Sediment transport in agricultural catchments—the need for methods to trace sediment sources

LILLIAN ØYGARDEN, JOHANNES DEELSTRA, HANS OLAV EGGESTAD & STINE MARIE VANDSEMB

Jordforsk, Centre for Soil and Environmental Research, Frederik A. Dahlsvei 20, 1432 Ås, Norway

lillian.oygarden@jordforsk.no

Abstract In the Agricultural Environmental Monitoring Programme (JOVA) runoff, losses of suspended solids and nutrients are measured. In the Skuterud (680 ha) and Mørdre (450 ha) catchments, soil erosion from agricultural land is considered to be the major source of particles. Information about agricultural practices on each field is collected to relate losses of particles to e.g. the area ploughed at the time of runoff. In spite of there being less area tilled than normal in the autumn 2000, soil losses were 5–6 higher than mean values for the 10-year monitoring period (1991/1993–2001). Autumn precipitation was 2–3 times higher and runoff 3–5 times higher than normal. A field inventory documented that not only tillage contributed to soil losses, but also preferential flow, erosion around hydrotechnical installations and especially bank erosion. It illustrates the need to have methods for tracing all sources of sediment for the planning of conservation measures.

Key words catchment; environment; erosion; monitoring; Norway; nutrient losses; runoff; tracers

INTRODUCTION

Runoff from agricultural areas is a main contributor to pollution of water. The European countries bordering the North Sea and Skagerak have agreed upon a 50% reduction of the nitrogen and phosphorus loads (Norwegian Ministry of Agriculture, 1991). In south eastern Norway soil erosion is a main contributor to the phosphorus losses. Due to a combination of marine sediments, cereal production and autumn ploughing, farm fields have been exposed to surface runoff and erosion during autumn and snowmelt periods (Lundekvam & Skøien, 1998; Øygarden, 2000). Soil losses have been especially high from areas that have also been artificially levelled. To reduce erosion and phosphorus losses, subsidies have been introduced for farmers to change farming practices (Norwegian Ministry of Agriculture, 1999). There is a focus on cost-effective measures to reduce erosion.

JORDFORSK is in charge of the Agricultural Environmental Monitoring Programme (JOVA) in Norway. One of the major objectives of this programme is to document the effect of different agricultural production systems and site-specific characteristics on erosion and nutrient losses to surface waters and to advise local and central policymakers about agricultural production systems and their environmental effects. The programme has been in operation since 1991 in 10 agricultural catchments varying in size from 1–20 km^2.

Annual variations in weather conditions can have a significant influence on the losses, but political decisions (i.e. subsidies) may also have an influence on the choice of cropping systems and tillage operation and can thereby influence the nutrient and soil losses. During the last 10 years new subsidies, with the objective to change tillage systems from autumn tillage to spring tillage in addition to subsidies for catch crops, buffer zones and sedimentation ponds, have lead to changes in agricultural practices. Within the Agricultural Environmental Monitoring Programme, information concerning agricultural practices is collected yearly for individual farm fields in the catchments and any changes in practices are thereby recorded.

Erosion in the southeastern part of Norway mainly occurs during the autumn and spring period (Lundekvam & Skøien, 1998; Øygarden, 2000). Erosion can occur due to: (a) saturated overland flow caused by prolonged rainfall on a non-frozen soil, or (b) overland flow caused by snowmelt and/or rainfall events on a frozen or partly frozen soil. In the second case rainfall intensities can be higher than the infiltration capacity of frozen or partly frozen soils. In the autumn of 2000 the southeastern part of Norway received unusual large amounts of precipitation leading to very high runoff, soil and nutrient losses.

This paper evaluates the losses, as measured on the Skuterud and Mørdre catchments (Fig. 1) during this autumn period and following winter, and compares them to previous monitoring periods. Special attention will be given to identifying the possible sources of the measured sediments. Results from the monitoring programme will be compared with findings from a research project studying erosion patterns at field scale, and the need of methods for tracing particles in catchments will be addressed.

METHODS

Description of the catchments

Mørdre catchment (680 ha) is located 45 km northeast of Oslo (Fig. 1). It is dominated by agriculture, covering an area of approximately 440 ha. The main crops are cereals

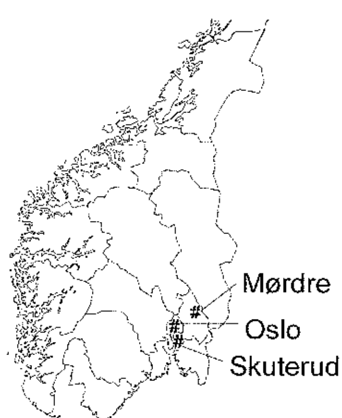

Fig. 1 The location of the Mørdre and Skuterud catchment in southeastern Norway.

in addition to minor crops like potatoes, ley and permanent grasses. The remaining area is covered by forest, bogs and housing.

The average normal annual temperature for Mørdre is 4.0°C, with a minimum of – 6.9°C in January and a maximum of 15°C in July. The normal annual precipitation is 665 mm, with a minimum of 34 mm in February and a maximum of 76 mm in August and September, respectively. Winters tend to be relatively unstable, with alternating periods of freezing and thawing. Marine fine deposits cover most of the catchment and are dominated by clay soils deposited due to icemelt at the end of the last ice age. A thin layer of silt has been deposited on top of the clay layer, following a large flood from one of the inland lakes formed during the last ice melt period. Due to land rise, numerous streams have eroded and intersected the landscape, which has lead to the formation of the characteristic topography with flat plains intersected by steep ravines. The catchment lies approximately 200 m above mean sea level.

Skuterud catchment (450 ha) is located 30 km southeast of Oslo. The main land use is agriculture, with cereals as main crops comprising a total area of 272 ha, in addition to a forested area of 129 ha. The remaining land use includes a housing area. The average annual temperature for Skuterud is 5.3°C, with a minimum of –4.8°C in January/February, and a maximum of 16.1°C in July. The normal annual precipitation is 785 mm, with a minimum of 35 mm in February and a maximum of 100 mm in October. Winters are usually unstable, with alternating periods of freezing and thawing. Marine fine deposits, occasionally rich in gravel and stone, cover most of the catchment. The average height of the catchment is 120 m above mean sea level. In general, the slopes are long and gentle on the western side of the main stream, while the eastern side has shorter and steeper slopes.

The agricultural land, both in the Skuterud and Mørdre catchment, is provided with an artificial subsurface drainage system. The drain spacing varies from 8 to 10 m while the drain depth is 0.80–1.00 m below soil surface. The drain pipes are 50 mm in diameter.

Discharge measurement system and water sampling

Water discharges are measured using a Crump-weir in combination with a data logger. A Crump-weir is a short crested weir, extensively used in the JOVA project to monitor

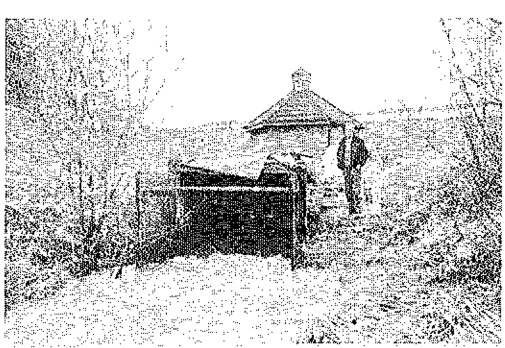

Fig. 2 Monitoring station in Mørdre catchment in the JOVA Programme.

runoff from agricultural dominated catchments (Fig. 2), (Deelstra & Øygarden, 1998a). Water levels are measured automatically using a pressure transducer and discharges are calculated on the basis of the known head–discharge relation for the weir. Water sampling is carried out on a volume proportional basis (Deelstra & Øygarden, 1998b). The water samples are collected on a bi-weekly basis and analysed for selected plant nutrients, dissolved solids (sediments) and pesticides. Discharge measurements were initiated in 1991 and 1993 in the Mørdre and Skuterud catchment, respectively. When presenting the results of the programme, an agro-hydrological year starts on 1 May, which coincides with the onset of farming activities.

Farming practices

As part of the Environmental Monitoring Programme (JOVA), all farmers in the catchments provide information about the farming activities concerning each field, and therefore the type and date of tillage are known. For each runoff period, losses of suspended solids can be related to the area ploughed or with stubble. Runoff periods before and after tillage can be compared to study the effects of tillage on soil losses from the catchments. In general it is assumed that most of the suspended solids measured in streams originate from farm fields and is especially due to autumn tillage.

Field inventory of erosion pattern

As part of an ongoing research project, all the individual farm fields in Mørdre and Skuterud are visited after major runoff events and snowmelt periods during the autumn and winter season, to map and measure erosion patterns. The objective is to identify and measure soil loss as a function of soil type, agricultural practices and runoff conditions in relation to soil moisture/temperature conditions. Width, depth and length of rills are measured and areas with sedimentation are registered.

RESULTS

Runoff and erosion during autumn 2000

The precipitation in southeastern Norway during the period October–December 2000 was 2–3 times higher than normal (Tables 1 and 2), which had a significant effect on the total runoff in the Skuterud and Mørdre catchment, being 5 and 3 times larger than the average for the same period, respectively (Table 2). The consequences of the increased runoff have been dramatic for soil loss and amounted to 1922 and 1066 kg ha^{-1} for the Skuterud and Mørdre catchment, respectively (Table 2), which was approximately 6 times the average soil loss of the previous autumn periods. High soil losses were measured in both catchments, despite the small area ploughed compared to previous years (Fig. 3). Due to the precipitation during autumn, less area than normal could be ploughed. In Skuterud a higher proportion of the area was sown with winter wheat which had been tilled earlier in the autumn prior to sowing.

Table 1 Normal temperature and precipitation at the Skuterud and Mørdre catchments.

	Temperature (°C)		Precipitation (mm)	
Period	Skuterud	Mørdre	Skuterud	Mørdre
May–Sep.	13.3	12.5	382	331
Oct.–Dec.	1.1	–0.5	232	186
Jan.–Apr.	–1.6	–3.1	171	148

Table 2 Soil loss (SS, kg ha^{-1}), runoff (Q, mm) and precipitation (P, mm) for the Skuterud and Mørdre catchment.

Catchment	Period	May–Sep.			Oct.–Dec.			Jan.–Apr.			Year		
		SS	Q	P	SS	Q	P	SS	Q	P	SS	Q	P
Skuterud	mean												
	1993–2000	199	81	372	323	139	232	927	218	210	1450	438	814
	2000–2001	192	76	342	1922	655	646	923	311	316	3037	1042	1305
Mørdre	mean												
	1991–2000	199	52	341	183	86	178	616	137	157	998	276	677
	2000–2001	390	47	321	1066	284	431	1109	145	185	2565	476	937

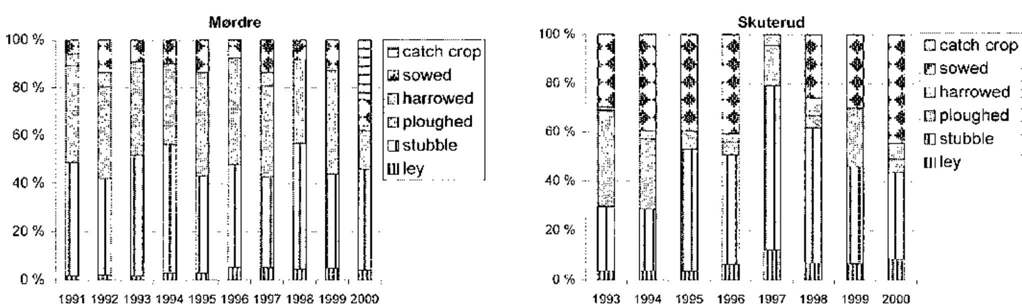

Fig. 3 Crop/tillage status (as % of total farmland area) in the Mørdre and Skuterud catchment in autumn.

For the autumn periods monitored before 2000, soil losses varied from 20 to 940 and 10 to 200 kg ha^{-1}, while the runoff varied from 35 to 180 and 7 to 140 mm for the Skuterud and Mørdre catchments, respectively. For both catchments soil losses are normally higher during the winter and snowmelt period than during the growing season.

Runoff and erosion during spring 2001

From January to April 2001 the precipitation at the Skuterud catchment was twice the normal, which lead to an increase in runoff compared with the average for the whole observation period. The soil loss of 923 kg ha^{-1} remained in the same order of magnitude as the average for the previous winter periods, but the losses were only about 50% of the losses during the autumn 2000 (Table 2). For the Mørdre catchment the precipitation was slightly higher than normal, which also lead to a small increase in the runoff compared with the average runoff of previous winter periods. However, there was a significant increase in the soil loss, being almost twice the average soil loss (Table 2) and higher than the losses during autumn 2000. During this winter period the two catchments differed substantially in soil losses. These two periods illustrate that it may be insufficient to only relate measured soil losses to the area tilled during the runoff events.

Field inventory of erosion pattern during autumn 2000

The main reasons for the differences in soil losses are often claimed to be the tillage methods practised in the catchments. However, soil moisture and soil temperature conditions can also be important. In this the study soil loss was surprisingly high considering the relative small area ploughed (Fig. 3). The inventory did not show much visible erosion on the tilled fields and no deep rills were encountered during the autumn period, making it difficult to explain the high soil loss.

Particles might have been lost as sheet flow in both stubble and winter wheat fields without developing deeper rills. In addition, particles might have been transported vertically through macropores and cracks to drainage systems. Such processes have been documented earlier for Norwegian conditions (Lundekvam, 1993, 2002; Øygarden *et al.*, 1997). Stream bank erosion may be another possible source of particles.

Field inventory of erosion pattern spring 2001

Winter wheat During the following winter the special weather conditions led to a nearly 100% death of the winter wheat in both catchments. Frozen subsoil conditions combined with rainfall on unfrozen topsoil led to high surface runoff. Sheet erosion was observed on areas with winter wheat which no longer had a good plant cover protection (Fig. 4) and plant root systems were visible as a consequence of sheet erosion.

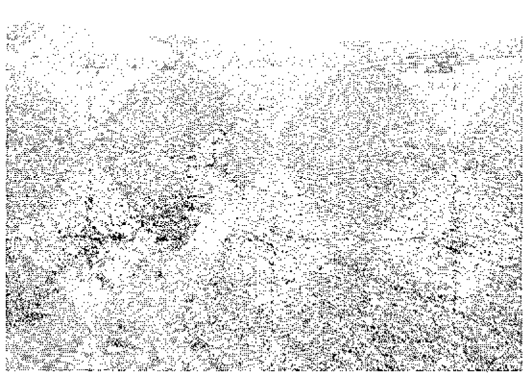

Fig. 4 Erosion in winterwheat where plant cover died during the winter.

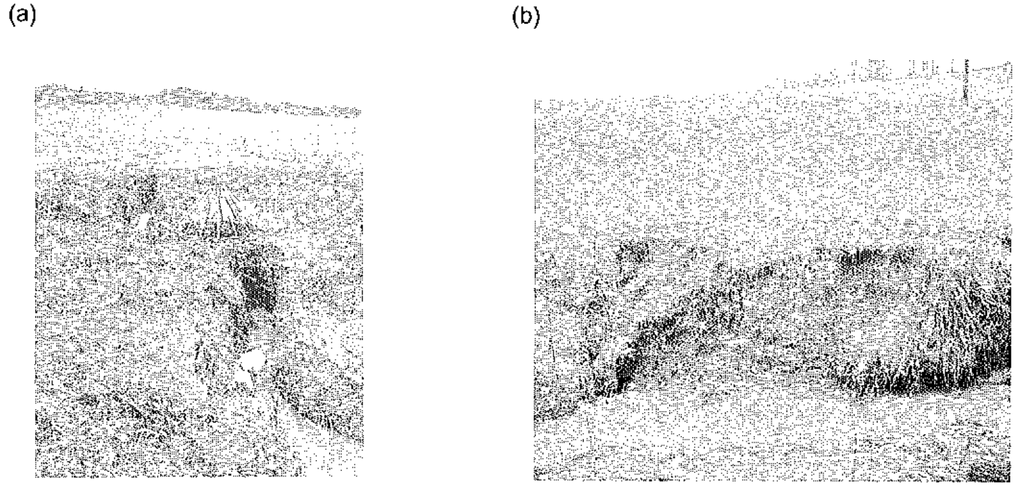

Fig. 5 (a) Erosion around inlet for surface runoff, (b) Bank erosion in Skuterud catchment.

Hydrotechnical means The field inventory in spring 2001 discovered much erosion around inlets for surface runoff (Fig. 5(a)). Also, in several fields pot holes were found above damaged drainage pipes. Erosion was also observed around outlets of drainage pipes into the streams. These types of erosion are difficult to quantify. However, since it was observed on several fields it is obviously a source which should be taken into account. The long wet autumn period leading to saturated soil might also have led to increased instability of drainage and hydrotechnical systems. In many of the fields the damage was not repaired but levelled over and erosion might therefore still continue.

Bank erosion Field inventory along the stream banks confirmed bank erosion in both catchments (Fig. 5(b)). A substantial amount of the measured particle losses might therefore also originate from bank erosion. However, quantifying the different sources was not possible with the methods used. Banks which have become unstable might also be a source of particle loss during later events. The extreme event during autumn 2000 might have had an effect on the following spring (on the unstable bank sides). The combination of unstable banks and drainage pipes outlets has also affected the soil losses. In the Mørdre catchment steeper slopes exist from the field to the stream. It is believed that in the Mørdre catchment many bankslides occurred during spring 2001 due to previously created instability. However, high discharge was the main reason for erosion of the stream banks in Skuterud.

DISCUSSION AND CONCLUSIONS

Soil tillage methods can have a significant influence on soil loss during autumn and spring periods in Norwegian catchments (Lundekvam & Skøien, 1998; Bechmann *et al.*, 1999; Øygarden, 2000). Often, the greatest erosion is measured in catchments with a large area ploughed during the autumn and winter period. The Norwegian government has had campaigns (including giving subsidies) to promote reduced tillage, especially on sloping lands. However, agricultural land is sometimes ploughed irrespective of slope. At present, the introduction of winter grain is promoted, however questions are raised concerning its effectiveness in erosion control. Although the ploughed area differs yearly, it is obvious that this was smallest in the autumn of 2000 for both catchments, while the soil loss was the highest. This clearly indicates that the rainfall and runoff events of 2000 had an extraordinary effect not seen before on soil loss. Soil loss may have been much larger if the same acreage of land had been ploughed but weather conditions resulted in no farming operations being carried out from October onwards.

In this study the high soil loss was unexpected considering the small area ploughed and the limited erosion visible on the tilled fields. The reason might be that the rainfall was prolonged and its intensity was too low to generate surface erosion. However, two months with high stream discharge during this period could result in bank erosion and also create bank instability. This long-lasting runoff resulted in instability of the agricultural drainage systems and areas around surface runoff inlets. These erosion processes were therefore higher than in normal years.

The water sampling routines used in the Monitoring Programme (JOVA) do not give information about the source of sediments. Source-apportionment of sediments is important as this might improve selection of areas for soil conservation. When farmers have adopted new routines for farming practices it is expected that this will have an effect and improve the water quality. Also, for this reason it is important to identify the sources that contribute to particle losses within the agricultural landscapes, both on farm fields and along the streams.

Bank erosion had been observed earlier in the JOVA-catchments especially after periods with high runoff, but never been quantified. Also, Bogen *et al.* (1993) carried out a study showing that in larger catchments bank erosion was the main source of sediment transported in major water courses. In a catchment in the same area as the Mørdre catchment losses from agriculture were estimated to be 45%, while the rest was due to natural processes like gully and stream bank erosion.

Erosion around hydrotechnical installations like inlets for surface water, outlets from drainage pipes into the river bank etc. was also observed. Especially poor technical design of inlets lead to concentrated runoff and erosion and particle transport from the agricultural landscape. These sources can only be documented with an annual field inventory.

Particle transport through drainage pipes in cracks and macropores have been documented to occur in these areas (Lundekvam, 1993, 2002; Øygarden *et al.*, 1997). It is assumed that preferential flow through macropores and cracks is more important than was assumed earlier for the Mørdre and Skuterud catchments. Macropores and cracks may have been well developed, especially during the very wet autumn 2000, following a dry summer.

Internationally, efforts have been made to select fingerprint properties to discriminate sediment sources in river basins, e.g. Walling & Woodward (1992) and Collins & Walling (2002). ^{137}Cs, ^{210}Pb and ^{7}Be are often used as source indicators. Tracers such as ^{137}Cs and ^{210}Pb, which can be used to identify both areas with erosion or sedimentation, are mostly used for determination of the long-term rate of erosion. Tracers used for tracing sediment sources during short-term events are more limited, but ^{7}B is a possibility.

This event illustrates that it is not sufficient to relate soil losses only to the tilled area in the catchment. There is a need to trace the sources and transport pathways for particles in catchments if one wants to implement effective means to reduce particle transport.

It is believed that the ongoing programme to document erosion at the field level is important for improved planning of measures to reducing erosion from agricultural areas. Further plans also include the use of tracers to find source areas of particles in the monitored catchments.

Acknowledgements This study was made possible by funding from the Norwegian Research Council, project no. 147954/720: Hydrological pathways in small catchments, water-particles, pesticides, and from the Norwegian Agricultural Authority funding the Agricultural Environmental Monitoring Programme, JOVA.

REFERENCES

Bechmann, M., Eggestad, H. O., Våje, P. I., Stålnacke, P & Vagstad, N. (1999) The Agricultural Environmental Programme in Norway. Erosion and nutrient runoff. Results including 1998/1999. Jordforsk report no. 103/99, 31 pp. ISBN 82-7467-354-9.

Bogen, J., Berg, H. & Sandersen, F. (1993) Forurensning som følge av leirerosjon og betydningen av erosjonsforebyggende tiltak. Norwegian Water Resources and Energy Directorate, report no. 21, 87 pp. ISBN 82-410-0206-8.

Collins, A. L. & Walling, D. E. (2002) Selecting fingerprint properties for discriminating potential suspended sediment sources in river basins. *J. Hydrol.* **261**, 218–244.

Deelstra, J. & Øygarden, L. (1998a) Measurement of runoff. In: *Measuring Runoff and Nutrient Losses From Agricultural Land in Nordic Countries* (ed. by L. Øygarden & P. Botterweg), 13–25. TemaNord, Agriculture/Forestry, Nordic Council of Ministers, 1998: 575.

Deelstra, J. & Øygarden, L. (1998b) Sampling technique and strategy. In: *Measuring Runoff and Nutrient Losses From Agricultural Land in Nordic Countries* (ed. L. Øygarden & P. Botterweg), 27–35. TemaNord, Agriculture/Forestry, Nordic Council of Ministers, 1998: 575.

Lundekvam, H. (1993) Soil erosion and runoff under different tillage systems. In: *Soil Tillage and Environment* (Proc. NJF seminar no. 228, Jokioinen, Finland, June 1993), 50–63.

Lundekvam, H. & Skøien, S. (1998) Soil erosion in Norway. An overview over measurements from soil loss plots. *Soil Use Manage.* **14**(2), 84–89.

Lundekvam, H. (2002) ERONOR/USLENO-Empirical erosion models for Norwegian conditions. Agricultural University of Norway, report no. 6/2002, 40 pp. ISBN 82-483-0022-6.

Norwegian Ministry of Agriculture (1991) Stortingsmelding nr. 64 1991–1992. om Norges oppfølging av Nordsjødeklarasjonene.

Norwegian Ministry of Agriculture (1999) Forskrift om tilskudd til endret jordarbeiding med mer. FOR 1999-07-02 nr. 793.

Øygarden, L. (2000) Seasonal variations in soil erosion in small agricultural catchments in southeastern Norway. In: *Soil Erosion in Small Agricultural Catchments.* PhD Thesis, Agricultural University of Norway, 2000, 8, 28 pp. ISBN 82-575-0418-1.

Øygarden, L., Kværner, J. & Jenssen, P. D. (1997) Soil erosion via preferential flow to drainage systems in clay soils. *Geoderma* **76**, 65–86.

Walling, D. & Woodward, J. C. (1992) Use of radiometric fingerprints to derive information on suspended sediment sources. In: *Erosion and Sediment Monitoring Programmes in River Basins*, (Proc. Oslo Symp., August 1992), 143–152, IAHS Publ. 210.