by measurements to be 20% of the load supplied by the glacier. It is thus likely that a major part of the load from the receding Tunsbergdalsbreen Glacier will be deposited in the two lakes. The large increase in sediment transport caused by the predicted climate change will thus affect the capacity of the hydropower reservoir further downstream to only a limited extent. The scenarios for the melting of the Tunsbergdalsbreen Glacier are presented in Fig. 5(a) and (b). The predicted increase in precipitation implies that the recession of the glaciers will proceed slowly during the first part of the 21st century. The front of Tunsbergdalsbreen will probably be situated upstream of the lake systems by 2050. The RegClim climate scenario may cause the equilibrium line to rise 260 m. This would cause the Tunsbergdalsbreen Glacier to melt away and the landscape with many lakes shown in Fig. 5(b) will appear.

Svartisen

The Svartisen hydropower plant utilises water from outlet glaciers of the Eastern and Western Svartisen ice caps and smaller glaciers situated in the same area. Five outlet glaciers drain directly into the Storglomvatn hydropower reservoir, which has a drawdown level of 125 m. Water is collected through 45 intakes and directed to the reservoir through large tunnel systems. From the reservoir the water flows to the power station located in the inner part of Holand Fjord (Fig. 6). The hydraulic head is 450 m. Sediment transport is measured in the tailwater of the turbine at the power plant. Bogen & Bønsnes (2001) reported measurements of the relative contributions from various sediment sources. The glaciers along the Southern tunnel supply 17 300 t year^{-1}, the glaciers along the Eastern tunnel 12 000 t year^{-1}, and the glaciers draining directly into the reservoir 120 000 t year^{-1}. The sediment yield coming from erosion of the reservoir varies with drawdown level and mode of operation of the power plant. It was estimated from sediment cores that this erosion amounted to 50 000 t during the first few years of operation. It can be seen from Fig. 7 that up to 30 000 t was delivered to the intake at the turbine of the powerstation. A large part is delivered from glacier outlets. However, the large amount of clay indicates that a significant proportion of sediment was derived from erosion of the reservoir bed during the first years of operation. The total sediment transport has since been subject to significant annual variation, but the sediment load is now stabilising around a level of 5000–10 000 t year^{-1}. It is expected that the installation of a new generator will allow significantly increased drawdown activity and thus cause more erosion. Grain size analyses indicate that the sediments that are eroded from the reservoir contain a higher proportion of fine fractions than the sediment supplied directly from the glaciers.

According to model studies carried out by Lappegard *et al.* (2006), the summer streamflow will increase by 15–70% during the melting of the glaciers. This model run was based on data from the catchment of the Engabre Glacier. It is likely that other glacier outlets from the Svartisen ice cap will behave in the same way. Long-term sediment supply from the outlet glaciers that drain to Lake Storglomvatn was investigated by Bogen & Bønsnes (2003). The sedimentation rates were observed to be 1–2 mm year^{-1} during the Little Ice Age and increased up to 6–7 mm year^{-1} as the glaciers reduced their volumes to their present state. It is thus also very likely that the sediment supply will remain high and even increase during the predicted temperature rise. The subglacial survey uncovered a closed depression beneath the central part of the glacier. Much of the sediment released during the final melting will be trapped in this lake.

The pathway from the glaciers to the intake of the Svartisen power station is relatively short and the sediment delivery from the glaciers around the reservoir may be expected to increase or remain at the present level until the lake has been uncovered. Most probably this will not happen until the latter part of the 21st century.

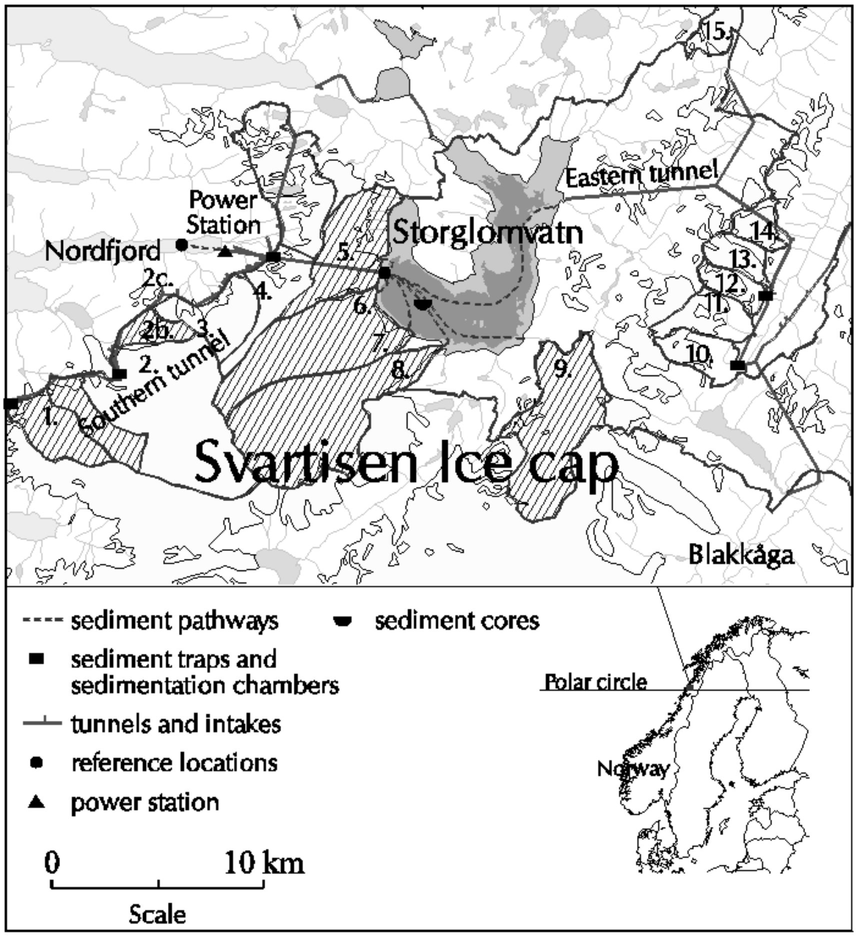

Fig. 6 Glaciers of the Svartisen area. The numbers refer to the various glaciers. The striped areas indicate glaciers where sediment loads have been estimated; the others have been measured.

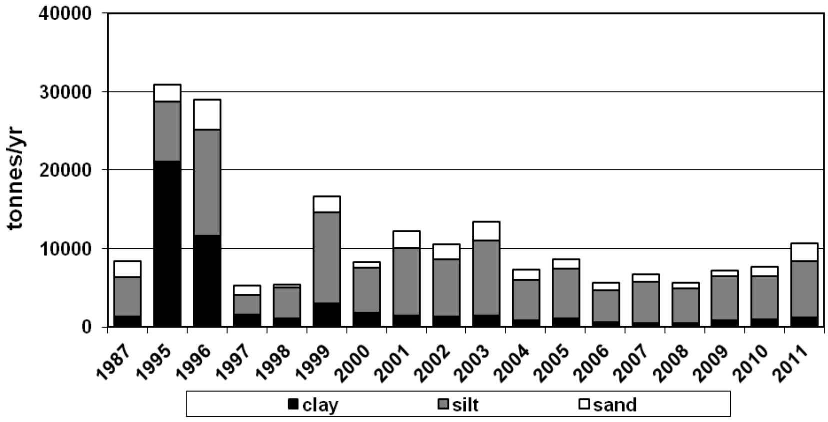

Fig. 7 The suspended sediment load passing through the turbine at the Svartisen power plant. Grain size analyses show the content of clay, silt and sand, and indicate that a large part of the sediment load occurred during the years of low drawdown of the reservoir in 1995 and 1996. The measurements in 1987 were carried out before the power plant was set into operation.

DISCUSSION AND CONCLUSIONS

The actual rates of erosion and sediment meltout from the glaciers as the temperature increases are difficult to predict because the subglacial sediments are not evenly distributed. In general, a high summer temperature causes extensive melting and high water discharge in the subglacial tunnels. If sediments are available, a high rate of sediment transport may result but this is not always the case. It was suggested by Bogen (1995) that both short duration and seasonal variations in sediment concentration reflect the way that sediment incorporated in the ice is melted out of the walls of the glacier tunnels. When water pressure is rising the subglacial tunnel or cavity is expanded by melting. As the water pressure falls, the tunnel or cavity is deformed by the overburden of the ice. The continuous opening and closing of channel networks and changes in the position of a channel system may be an important mechanism for producing mobile sediment.

As melting reduces the thickness of the glacier, the way sediment is delivered to the subglacial channel system changes. Tunnels stay open and sediment may be washed out more easily along the glacier sole. The thickness of the glacier is thus a critical factor for sediment delivery.

Winter precipitation and summer temperature are the most important factors controlling glacier mass balance and runoff in the glacial meltwater rivers. As the winters become warmer, snow storage will probably decline at low altitudes, but increase in the higher altitudes as a result of greater precipitation in the western part of the country. 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). It is thus reasonable to expect that the critical thicknesses will not be reached until the latter part of the 21st century.

The investigations of the different glaciers discussed here show that the impact of climate change on sediment delivery to downstream river reaches is very much dependent on the terrain surrounding the glaciers and other conditions at each location. Glacially sculptured overdeepenings often occur in such areas. These overdeepenings may form efficient sedimentation basins and limit downstream sediment delivery. This means that the sediment delivery to the sea will not always attain the high levels that could be expected from the glacial sediment supply.

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