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The impact of erosion protection work on sediment transport in the River Gråelva, Norway

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Abstract The impact of erosion protection works on downstream sediment delivery was evaluated in a study of the River Gråelva in central Norway. Channel degradation and the associated undercutting of adjacent slopes have formerly uncovered pockets of quick clay and triggered major quick clay slides. To prevent further slides the river bed and banks have been reinforced with a layer of rock armouring. The stabilization work started in 1992. When conditions were still close to natural in 1992 and 1993, maximum sediment concentrations were in the range of 15 000–25 000 mg l^{-1} and the calculated annual suspended sediment transport was 163 000 and 99 000 t $year^{-1}$, corresponding to sediment yields of 8150 and 4950 t km^2 $year^{-1}$. Maximum concentrations in 2000 and 2001 did not exceed 6000 mg l^{-1} and the annual sediment transport had decreased enormously, to 11 800 and 18 500 t $year^{-1}$, giving sediment yields of only 590 and 925 t km^2 $year^{-1}$. However, a year-to-year variability controlled by climatic variables was still present.

Key words erosion protection work; quick clay slides; Norway; suspended sediment

INTRODUCTION

It is sometimes desirable to reduce erosion activity within catchments. High sediment loads may reduce water quality and have a negative impact on ecology. It is thus of interest to study the effect of erosion protection work on erosion activity and sediment transport. In the marine clay areas in Norway, erosion activity may trigger large magnitude quick clay slides. The clays 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. These can extend almost to the marine limit (ML), defined as the highest level that was once covered by the sea at any location after the ice sheet withdrew. In the lower-lying parts, large thicknesses of clay had been deposited.

When clays are deposited in seawater, the individual particles (which are flat plates) are bonded edge-to-centre by the salt, producing a strong card-house structure (Fig. 1). However, once uplifted above sea level, groundwater leaching of the salt commences and the clays are transformed into quick-clays (Rosenqvist, 1960). This is a slow process, millennia rather than centuries, and is followed by the development of a drying crust. As the surface soil dries and hardens, the quick zone is not usually visible close to the surface. Quick-clay has reduced mechanical strength and is highly susceptible to liquefaction if subjected to shock waves or excess loading. Slope failure caused by the removal of downslope support, as in river undercutting, has a similar effect. The hollow card-house structure then collapses, releasing the enclosed pore water to form a clay slurry. A body of quick-clay may be kept in

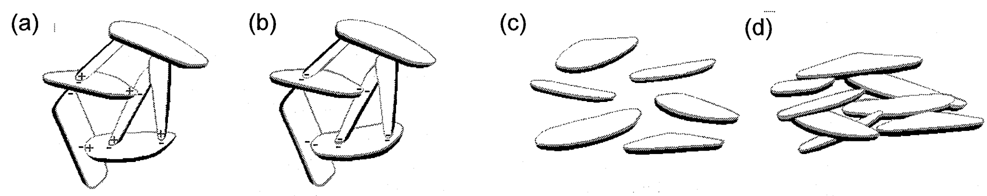


Fig. 1 Illustration of the formation of quick-clay: (a) Deposition of clay particles in card–house structure in saltwater. Particles are edge-to-face bonded by the salt; (b) Above sea level: salt is washed away. As bonding is destroyed the structure becomes unstable; (c) Quick-clay subject to liquefaction. Structure collapses, excess water produces a low viscosity slurry; and (d) After the slide: Flat-lying grain structure contains less water and becomes stable.

place if the surrounding soil is stable. Fluvial erosion in areas with marine clay deposits in Norway has triggered numerous large quick-clay slides, Bjerrum (1971). The clay areas are often densely incised by V-shaped gullies and thus highly vulnerable to erosion. In Scandinavian literature these landforms are termed "ravines", a usage employed here.

The River Gråelva drains an area of 47.6 km^2, of which about 20 km^2 is covered by marine clay, situated below 150 m a.s.l. (Fig. 2). Over two thirds of the trunk stream channel is situated in the clay area. A survey of the soils in the clay areas has revealed that there are large pockets of quick clay in the catchment (Gregersen, 1991). Over the years a number of large magnitude slides have occurred. A list of major slides occurring between 1676 and 1995 is given in Table 1. Seven large volume slides were recorded during this period. To remove the slide hazard, it was decided to carry out erosion protection work along the

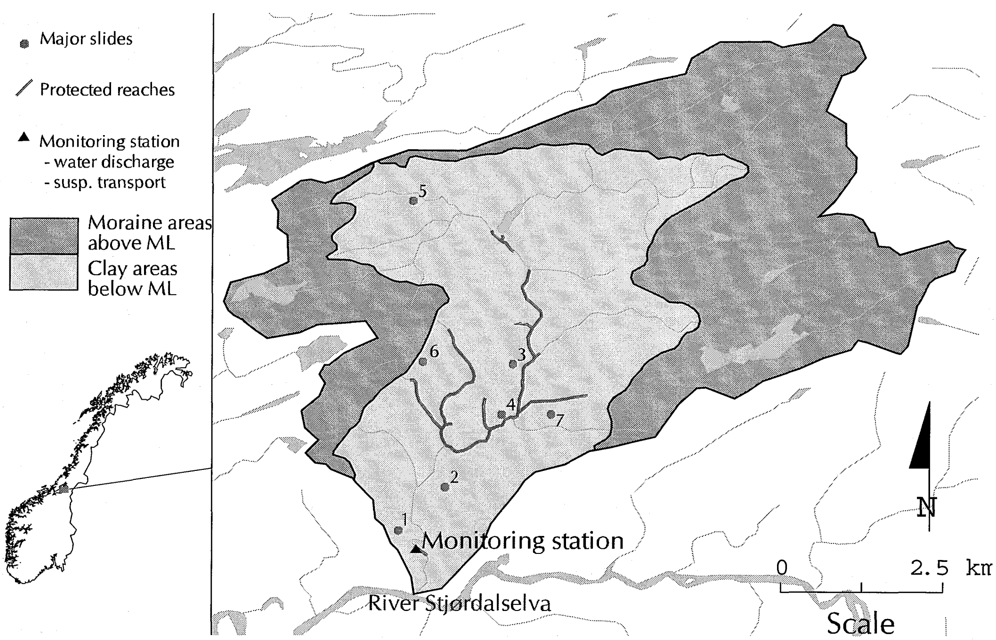


Fig. 2 Map of the Gråelva basin with major landslides locations and protected reaches indicated. See Table 1 for explanation 1–7.

Table 1 Major slides in the Gråelva river catchment.

No	Year	Location	Incidence
1	1676	Børstadfallet	The farm Børstad destroyed
2	1686	Kylloraset	7 people killed
3	1893	Mørsetfallet	Landslide, 800 000 m^3 clay
4	1921	Kvålsvedjan	Landslide, 1 ha land
5	1962	Hovfallet	Landslide 20–30 hectare land, 1 killed
6	1975	Bangmarka	Landslide 1 ha woodland
7	1995	Skjelstadmarka	Landslide 10^{-1} ha land

degrading reaches of the river. A sediment transport monitoring programme was initiated at the same time as the construction work.

SEDIMENT SOURCES AND EROSION PROTECTION WORKS

In areas above ML the overburden is thin and discontinuous, providing negligible sediment yield compared with the clay area. The most important sediment source in the Gråelva catchment is supplied by mass movement caused by river channel degradation. A number of river reaches have been found to degrade. A river at bankful discharge will tend to degrade until a stable equilibrium profile or a stable armouring layer is established. Bjerrum (1971) studied the longitudinal profiles of rivers in clay areas in Norway and found an empirical relation describing the equilibrium profile:

$$S_{cr} = 0.0116A^{-0.55} \qquad (1)$$

where S_{cr} is the critical gradient and A is the catchment area of the reach. Bogen & Sandersen (1991) investigated a similar clay area in southern Norway and found that the large floods were of decisive importance in this connection. During these events, high gradient reaches tended to degrade until a new equilibrium was obtained. Sandersen (1993) used equation (1) to compute the stable equilibrium profile of the River Gråelva. The gradient of the present longitudinal profile is in some reaches 2–4 times that of the calculated stable gradient (Fig. 3(a)). Unless an armouring layer slows down the erosion, the main channel will continue to degrade and in turn destabilize the tributaries. This may cause a further instability of the slopes adjacent to channels and trigger minor landslides and accelerate the soil creep as illustrated by the cross sections in Fig. 3(b). The soil creep is caused by repeated freeze/thaw and wetting/drying cycles. Creep velocity increases with slope gradients. In steep ravines in the clay areas there is a continuous supply of sediment to the river channels. Sandersen estimated the sediment delivery to the Gråelva from creep to be of the order of 10 kg $year^{-1}$ m.

Landslides occur during periods of high precipitation and snowmelt causing high pore water pressure on high-gradient slopes. Vegetation has an important influence too, as it has a binding effect and reduces the soil water content by evaporation and consumption of water. The volumes of the landslides along the river have been observed to vary mostly from a few to several thousand m^3. However, slides of 100 000 m^3 have been triggered by fluvial erosion in the Gråelva catchment. On some reaches the bed has been protected naturally by boulders and stones eroded out from the soil but lateral erosion on these reaches may move the channel, initiating a new phase of degradation.

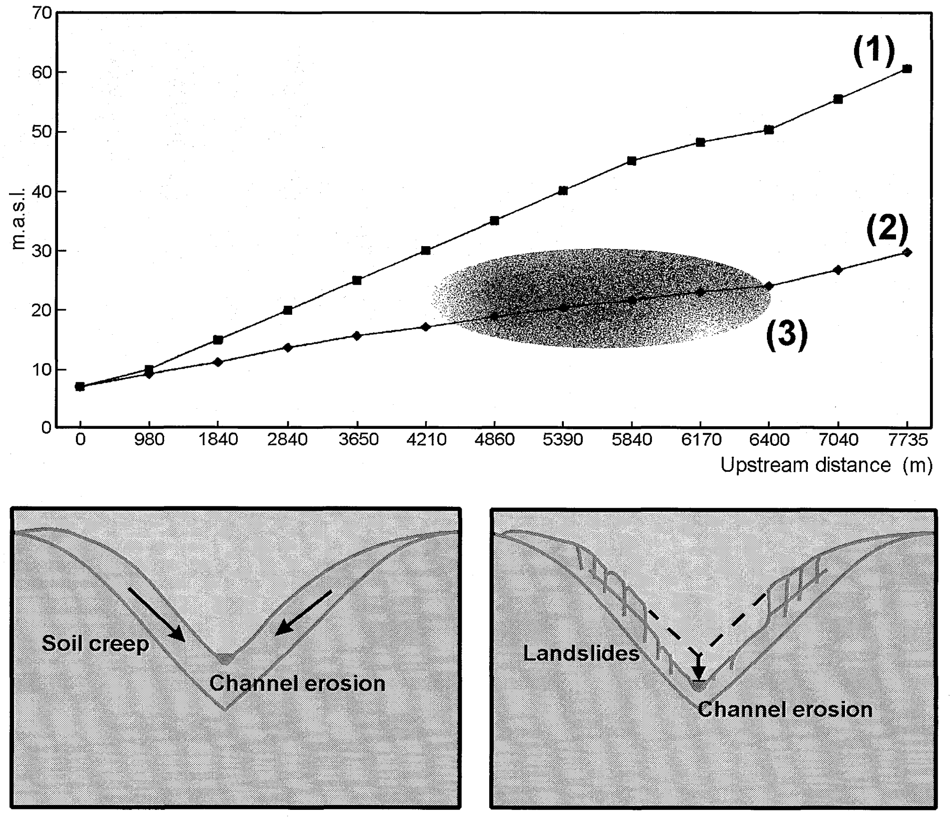


Fig. 3 (a) (1) Channel gradient of River Gråelva; (2), Calculated theoretical equilibrium slope; (3), Schematic illustrating channel incising pocket of quick clay. (b) Cross sections illustrating the processes of erosion associated with channel degradation.

The erosion protection procedure is schematically illustrated in Fig. 4. The bed of the main river was raised and covered by an armouring layer of cobbles and boulders. To prevent further degradation of tributaries, their erosion bases were also artificially raised. The level of the channel floor was thus in some places built up about 1.5–2 m above the natural bed level. The work was initiated in July 1992 but progress varied much from year to year. In 1999 a 4 km long reach was secured, whereas in some years like 1995 and 1998 there was little or no construction activity. By 2001 a total of 10 km had been secured along the main channel and tributaries.

SUSPENDED SEDIMENT TRANSPORT

Sediment concentration and water discharge were measured at Børstad (Fig. 2). The sampling programme involved an ISCO automatic sampler programmed for sampling at a rate of 2–4 samples a day throughout the season. Water samples were filtered through Whatman GF/C filters and the concentration of organic and inorganic particulate matter was

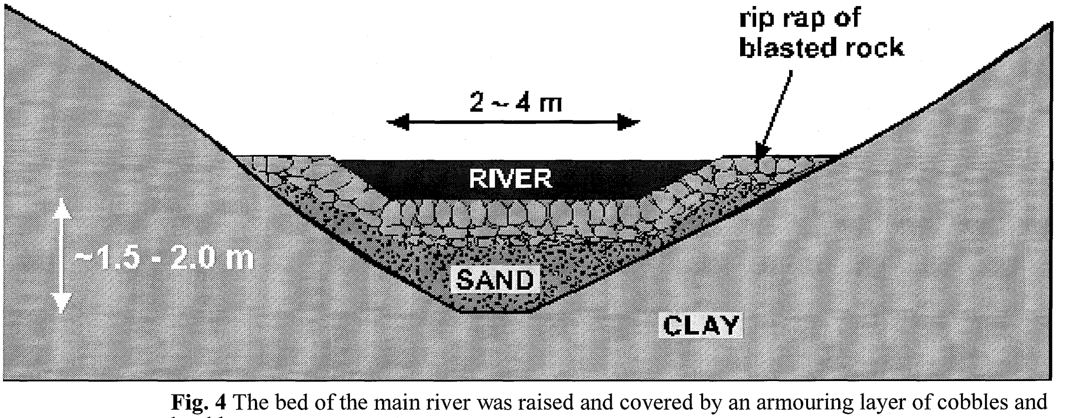


Fig. 4 The bed of the main river was raised and covered by an armouring layer of cobbles and boulders.

determined by weight loss on ignition at 500°C for 2 h. For further description of the sampling methods, see Bogen (1988, 1992). The hydrological regime in the River Gråelva is characterized by low self regulation. The flood events are peak floods of short duration alternating with long periods of very low water discharge. Sometimes floods also occur during winter, when runoff may take place on frozen topsoil. As infiltration is limited under such conditions, the upper part of the soil may become oversaturated and easily eroded.

The seasonal variation in suspended sediment concentration in 1993 is selected as an example of conditions close to natural (Fig. 5(a)). In January and February there were several winter flood events caused by rain in temperatures above 0°C. Flood events due to combined snowmelt and rain occurred in April and May. The summer months were dry but from late July until October there were frequent rainfloods. The maximum recorded concentration of suspended sediments in 1993 was >15 000 mg l^{-1} and on three other occasions that year the concentrations exceeded 10 000 mg l^{-1}. In 2002 the pattern of flood events and the magnitude of water discharges were comparable to those in 1993. The concentrations nevertheless remained low, with a maximum of 3500 mg l^{-1}; the concentration exceeded 1000 mg l^{-1} only on one other occasion that year (Fig. 5(b)).

The calculated annual sediment transport rates show a distinct overall decrease during the period of measurement, from 163 000 t $year^{-1}$ in 1992 to 5800 t in 2002 (Fig. 6). The

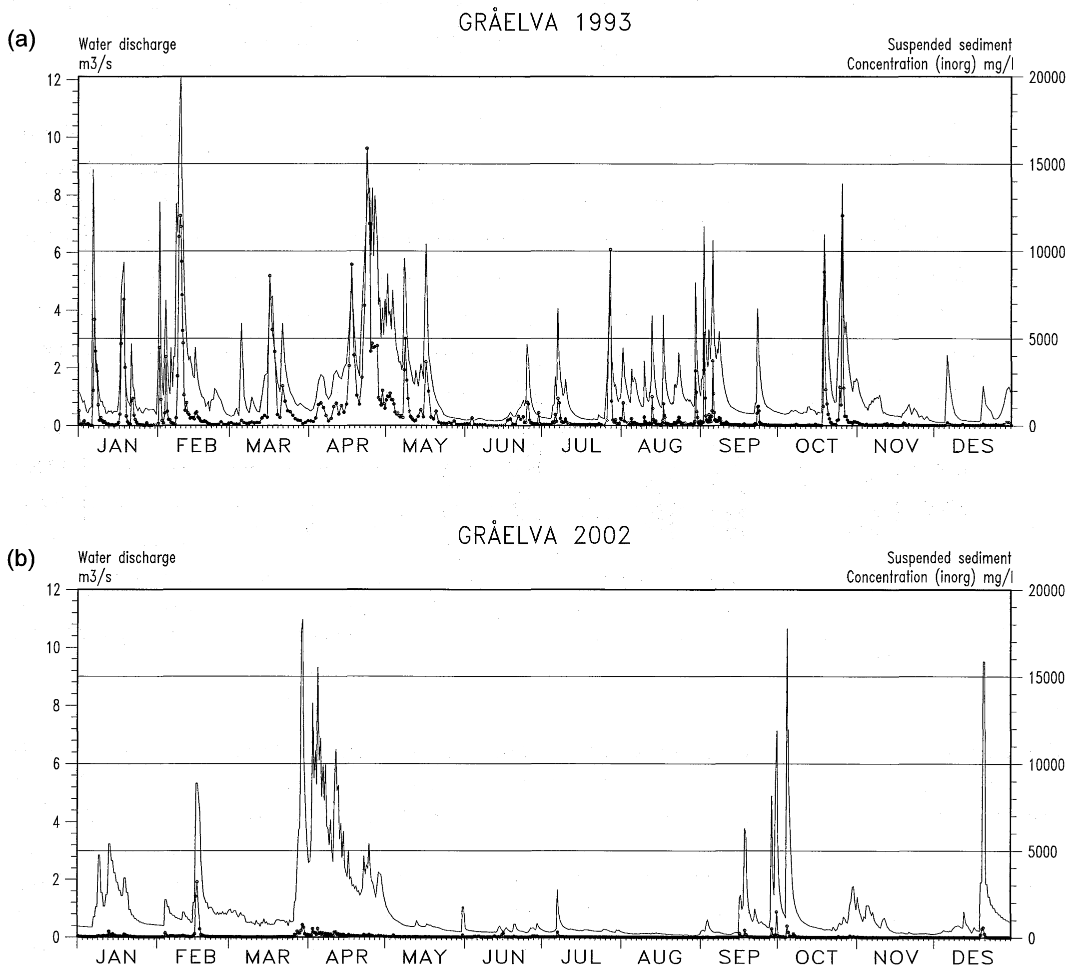
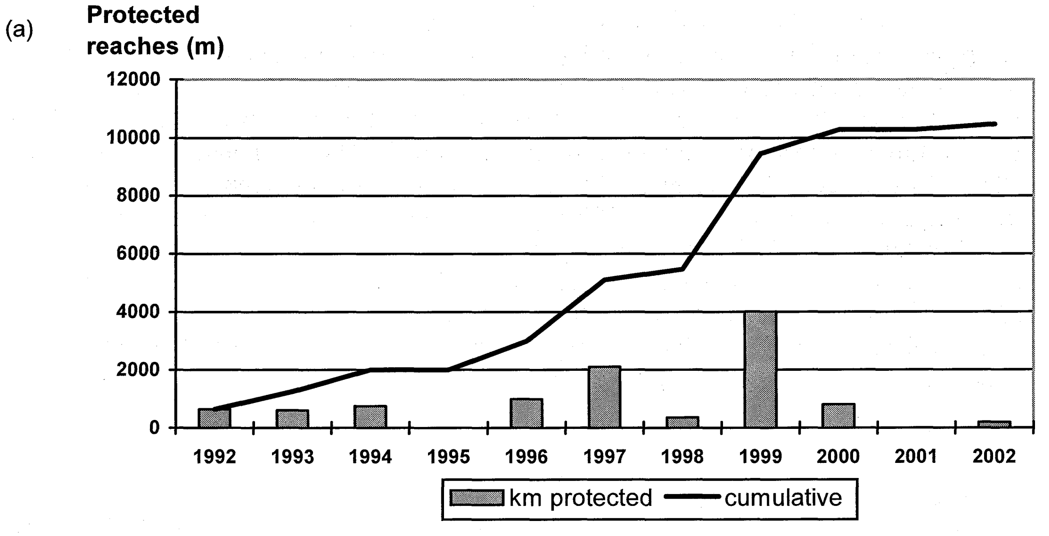


Fig. 5 The seasonal variation in suspended sediment concentration in 1993 and 2003. Water discharge (line) and suspended sediment concentrations (dots). (a) 1993 (at early stage of protection work) (b) 2002 (after 10 km of channel protected).



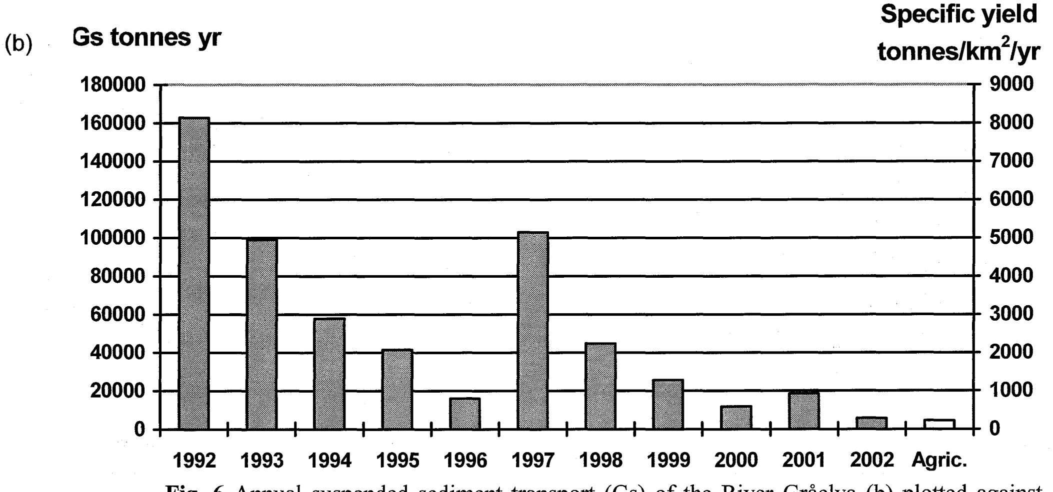


Fig. 6 Annual suspended sediment transport (Gs) of the River Gråelva (b) plotted against erosion protection work progress (a). Agric, indicates estimate of mean annual sediment yield from cultivated land.

decrease coincided with the progress in the erosion intervention programme, see Fig. 6 (upper). The primary cause of the reduction in particle concentration and sediment yield was the decrease in landslide activity and lateral erosion. Bønsnes *et al.* (2000) found a significant correlation between suspended sediment concentration and water discharge. This probably reflects the fact that a major part of the sediment sources are situated close to the river channel and are thus affected by a rise in water discharge. The regression curves did not change very much throughout the period of measurements. It is therefore likely that the dominating erosion processes remain the same but in total have much less effect than previously.

A comparison between sediment yields in other Norwegian rivers (Bogen, 1996) and those measured in the River Gråelva when conditions were still close to natural shows that the latter are the highest on record. Despite the large reduction in sediment transport, the sediment yield is still high when compared to other areas. The sediment yield of agricultural land within the River Gråelva catchment (225 t km^{-2} $year^{-1}$) is included in Fig. 6 for comparison. When the erosion protection works have been completed, erosion by surface runoff (including the contribution from agricultural land) will become the most important sediment source.

Some of the year-to-year variation in sediment transport is not explained by the influence of the erosion protection work alone. The decreasing trend was interrupted by a sharp increase from 16 000 t in 1996 to the 100 000 t measured in 1997. In 1998 the transport decreased once more, but only to 45 000 t, which is still higher than the annual yields in 1995 and 1996. However, in 2002 the transport was down to 5800 t.

The overall reduction in sediment transport totals as sediment sources were cut off may be due to the natural variability controlled by weather conditions. The number of flood events and the pattern of precipitation are subject to large seasonal and annual variations. To study the impact of such climatic variables an analysis was carried out involving a simple classification of the number of water discharge events above a certain threshold level.

To avoid including interrelated floods, the water discharge had to fall below a certain prestated level before the next flood was regarded as a separate one. The result of an analysis of the total number of flood events within each year is shown in Fig. 7. A peak over threshold technique was applied, involving three different threshold levels: 3.7 m^3 s^{-1}, 4.6 m^3 s^{-1} and 5.6 m^3 s^{-1}. These levels correspond to 2–3 times the standard deviation of the mean water discharge for the period of observation (Shaw, 1983).

The results of the analyses indicate that the low transport total in 1996 was largely due to the lack of floods that year, while the high total in 1997 may be explained by the occurrence of a number of flood events. The very large transport total in 1992 was also associated with the number of floods, but especially with the fact that one of these floods occurred during winter conditions. The large flood in January that year accounted for 80 000 t transport measured during just 1 week. During the period 1992–1996 a decrease in the number of floods augmented the effect of erosion protection work. During the period 1997–2002 there was again a marked decrease in sediment transport, despite the number of flood events

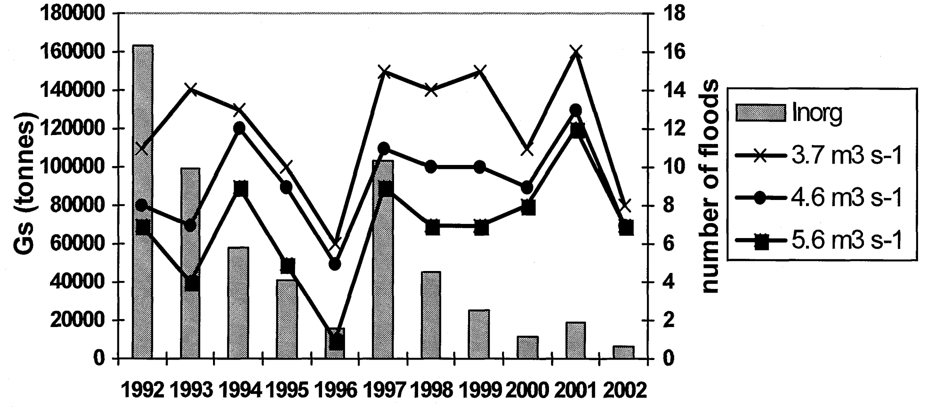


Fig. 7 Annual inorganic suspended sediment transport in the River Gråelva plotted together with the annual number of flood events exceeding the specified magnitudes.

increasing or remaining constant. Most of the decrease in sediment transport during this period can therefore be attributed to the effectiveness of the erosion protection work.

Berger *et al.* (1997) investigated the ecological impacts on the freshwater ecosystem after the stabilisation of the river bed and concluded that the erosion protection work seemed to have had a positive effect. There have been increases in the density of both bottom living organisms and younger fish within the river reaches affected by construction. This was attributed to an increase in algae production because of improved light conditions, and to improved fish habitats.

CONCLUSIONS

The aim of this paper is to report from investigations carried out to study the impact of erosion protection work on sediment transport in a river, the Gråelva, flowing in one of the marine clay areas of Norway.

River channel degradation and the associated undercutting of adjacent slopes followed by frequent small scale mass movement events are the main erosion processes. In the past this erosion activity has uncovered areas of quick clay and triggered several major slides. To reduce the slide hazard, erosion protection work has been carried out along the degrading reaches of the river. At the start of the construction work a sediment transport monitoring programme was initiated.

During 1992 and 1993, when the river conditions were still close to natural, there were several flood events with maximum concentrations in the range of 15 000–25 000 mg l^{-1}. In 2002 the maximum concentration was only 3500 mg l^{-1} and otherwise exceeded 1000 mg l^{-1} on only two occasions that year. The annual sediment transport rate had thus decreased from 163 000 t $year^{-1}$ in 1992 to 5800 t $year^{-1}$ in 2002. This great reduction in annual sediment yield, resulting from the cutting off of major sediment sources, did not result in a continuous decrease in sediment transport totals. A year to year variability controlled by climatic variables was still present, manifesting itself in the number and character of flood events.

During the period 1992–1996 a decrease in the number of floods thus strengthened the reducing effect of the erosion protection work. The marked decrease in sediment transport during the period 1997–2003 can be attributed to the impact of the erosion intervention programme as the number of flood events was increasing or constant during this period. The erosion protection work also had a positive impact on the freshwater ecosystem. There has been an increase both in the density of bottom living organisms and younger fish within the river reaches affected by construction.

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