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The contribution of gully erosion to the sediment budget of the River Leira

J. BOGEN, H. BERG
Norwegian Water Resources and Energy Administration, PO Box 5091, Majorstua, N-0301 Oslo, Norway

F. SANDERSEN
Norwegian Geotechnical Institute, PO Box 3930, N-0806 Oslo, Norway

Abstract This paper reports the results of a research project aimed at quantifying the sediment budget of the River Leira in southern Norway in order to reduce its sediment load and improve water quality. The sediment load arises from the erosion of agricultural land and from extensive gullying in the drainage basin. The sediment budget was determined through a monitoring programme that included several stations along the main stem of the river and in the gullies. Long term variability in sediment transport was determined by analysis of lake deposits, overbank sediment from flood plains and long term records of floods and landslides. An examination of the stability of the gullies revealed the presence of two types. In the unstable type, the dominant process was landslides, whereas lateral erosion in streams and soil creep characterized the stable ones. The measured annual sediment load was 5431 and 507 t respectively in the two gullies, corresponding to sediment yields of 1131 t km^{-2} $year^{-1}$ and 141 t km^{-2} $year^{-1}$. The mean annual sediment load was measured to be 73 000 t in the lower part of the main stem. Using the USLE equation, the erosion of agricultural land was estimated to contribute about 45% of the total load. Gully erosion and river bank erosion thus contribute 55% of the total load. The long term record of major floods and landslides shows a corresponding periodic behaviour. Subsequent to large floods, the baselevel of the gullies is lowered and the frequency of landslides increases. The sedimentation rate of lake and overbank sediments increases with the combined effect of frequent floods and landslides and the changes in agricultural practice that took place in the last part of the 1960s.

INTRODUCTION

A degradation of water quality of lakes and rivers in the Romerike region, southern Norway due to increased sediment loads has been experienced since the end of the 1980s. Particle-bound nutrients resulting from the erosion of agricultural land have been observed to pollute water bodies elsewhere. Thus, the deterioration of water quality was believed to be due to erosion associated with agricultural activity. A significant change in agricultural practice has also taken place during the 1970s. This change involved extensive levelling of steep slopes to permit increased production of cereals.

However, the presence of large ravine valleys and gullies in the marine clay areas of Romerike is also a sign of extensive erosion outside the cultivated areas. Thus, the agricultural authorities in the counties of Oslo and Akershus initiated a research project to carry out a sediment survey and assess the contribution of various sediment sources to the sediment budget. The River Leira was chosen as a reference basin and one of the aims of the project was to suggest measures to reduce sediment loading and improve water quality. This paper focuses on the sediment transport studies and the long term role of natural background processes *vs.* agricultural activity in the sediment budget of river basins. Other aspects of the project have been reported by Bogen *et al.* (1993).

PROCESSES OF EROSION

The River Leira drains an area of 659 km^2 (Fig. 1). About 133 km^2 of the 380 km^2 covered by marine clay, is cultivated. The area above the limit of marine clays is covered by boreal forests. The overburden in this area is thin and discontinuous and rocky outcrops are abundant. The sediment yield of this area is negligible compared to the clay area.

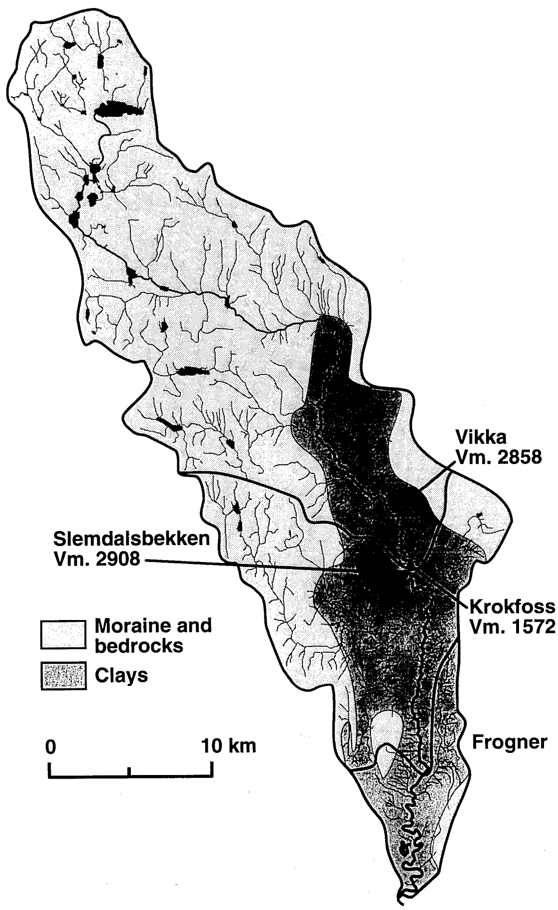

Fig. 1 Map of monitoring stations in the River Leira.

Extensive erosion takes place in the clay area. In spring and late autumn ploughed fields have no vegetation cover and erosion by surface runoff dominates on cultivated land. Channel erosion takes place along streams and also in the subterranean drainage system that sometimes exists in clay areas.

A close examination of the gullies in the area reveals that they are of two types. In the unstable type, landslides are abundant. The stream channel is degrading and scars of numerous landslides are visible along the gully walls. These gullies have a V-shaped cross section, and the main stream is often deeply incised. The other type of gully appears to be stable and a flood plain is often developed along the stream. Lowering of the channel is limited and the channels are often subject to lateral migration. Slides are infrequent in these gullies and soil creep is the dominating mass movement process that is supplying sediments to the river channel.

THE MONITORING PROGRAMME

Several monitoring stations were set up to monitor the sediment load from the various parts of the clay area (Fig. 1). The monitoring station at Vikka is situated in a gully of the stable type where a dominant part of the sediment supply is derived from soil creep. The monitoring station in Slemdalsbekken covers an area where the dominant part of the sediment is derived from sheet slides and slumping. The station at Krokfoss was set up to measure the sediment transport in the main stem in the upper part of the river system. The sediment transport at all stations was measured using the methods described by Bogen (1988) and Bogen *et al.* (1993). The sampling strategy involves the use of ISCO automatic samplers programmed for sampling at a rate of 2-4 times a day throughout the season. A local water agency, ANØ, took discharge proportional samples in the river at Frogner. Here the frequency of sampling is increased with discharge and all samples are integrated on a weekly basis.

SHORT TERM AND SEASONAL VARIABILITY IN SEDIMENT TRANSPORT

In general, high discharge implies high sediment concentration and a high sediment transport. However the availability of sediments for transport is also important and there is no simple relationship between sediment transport and discharge. Three seasonal sediment regimes may be recognized: a snowmelt regime in spring, an autumn rain flood regime, and a summer rain flood regime.

Flood events due to snowmelt proceed more slowly than those due to rain, and the sediment load tends to increase with discharge at a more rapid rate during the autumn rainfloods compared to snowmelt conditions in spring.

In summer, suspended sediment concentrations vary almost independently of discharge. Rain floods during this period are often preceded by long periods of low discharge. As shown by Bogen (1980), the actual concentration reached during such a flood is dependent on the amount of sediment deposited in the upstream channel reaches during the preceding low water period. In addition, the relative contribution from sediment sources is subject to seasonal variations. In spring there is less vegetation cover and greater erosion of agricultural land than during autumn when channel erosion seems to dominate. Seasonal changes in grain size have also been attributed to seasonal in

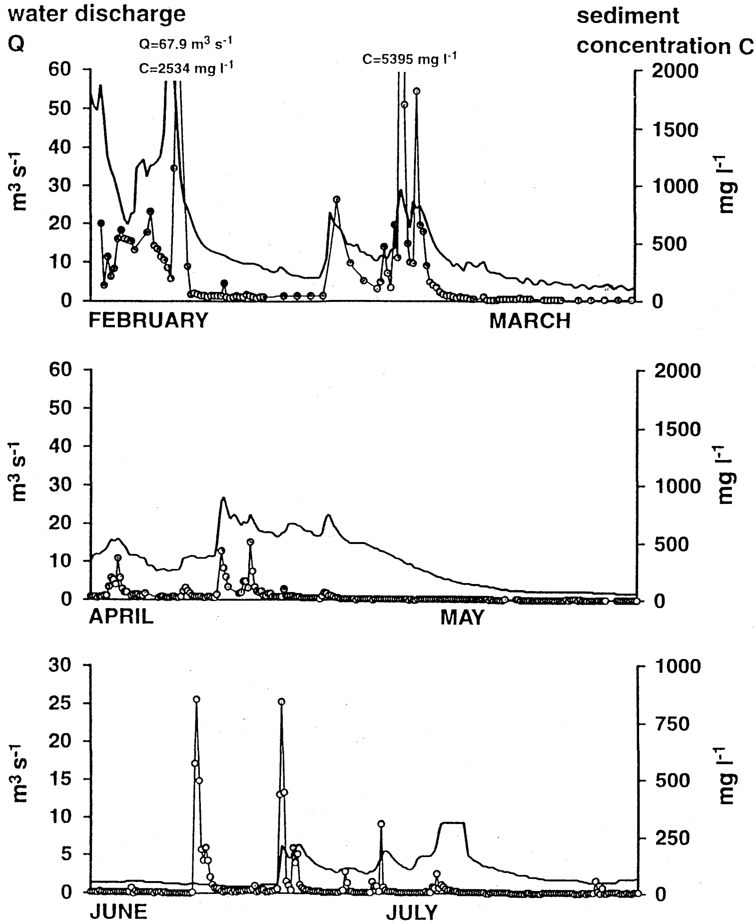

Fig. 2 Water discharge and sediment concentration at Krokfoss in the River Leira during the months February-July 1990.

sediment sources (Bogen 1992). Slides and slumping that affect the river channels may also cause short-term irregular increases in concentration. Such an incident happened on the 12 June 1990 when the concentration rose to more than 800 mg l^{-1} with a low and constant discharge (Fig. 2). During a subsequent increase in discharge considerable amounts of sediment were available in the channel and the concentration reached about the same level. After 3 July most of the sediments supplied by this slide had been transported downstream and concentrations returned to a low level.

ANNUAL TRANSPORT

There is considerable variability in the sediment transport from year to year at the individual monitoring stations. These variations are not only due to different runoff conditions but also to other factors. The sediment transport at Krokfoss was low in 1989 because of a relatively dry summer and autumn. In 1990 the load was considerably larger. About 75% was transported during the winter flood event in February that year.

During this event the runoff took place on frozen topsoil. As infiltration was limited, the upper part of the soil became oversaturated and was extensively eroded.

Winter floods are rare in this area. However, in 1992 unusually high water discharge occurred in late November and December at a time when winter conditions normally prevail (Fig. 3). The total load transported in 1992 was however less then that of 1991 due to the large total runoff in 1992 (Table 1).

Total runoff is important to a certain extent. The availability of sediments for transport is however also controlled by the conditions during the actual flood. In Vikka and Slemdalsbekken a similar pattern is observed. However there is a difference between the two gullies. The supply-control of the suspended sediment transport in Slemdalsbekken seems to be of less importance. The large number of landslides in this gully may cause a high load even in years with a low runoff.

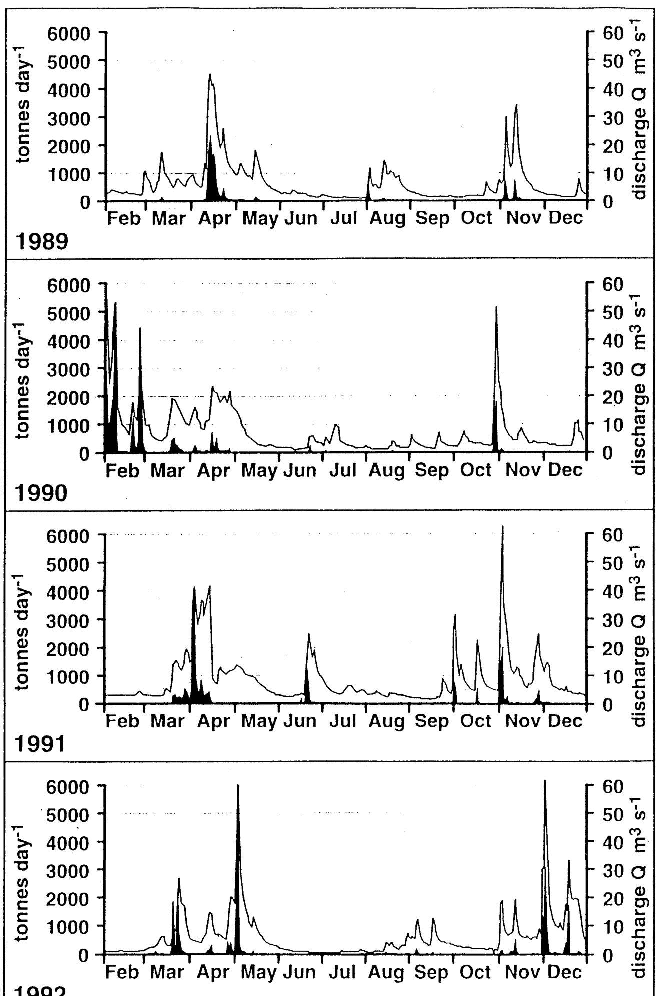

Fig. 3 Sediment transport at Krokfoss in the River Leira during the years 1989-1992. Sediment load is shaded.

Table 1 Annual sediment transport and water discharge at Krokfoss, Slemdalsbekken and Vikka.

Station		Year: 1989	1990	1991	1992	Mean	Mean sediment yield (t year^{-1} km^2)
Krokfoss	Q (mill m^3)	177.21	205.17	277.79	182.87	210.76	
	G_s (t)	15 871	39 751	31 600	28 683	28 976	161
Slemdalsbekken	Q (mill m^3)			4.57	2.98	3.77	
	G_s (t)			5 572	5 289	5 431	1131
Vikka	Q (mill m^3)	2.36	2.40	2.46	2.82	2.51	
	G_s (t)	223	313	278	1 215	507	141

In Vikka, a minor increase in total runoff in 1992, caused a high load. A possible explanation for this is the high number of individual flood events that occurred in this year. Erosion along river banks is an important source of sediments in Vikka. River banks tend to collapse during the recession of a flood due to the process of groundwater erosion. In this way the frequency of water level fluctuations is a controlling factor.

At Frogner, ANØ estimated a mean transport of 73 000 t year^{-1} during the years 1983-1992.

LONG TERM VARIABILITY IN SEDIMENT TRANSPORT

The field studies in this project were initiated in 1989. In October 1987 a major flood occurred in the area, which was the largest flood on the record. At the station Krokfoss on the main stem of Leira the recurrence interval has been computed to 100 years (Krokli & Voksø, 1994). In several of the gullies it was evident that the local erosion bases was lowered during that flood. This lowering of the main stream generated slope instability and subsequently a number of slides were triggered. The landslide frequency will remain high until the slopes regain a stable position.

A plot of the landslides recorded in this century against water discharge data suggest that major floods triggered most slides on the record. The slides occurred at the time of the flood or in the period immediately after (Fig. 4). The slides that occurred in the 1970s are an exception. These slides were triggered by the levelling of slopes on cultivated land.

The water level in the nearby Lake Hurdalssjøen is used to extend the short record of water discharge at Krokfoss. This lake is regulated and only flood levels show natural conditions. For this reason, only the flood levels are included in Fig. 4. A periodical pattern of flood levels seems to be present in the Hurdalssjøen data series. Periods with frequent flood levels seem to occur after low water intervals of 10-15 years.

Similar discharge fluctuations were found in other rivers in the same area (Bogen *et al.*, 1993). Probst (1989) and Probst & Tardy (1985) described similar long term streamflow fluctuations in 50 major world rivers. The long term discharge fluctuations appeared to be synchronous in regional areas. Such fluctuations must have important impacts on the transport of dissolved and suspended matter in rivers.

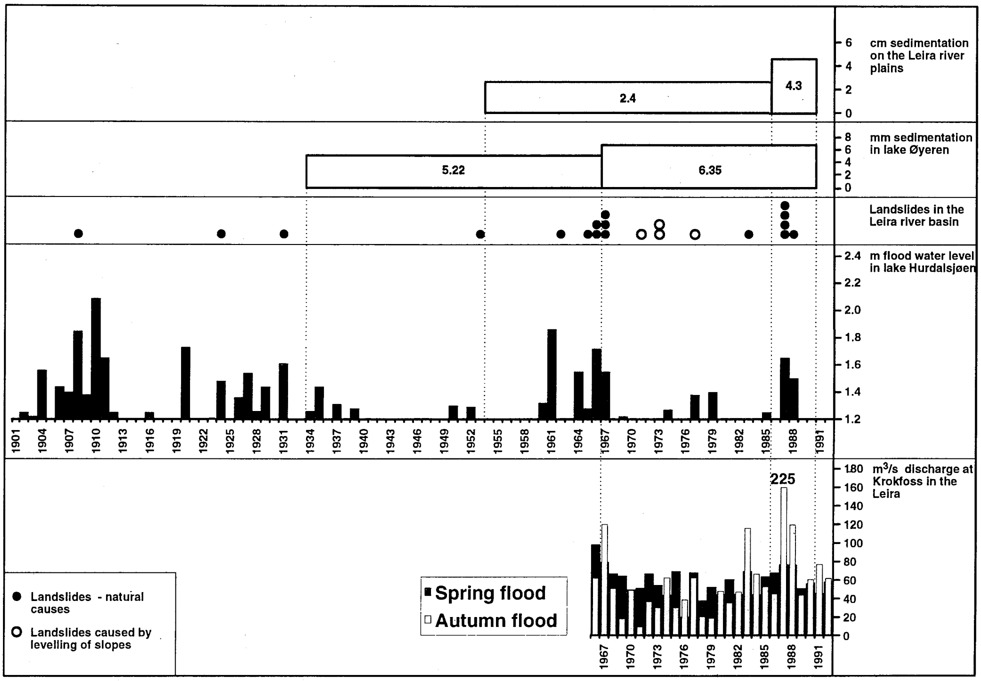

Fig. 4 Co-plot of overbank sediments from flood plains, sedimentation rates in Lake Øyeren, occurrence of landslides and water levels and water discharge throughout this century.

THE LONG TERM SEDIMENT BUDGET

The sediment transport measurements in the gullies Vikka and Slemdalsbekken were used to find a relation between their sediment yield and potential erosion. This relation was used to estimate the total contribution from natural processes in the Leira catchment (Bogen *et al.*, 1993). Erosion of agricultural land was estimated with the USLE. As a result of these calculations the gully and river bank erosion contribute 55% of the total load whereas erosion from agricultural land contributes the remaining 45%. The seasonal and year to year variability in the sediment transport data demonstrates the need for long data series. To obtain more information about long term variations, lake sediments and overbank sediments from river plains were used as a substitute. Dating of overbank sediment sequences from the flood plains of the River Leira indicated an increase in sedimentation rates from a mean value of 2.4 cm year^{-1} during the years 1954-1985 to 4.3 cm year^{-1} in the years 1986-1990. Dates were based on the measurement of the activity of ^{137}Cs and ^{134}Cs in four individual profiles (Walling *et al.*, 1992). The years of reference were the year of the Chernobyl accident, 1986 and 1954 when radioactivity from nuclear bomb testing began to be recorded worldwide.

Layers in the bottom sediments of Lake Øyeren deposited during major floods in 1934 and 1967 allowed determination of an increase in sedimentation rate from 5.22 mm year^{-1} during the years 1934-1967 to 6.35 mm year^{-1} during the years 1967-1990. This lake receives sediments from several rivers although the Leira contributes a dominant part (Bogen & Nordseth, 1986). Several factors are of importance for the long term variability of sediment transport. Changes in land use may in part be responsible for the 22% increase in lake sedimentation after 1967 when agricultural practice went through large scale changes. However, gully erosion reinforced by major floods was also significant during the same period as shown by the large increase in overbank sedimentation during the floods at the end of the 1980s.

A tentative sketch, that is based on the factors affecting the long term variations in sediment delivery from the two types of sources, is shown in Fig. 5. Both gully erosion on agricultural land will be influenced by long term changes in the hydrological regime. A lowering of base levels during a period of floods may be followed by some years of high loads in the streams from the unstable gullies. Changes in agricultural practice may also influence the transport rate on the scale of decades.

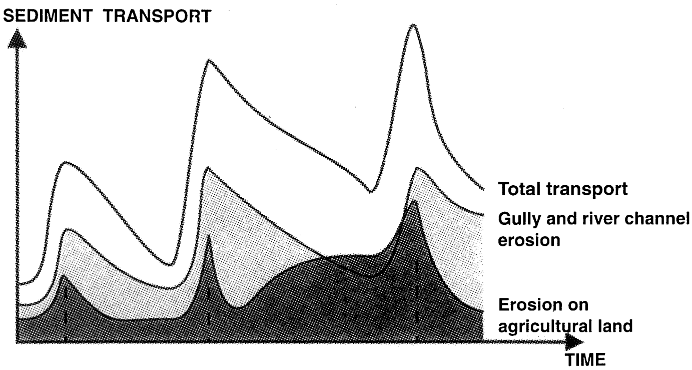

Fig. 5 Hypothetical diagram of long term variations in the sediment budget of the River Leira. The sediment load of the river is a sum of the sediment delivery from erosion on cultivated land and natural erosion in gullies and river channels.

DISCUSSION

The results reported in this paper stress the important contribution of major floods to the processes of erosion in the River Leira. As a limited number of active gullies dominate the sediment budget, a suggested remedial measure to prevent stream degradation is to secure the gully bed by erosion control means. This will limit the lowering of base level during large magnitude floods. In addition, it is recommended to extend the period of vegetation covered topsoil on cultivated land and to carry out ploughing in springtime rather than autumn.

It is likely that the long term variations in sediment transport caused by the variations in runoff magnitude may be present in larger regions and thus affect the ecology of larger water bodies and coastal areas. In this context it is important to take into account both long term and short term variability when planning the sampling strategy for monitoring programmes.

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