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Sediment transport rates of major floods in glacial and non-glacial rivers in Norway in the present and future climate

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Abstract This paper considers possible sediment transport impacts in both glacial and non-glacial rivers in Norway from climate scenarios predicted by the RegClim (2005) project. The significance of high magnitude, low-frequency events as sediment transport agents is discussed on the basis of sediment transport measurements during major floods in various types of rivers. It was found that suspended sediment concentrations and volumes were dependant on the availability of sediments, the type and character of the erosion processes, and the temporal development of the flood. Measurements in a glacier outlet river during a flood of 100-year recurrence interval gave a high sediment load, but of the same order of magnitude as the mean. The reason for this is attributed to a limited availability of sediment for erosion in the subglacial channels. In reaches downstream from the glaciers and in non-glacial rivers, measurements during floods of 100- to 200-year recurrence indicate transport rates of about 30–40 times the mean of the preceding years. Due to the predicted increase in precipitation high-lying glaciers may advance in the first part of the 21st century. As a result of the continued increase in temperatures a general recession will occur and most glaciers will have disappeared by 2100. This will probably increase the formation of glacier dammed lakes that may generate lake outbursts. Large magnitude floods are found to be an important controlling factor of ravine development in the clay areas. It is thus anticipated that the equilibrium of the ravines will be altered by climate change because of the increase in flood frequency and magnitude. As a result, an increase in vulnerability to clay slides may take place.

Key words climate change; erosion; major floods; sediment transport

INTRODUCTION

Floods are important events that can extensively change river systems, with serious consequences both for the natural environment and human activity. One of the predicted effects of CO_2-induced climate change is a significant increase in the number of flood events in Norway. It is thus the aim of this paper to discuss the observed impact of large magnitude floods in the past as a basis for assessing the impact of future climate change.

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).

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 these scenarios the winter minimum temperatures in Norway towards 2100 will increase by 2.5–4ºC above the present level, dependant on location. The summer maximum temperatures will also be 2.5–4ºC higher and warm summer days with temperatures above 20ºC will be more common in the southeastern part of the country. There will be an increase in total annual precipitation, varying between 5% and 20% in different parts of the country, Fig. 1. 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 (RegClim, 2005).

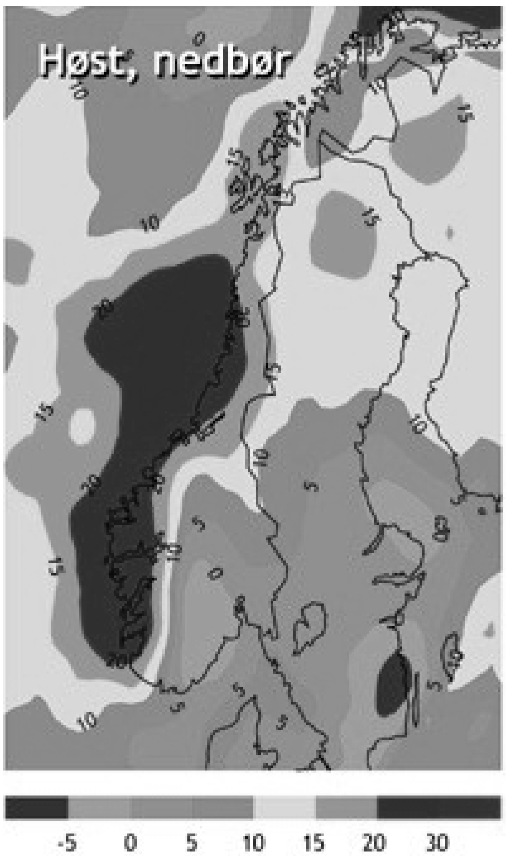

Fig. 1 Reg Clim (2005) scenario predicting an increase in total annual precipitation towards 2100, varying between 5% and 20% in different parts of the country.

These scenarios have been converted into runoff predictions by model simulations (see among others, Engen-Skaugen *et al*., 2002; Roald *et al*. 2002; Tveito & Roald, 2005). Sælthun *et al*. (1990, 1998) used a different method, but came essentially to the same conclusions. The results of these model simulations of particular relevance to river sediment transport processes are that the seasonal distribution of runoff will change (with autumn and winter floods becoming more frequent); runoff in certain areas will increase in response to increased precipitation and glacier melt; floods will increase in frequency and magnitude, with extreme flood situations developing more frequently—especially with increasing summer temperatures.

To predict the potential effects of climate change on sediment transport it is necessary to have a sound knowledge of the processes involved, both those responsible for sediment availability and those which operate during the actual floods. This then can be applied in managing their impact on the landscape.

However, the Norwegian sedimentary environment is diverse, and conditions vary considerably from one region to another. As sediment sources are unevenly distributed within drainage basins, only parts of the river courses may be alluvial. Sediment yields range widely in character between regions. Bogen (1996) defined six source type-areas where soils and erosion and sediment production processes were essentially of the same kind. A different grouping of these categories is employed in the present paper. The glacier outlets are included in the glacier-fed group, the Arctic area is excluded, while mountain and forest areas are discussed under one heading as the unglaciated mountain rivers.

Climate changes will affect the processes within these regions in different ways. In this paper, the main focus is on large magnitude events where sediment transport measurements have actually been obtained. But such data are rare, in part due to the low frequency of the events, but also to the difficulties involved in sampling during extreme conditions.

GLACIER-FED RIVERS

More than 2600 km^2 of Norway is covered by glaciers, comprising about 1600 glacier units.

Within the glacier-fed rivers category, catchments where the monitoring stations are situated close to the glacier front are of special interest, since a dominant part of the sediment budget is derived from subglacial erosion. Sediments derived from weathering processes in the mountains surrounding the glacier may also contribute, but in mainland Norway this may be considered negligible.

Sediment concentrations in glacier meltwater 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 due to seasonal changes in 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 rivers is the amount that is removed from the glacier sole. However, the concentration of sediment in the ice at the glacier sole is determined by glacial quarrying and abrasion processes. Thus the supply of sediment on a timescale of centuries is determined by glaciological parameters, whereas the actual sediment export each year is dependant on meteorological parameters that control the rate of melting in the subglacial conduits. During the years 1986–1997 the annual maximum concentration of suspended sediments measured in the meltwater river from Nigardsbreen varied between 280 mg L^{-1} and 2157 mg L^{-1}.

On 14 August 1979 a large magnitude flood occurred in the Jostedalen valley on the eastern side of the Jostedalsbre ice cap. The recurrency interval was estimated at 100 years by Gjessing & Wold (1980). The maximum daily precipitation of 77.8 mm in the valley was measured at Fåberg, in the middle reaches, and was 35.9 mm higher than the maximum recorded during the previous major flood in 1898. At the front of Nigardsbreen glacier the precipitation that day was 95 mm, resulting in a maximum discharge of 95 $m^3 s^{-1}$ in the glacier river and a maximum sediment concentration of 3200 mg L^{-1}.

During 14–16 August, the days of high water discharge, the measured suspended sediment transport totalled 9600 t. This is a very high value for a single flood, but it is not an extreme level. It is close to the annual mean of 9718 t for the period of measurement, Fig 2. There thus appears to be an upper limit to the magnitude of sediment transport in a glacier meltwater river during a single flood. Glaciers may produce large amounts of sediment and the sediment load in the glacier fed rivers may be high during floods. When runoff attains extreme values the sediment load does not necessarily become extreme. The most probable reason is that the sediment availability in the subglacial channels is limited. Fresh sediment is supplied from the melting of sediment-laden ice during the rising water stage. A large magnitude flood like the one in Jostedalen in 1979 may drain rapidly with a large part of the runoff flowing supra- or englacially in parts of the glacier that contain little or no sediment. The same reasoning applies for the bed load. In 1979 a total of 14 000 t of gravel was deposited on the delta in the lake downstream from the glacier, (see Fig. 2). This is a high annual transport rate, but records show it has been exceeded in some of the years that had lesser floods.

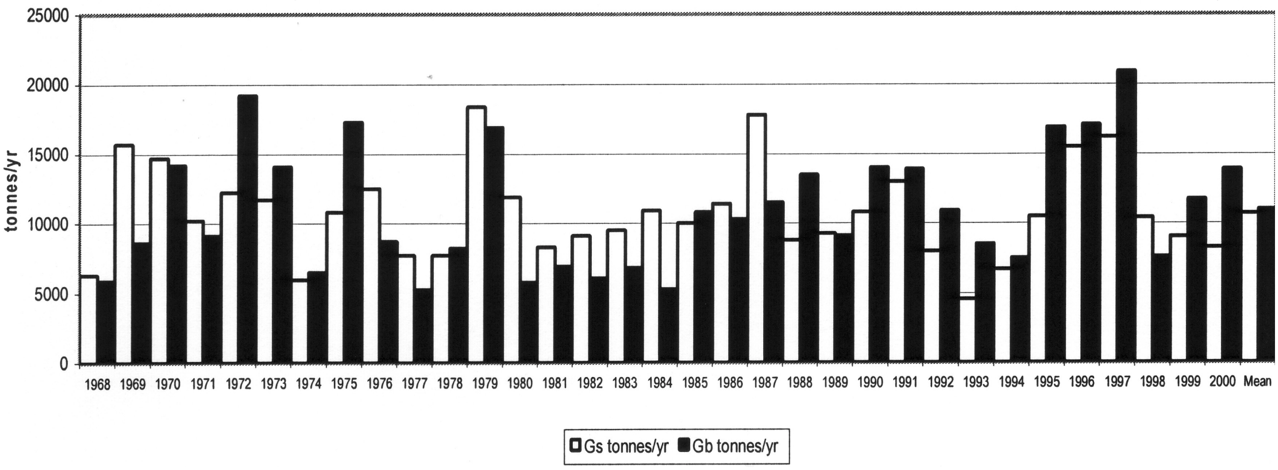

Fig. 2 Suspended sediment load and bed load in the meltwater river from Nigardsbreen during the years 1968–2000.

UNGLACIATED MOUNTAIN RIVERS

In the spring of 1995 the southeastern part of Norway experienced the largest flood recorded since the devastating flood of 1789. There were three main contributory factors (Tollan 1995; Sælthun & Tollan 1996). High winter precipitation produced large snow storage, 120–140% of the normal. The spring was cool delaying the snowmelt and giving favourable conditions for simultaneous and rapid snow melting through a wide range of elevations when the temperature rose. A stagnant weather front stationed over east Norway at the end of May produced widespread and heavy precipitation. This flood was of a 100–200 years recurrence interval and affected large areas in southern Norway. In parts of the Glomma watershed its magnitude corresponded to a 1 in 200-year flood. About 150 km^2 of farmland was flooded and there was severe erosion along the main valleys of the rivers Glomma and Lågen. More than 7000 people had to be evacuated from their homes.

The reference river basin Atna in the Rondane Mountains is a tributary of the Glomma. The sediment transport in the upper part catchment was measured at Lia Bridge where the flood reached its maximum value on 1 June at 100 m^3 s^{-1}. The highest measured concentration of suspended sediment was 606.1 mg L^{-1}. This is a high value, since the concentration in the preceding years remained below 20 mg L^{-1} for most of the time. However, the discharge of the 1995 flood was exceeded in 1996, when a rain-generated flood reached its maximum value of 118 m^3 s^{-1} on 18 June and the exceptionally high suspended sediment concentration of 2023.8 mg L^{-1} was recorded. This very high concentration was probably due to the abundant erosion scars created by the large flood in the preceding year. The 1996 rainstorm only affected a small area, but it may have been very intense. As the total volume of the precipitation was small, the water discharge in the lower parts of the Atna catchment was no higher than normal. At the station in the upper Atna the 1995 and 1996 floods were of 100–200 year recurrence intervals.

The variations in total annual transport of suspended sediment at Lia Bridge (Fig. 3) reflect the variation in concentrations. The conspicuous year to year variation is superimposed on a general decrease from 962 t in 1987 to 79.4 t in 1994, indicating a long-term trend. The large floods that occurred in 1995 and 1996 caused a huge increase in the transport rate to 13 200 t, 44 times the mean of 300 t year^{-1} of the five preceding years. Afterwards sediment transport remained at a high level but once more with the annual fluctuations displaying a gradual overall decrease. The pattern of long-term variation was found to be due to channel changes caused by the major floods (Bogen, 2004). Sediment is chiefly acquired by the river channel undercutting moraines and glaciofluvial deposits. Exhaustion of sediment sources occurs as the face of the deposit is eroded back, requiring ever higher water levels to achieve contact.

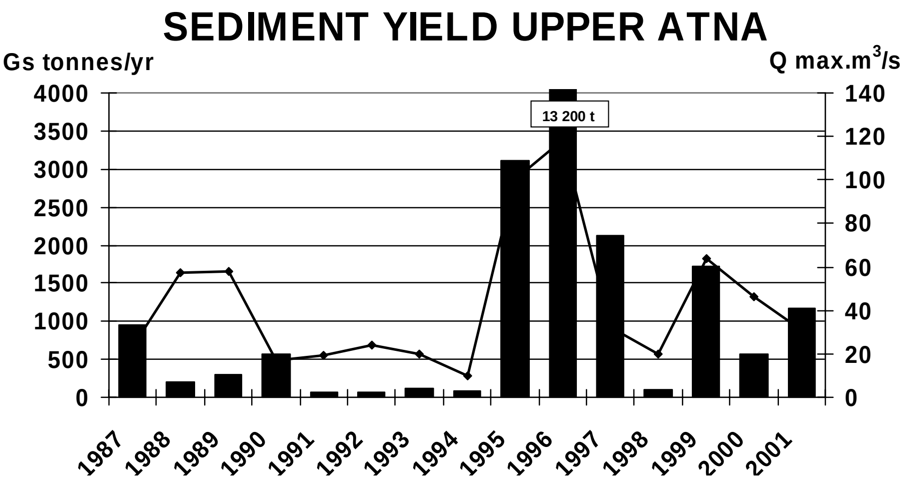

Fig. 3 Mean annual suspended sediment concentration (columns) and total runoff (lines) at Lia bridge.

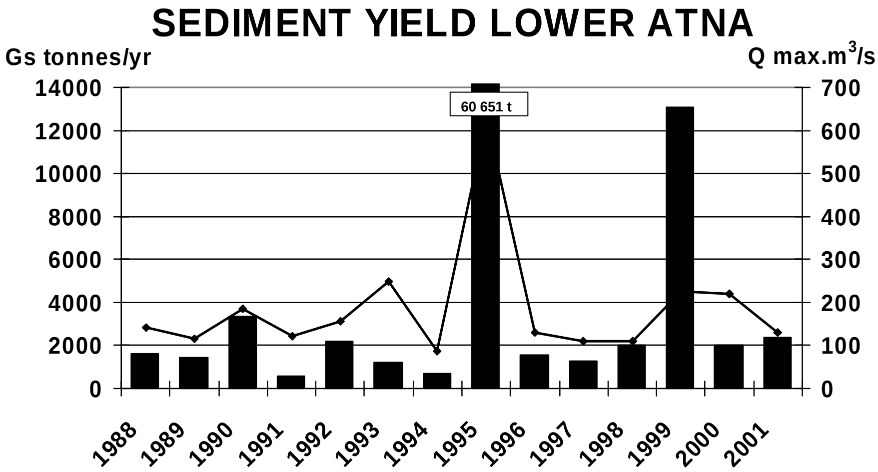

Fig. 4 Annual suspended sediment transport (columns) and maximum annual water discharge (lines) at Fossum bridge in lower Atna.

At the Fossum Bridge station in the lower Atna no permanent change in sediment availability attributable to the 1995 flood was observed. The catchment area draining to this station is situated predominantly below the tree-line. Erosion intensity is usually low, not least because sediments are protected by vegetation cover. The difference between normal and extreme flood conditions can nevertheless be great. In the lower part of the Atna drainage basin a 7-year mean of 1586 t was measured, corresponding to a sediment yield of 2.36 t km^{-2}. During the extreme flood of 1995, sediment transport increased to 60 651 t at the same location. Transport volumes returned to a normal level during the following years since the sediment sources were no longer available, Fig. 4.

Bed load transport rates have not been studied during major floods in the Atna, but channel studies and dated flood plain sediments indicate that the flood of 1789 was responsible for considerable transport with part of the meandering channel pattern in the Upper Atna being transformed into a braided river reach during the event by the excessive supply of bed load.

RIVERS IN CLAY AREAS

The clays in Norway were deposited in the sea in front of the retreating ice sheet during the last deglaciation about 10 000 years ago, when the land was still considerably depressed by glacio-isostatic loading. Subsequent emergence of the shallower areas through isostatic recovery gradually exposed large tracts of clay as dry land.

The clay areas are often densely incised by V-shaped gullies and thus highly vulnerable to erosion. In the Scandinavian literature these landforms are termed “ravines”, a usage employed here. Measurements shows very high erosion rates in the clay areas (Bogen, 1996).

In November 1987 a major flood occurred in southeast Norway. In the Romerike area northwest of Oslo, 97 mm of precipitation was recorded in one day. The specific runoff in the area reached 400–500 L s^{-1} km^{-2} and the recurrence interval has been computed at 100 years (Engen, 1988). In several of the ravines in the Leira catchment the local erosion base was lowered by as much as 2 m during this one flood.

A more comprehensive study of the river Leira clay areas revealed two types of ravines (Bogen & Bønsnes, 2000). One type was unstable, with abundant landslides. The ravine stream channel was incising and numerous landslide scars were visible along the ravine walls. These ravines have a V-shaped cross-section and many are deeply incised. The other type of ravine seems to be stable, often with a flood plain developed along the ravine stream. Lowering of the channel has been limited and the channels are prone to lateral migration. Slides are infrequent in these ravines and soil creep is the dominant mass movement process supplying sediments to the main stem. Their longitudinal profiles are close to the equilibrium profile derived by Bjerrum (1971) from a study of ravines in Norway:

$$S_{cr} = 0.0116A^{-0.55} \tag{1}$$

where S_{cr} is the critical gradient and A is the catchment area of the reach. Unless an armouring layer develops, the main channel will continue to incise until this equilibrium profile is attained. The actual profile and the computed equilibrium profile of selected examples of the two types of ravines are presented in Fig. 5. The incising ones are characterized by a high sediment yield with 1256 t year^{-1} km^{-2} being measured in the tributary Slemdalsbekken. The more stable conditions in the Vikka tributary yielded 158 t year^{-1} km^{-2}.

Large floods are thus of decisive importance to the erosional activity in this type of landscape. As a result of these events, high gradient reaches tended to incise until a new equilibrium is obtained. A co-plot of major slides and floodwater levels revealed

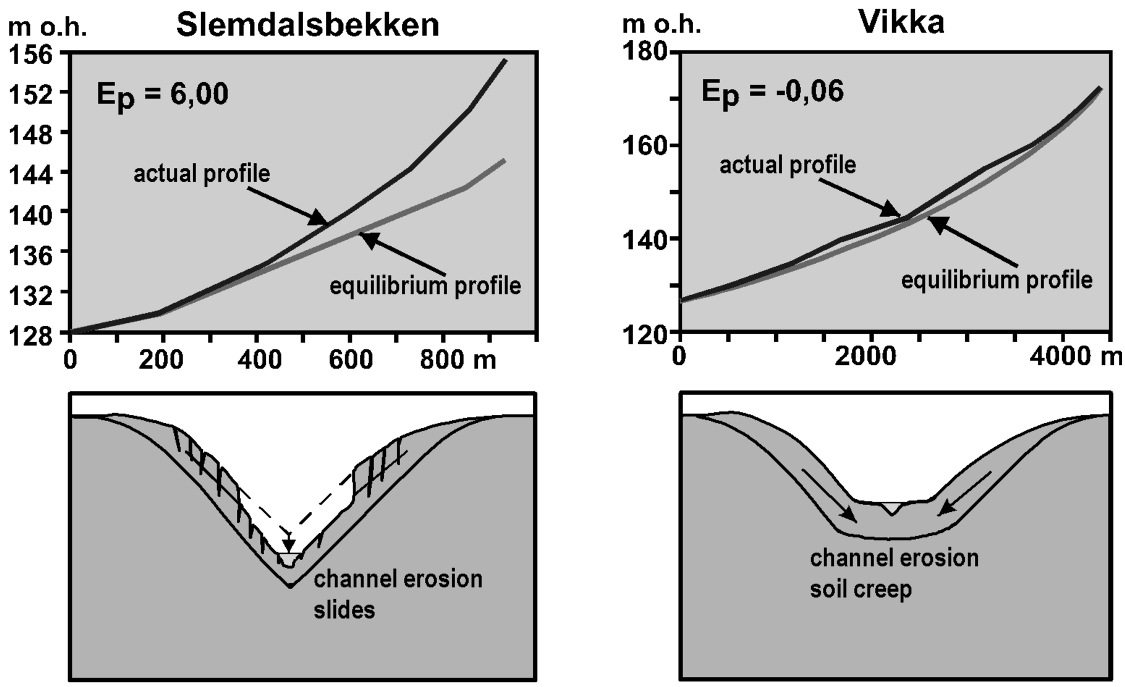

Fig. 5 Upper: Channel gradient and calculated theoretical equilibrium slope of incising and stable streams. Lower: Cross sections illustrating the processes of erosion associated with channel incision.

that all the recorded slides in the 20th century were associated with floods (Bogen & Bønsnes, 2000). The slides occurred during the flood itself or in the period immediately after.

CLIMATE CHANGE EFFECTS

The runoff will increase as a result of the marked increase in total annual precipitation, with a predicted maximum precipitation increase of 20% in the western part of the country. In glacier-fed rivers the runoff will be even higher due to additional glacier melting caused by the temperature rise. The increased runoff will in general increase the channel erosion until the river channels have established a new equilibrium. River channels continually adjust their morphology in response both to the hydrological regime and the sediment load imposed upon them by upstream drainage basin conditions. Channel changes occurring as a result of natural changes or human impacts upon water and sediment supply have been subject to much debate (Simon & Darby, 1999).

In Norway, a striking example is the changes that took place in the Sub-Atlantic on a meandering reach of the River Glomma. Radiocarbon dates indicate that a straightening of the river channel took place 2000–1680 BP, Fig. 6. At that time the climate had changed to become more cold and humid in contrast to the preceding warm and dry Sub-boreal period.

In glacier-fed rivers, the conditions will be more complicated. Winter precipitation and summer temperature are the most important factors controlling the glacier mass balance. As the winters will be warmer, snow storage will probably decline at low

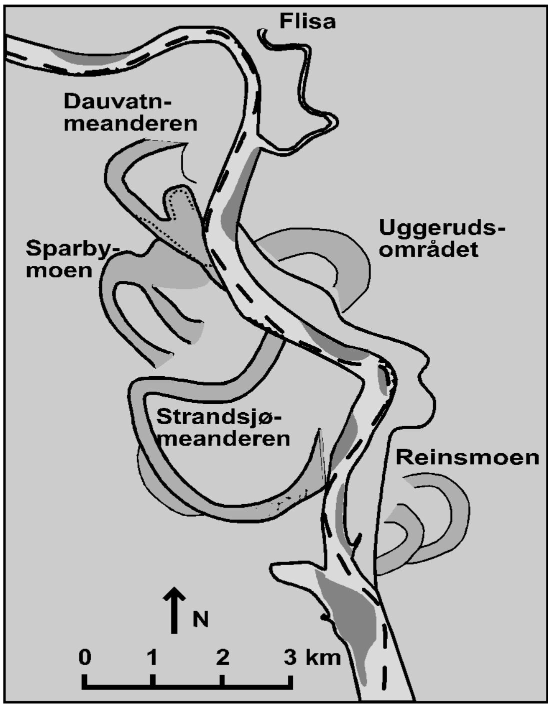

Fig. 6 Climatic changes led to channel changes in the River Glomma 2000–1680 BP. Radiocarbon dates by Beisland (1983)

altitudes but increase in the higher altitudes as a result of increased rates of 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). According to these results, 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 a negative net balance and a general recession. It is believed that most glaciers will have disappeared by 2100.

Studies of sedimentation rates in lakes (Bogen, 2004) indicate that more sediment is supplied from glaciers during periods of negative net mass balance. A sediment core taken from the proglacial lake Storglomvatn in northern Norway revealed a mean sedimentation rate of 1.6 mm $year^{-1}$ for the period 1695–1845. This was during the "Little Ice Age", a cold period with increased precipitation in the form of snow. After 1850 the sedimentation rate increased slowly to about 2.5 mm $year^{-1}$ by 1920. Since then there has been a more rapid increase, to almost 7 mm $year^{-1}$ in the period 1985–1995, although regulation of the lake initiated in 1920 may be partly responsible. Warburton (1999) also conclude from studies of alpine glaciers that sediment yield may decline due to a reduction in meltwater.

An extensive recession of glaciers will probably increase the formation of glacier dammed lakes. Such unstable lakes tend to be formed in locations where tributary glaciers melt back at a faster rate than the main glacier (Liestøl, 1956). It is likely that the number of such lakes will increase during periods of extensive glacier melting, with an anticipated consequent increase in the frequency of floods originating from glacial lake outbursts.

In the unglaciated mountain areas the local availability of sediment is an important factor controlling the extent to which channel changes can take place. The increase in the number of extreme events will expose more extensive areas to erosion. In the river Atna, channel studies and dated flood plain sediment along the main course of the river indicate that a major flood in 1789 was responsible for considerable transport (Langedal *et al*., 1996). Part of the meandering channel pattern was transformed into a braided river reach during the event because of the excessive supply of bed load.

More attention should be given to the predicted increase in the occurrence of intense summer rain-generated floods of short duration, like the 1996 flood in the river Atna. As the summers get warmer the number of such floods will increase in certain regions. Another event of this kind was the rain-generated flood that occurred on "Fulufjell", a mountain area on the border between Norway and Sweden on 30–31 August 1997. The estimated daily precipitation was 400 mm. The capacity of the streams in the area was exceeded and their beds were transformed into broad gravel pavements because of the extreme supply of coarse material.

In the clay areas it is anticipated that the equilibrium of the ravines will be altered because of the increase in flood frequency and magnitude. In ravines with a high erosion potential, stream incision will increase. In some areas this will increase vulnerability to clay slides as has been observed in the River Gråelva (Bogen & Bønsnes, 2004). Ravines characterized by little erosion potential will initially probably adapt by modification of the channel geometry. If climate change is more marked it is possible that here also the equilibrium profile will alter, thereby increasing the erosion potential. This also could lead to channel incision in ravines which previously were considered stable as the constants in equation (1) may be changed.

CONCLUSIONS

Sediment transport rates of major floods in glacial and non-glacial rivers in Norway in the present and future climate is discussed in this paper. Model runs indicate that high-lying glaciers are likely to advance because of the increase in precipitation. Due to the temperature rise, most glaciers will be disappeared by 2100. This will probably increase the formation of glacier dammed lakes that may generate lake outburst floods.

Large magnitude floods in glacier meltwater rivers do not carry extreme loads of sediment because of the limited availability of sediment in subglacial conduits. In reaches downstream from the glaciers and in non-glacial rivers, measurements during floods of 100- to 200-year recurrence intervals indicate given transport rates about 30–40 times the mean of the preceding years. It has been seen in some areas that when the transport capacity of the streams has been exceeded their beds have been transformed into broad gravel pavements. In the clay areas it is expected that an increase in flood frequency and magnitude may alter the equilibrium of the ravines and increase stream incision. Ravines that are stable in the present climate may also be affected. It is anticipated that the increased runoff and sediment input will cause channel changes in many rivers until a new equilibrium have been established.

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