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Erosion and surface runoff in small agricultural catchments

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Abstract Runoff, soil erosion and nutrient losses have been measured since 1986 in six small catchments (0.3-3.2 ha) situated on marine sediments in southeastern Norway. Monitoring stations were established for runoff measurement and discharge proportional water sampling. The objective has been to quantify soil erosion from agricultural areas and to find efficient farming practices which can reduce erosion. Soil losses have varied from between 10 to 4940 kg ha^{-1} within a 6-year period. Highest losses were measured during winter and the period of snowmelt. Rainfall on partially thawed soil led to especially high losses. The annual number of days with surface runoff varied between 5 and 71, and annual total surface runoff varied between 29 and 242 mm. In some catchments, surface runoff only occurred during snowmelt and the winter period. Autumn tilled fields had the highest soil losses. No tillage before spring and the use of grassed waterways was seen reduce soil losses.

INTRODUCTION

In northern countries, the winter period is often characterized by snow cover and periods with frozen soil. Moreover, the winter, and especially the snowmelt period with sudden thawing, is often the most important period for runoff and erosion. Surface runoff measurements have shown that Norwegian agricultural areas on marine sediments which are autumn-tilled are especially vulnerable to erosion (Njøs & Hove, 1986; Lundekvam, 1993). Many of these areas typically have long and steep slopes often as a result of artificial levelling. Areas underlain by marine sediments, used in the past for grassland, have been levelled in order to grow grain and to use larger machinery. This levelling has locally exposed the subsoil, which has a denser structure, lower organic matter content, lower infiltration capacity and higher risk of runoff and erosion. In order to fulfil the commitments of the North Sea Declaration, which require a reduction of *c.* 50% in the total phosphorus load discharged by rivers, a reduction in erosion from agricultural areas is especially important. Farmers in Norway now receive subsidy payments to leave their fields as stubble (not tilled) during the winter period. The highest reduction in phosphorus and soil losses could be achieved if the areas most susceptible to surface runoff were left as stubble during the winter period. In 1986, when the present study began, few investigations had clearly documented the relationships between catchment area, soil type, management practices and the risk of surface runoff and soil erosion for Norwegian conditions.

The objectives of the present investigation were to (a) document runoff, erosion and nutrient losses from small catchments of different size, topography and cultivation practices, (b) study how hydrological factors influence runoff and nutrient losses, especially the variations in runoff pattern during different seasons and the importance of winter conditions and snowmelt, and (c) study the effect of different farming practices on erosion losses.

MATERIALS AND METHODS

Field site description

The study area was the Lodding catchment (2.1 km^2) in Ullensaker, north of Oslo, Norway. Six small catchments (from 0.3 to 3.2 ha) were chosen for runoff measurement (Fig. 1). The area is situated on marine sediments, and cereal production with autumn tillage is the dominant cultivation practice. Each catchment consisted of a single farmer's field, with one management and tillage practice within it. All surface runoff was collected in pipes around the field boundaries and was channelled to the measurement station. The soil was classified as silt loam for catchment 101 and silty clay loam for the other catchments. Catchment characteristics are given in Table 1.

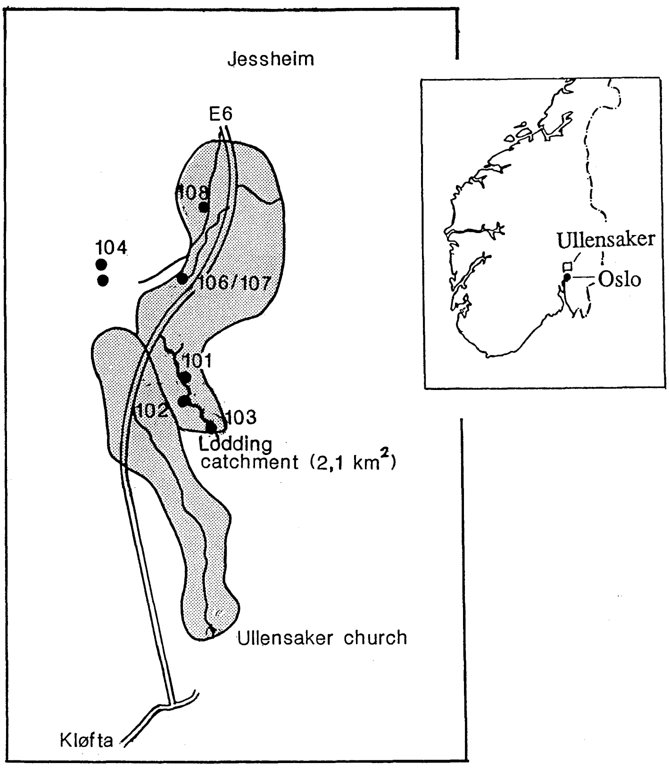

Fig. 1 Location of field sites.

Table 1 Catchment characteristics for the study catchments.

Catchment	Size (ha)	Slope length (m)	Width (m)	Slope length (%)	Form	Clay (%)	Silt (%)	Sand (%)
101	0.36	100	50	12	Conc.	34	63	3
102	3.25	175	250	3-14	Conc.*	32	64	4
103	0.41	113	40	12	Plane	34	65	1
104	0.35	75	63	14	Plane	33	65	3
106	0.86	155	70	4-9	Conc.	35	60	5
108	0.44	113	50	6-16	Conc.*	26	67	7

*Concave with valley waterway.

Runoff measurement

Each catchment was equipped for measurement of surface runoff and water sampling (Fig. 2). In one of the catchments, drainage water was also measured. Water levels were automatically recorded using a pressure transducer connected to a data logger. A mechanical limnigraph, was also installed to record water level. Volume proportional, composite runoff samples were taken using tipping buckets, during every runoff event

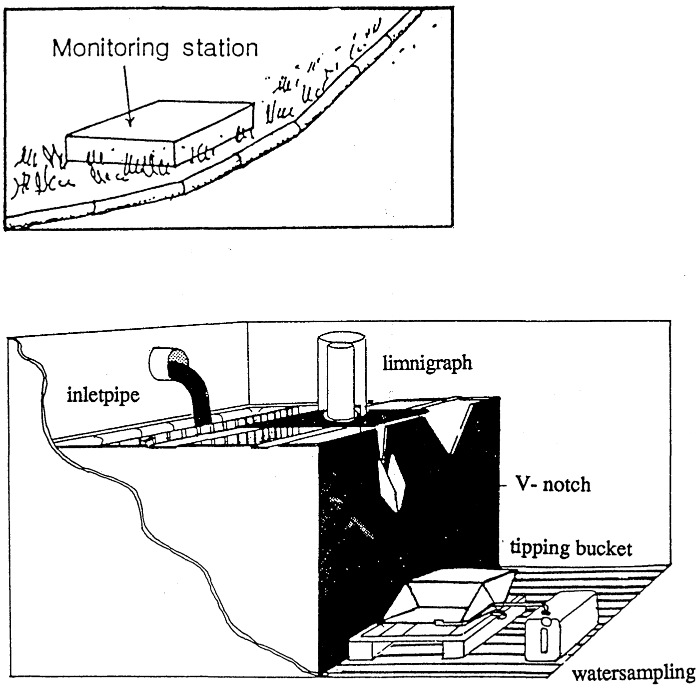

Fig. 2 Monitoring station for measurement of runoff and nutrient losses in small catchments.

and on each day during snowmelt. In addition, timed samples were taken during periods of substantial surface runoff, especially during winter and the snowmelt period. Total runoff was calculated and water samples were analysed for suspended solids, nitrogen and phosphorus. The water sampling was event-based and controlled to avoid mixing of samples from before and after farming activity.

Catchment activities

Cereal growing occurred in all catchments, but with different tillage and management practices. Comparisons were made between catchments with and without autumn tillage. The effects of grassed waterways, no tillage in valley depressions, winter wheat cultivation and better control of surface runoff were also studied (Øygarden, 1989). This paper presents some of the preliminary results from these runoff measurements, focuses on the hydrological results, and briefly considers the effects of the different management practices.

RESULTS

Seasonal runoff

The total number of runoff events in the 6-year measurement period for the different catchments varied between 24 and 135 (Table 2), and the annual surface runoff varied between 10 and 242 mm (Table 3). Total annual soil losses varied between 10 and 4940 kg ha^{-1} (Table 4). In order to explain these large differences, it is necessary to study the seasonal distribution of surface runoff.

Winter period For the first 3 years, surface runoff during winter varied between 14 and 61% of the total annual surface runoff, and several rainfall-runoff events also occurred in the autumn period. The last 3 years experienced less precipitation than normal during the autumn, and the winter period therefore contributed between 47 and

Table 2 Number of annual runoff events in the period 1987-1992. Events during the winter period January to May (1/5) are given in brackets. (Station 107 collects the drainage runoff from catchment 106.)

Catchment	1987	1988	1989	1990	1991	1992	Total
101	8 (1)	9 (5)	3 (1)	6 (6)	7 (7)	8 (8)	41 (28)
102	14 (5)	23 (14)	13 (6)	13 (13)	20 (13)	22 (20)	105 (71)
103	0*	0*	3 (3)	8 (8)	7 (7)	6 (6)	24 (24)
106	20 (5)	24 (13)	16 (7)	20 (11)	29 (17)	29 (19)	138 (77)
107	28 (10)	29 (14)	16 (5)	17 (8)	31 (15)	14 (11)	135 (63)
108	11 (4)	18 (10)	8 (4)	10 (10)	19 (13)	12 (12)	78 (53)

*Problems with data recording.

Table 3 Total surface runoff (mm) in the period 1987-1992. Runoff coefficients (runoff in % of precipitation) are given in brackets. (Station 107 collects the drainage water from catchment 106.)

Catchment	1987	1988	1989	1990	1991	1992
101	33 (3.3)	102 (9.2)	71 (9.0)	127 (15.6)	31 (3.9)	52 (8.5)
102	88 (11.5)	97 (8.9)	30 (3.7)	128 (15.8)	29 (3.4)	36 (7.3)
103	*	*	10 (1.3)	121 (14.9)	27 (3.8)	21 (3.6)
104	26 (2.6)	41 (3.8)	*	*	9*	77 (13.3)
106	238 (23.3)	292 (26.2)	178 (22.5)	216 (27.1)	242 (34.5)	158 (27.4)
107	357 (35.0)	404 (37.2)	123 (15.6)	54 (6.6)	165 (21.3)	93 (16.1)
108	188 (18.4)	327 (30.1)	130 (16.4)	232 (28.7)	175 (22.5)	146 (25.3)

*Problems with data recording.

Table 4 Soil loss (kg ha^{-1}) in the period 1987-1992 for catchments 101-108. (Station 107 collects the drainage runoff from catchment 106.)

Catchment	1987	1988	1989	1990	1991	1992
101	740	260	75	1520	80	1083
102	520	150	30	1570	10	20
103	0	0	10	121	27	21
106	2020	1860	720	2630	570	200
107	3010	2760	1420	310	340	120
108	1120	400	200	4940	840	3580

100% of total annual surface runoff. Both in 1990 and 1992, catchments 101, 103, 102 and 108 had no surface runoff outside of the winter period (Table 2). Catchment 106, however, was the one catchment that experienced autumn runoff events during all three of these years. For catchment 106, the winter period accounted for between 55 and 65% of the total runoff. The soil in catchment 106 is a levelled silty clay loam with an unstable structure. It is susceptible to surface sealing and has a lower infiltration capacity than the soils in the other catchments studied. Therefore, rainfall outside the winter season in this catchment often leads to surface runoff, even when the soil is not saturated.

Snowmelt Catchments 102, 106 and 108 experienced surface runoff every winter due to the melting of the snow cover. For the smallest catchments (101, 103, 104), however, surface runoff during snowmelt was dependent on whether the soil was frozen or not. In 1990 and 1991, for example, snowmelt occurred over frozen soil and several runoff periods were recorded in catchments 101 and 103. In contrast, in 1987 and 1988, there was no frost and snowmelt lasted several weeks, so that most of the meltwater infiltrated into the soil. Field observations showed concentrated waterflow in valley depressions in catchments 102 and 108, which began early during the snowmelt. The infiltration of meltwater and the concentrated waterflows in the valley waterways were due

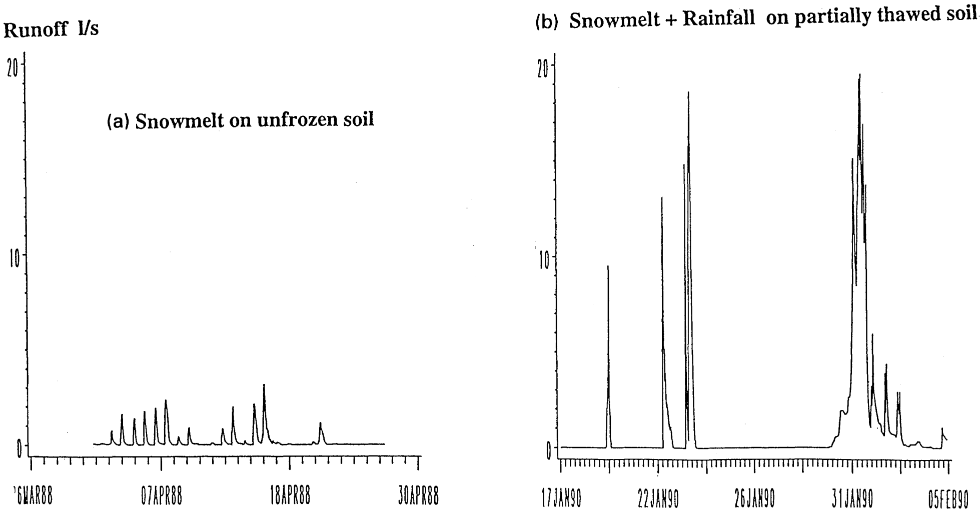

Fig. 3 Runoff pattern during different winter conditions: (a) snowmelt on unfrozen soil, (b) snowmelt with rainfall on frozen soil.

to saturated contributing areas. Figure 3 illustrates a typical runoff pattern for catchment 106 during a snowmelt period with daily fluctuations in surface runoff. A similar diurnal pattern existed for catchments 102 and 108, but not for catchment 101, where most of the snowmelt water infiltrated. Snowmelt in March 1991 occurred when the soil was frozen to a depth of 44 cm (measured in February). Rainfall events during snowmelt also gave high runoff. Under these conditions, all the catchments had surface runoff. Most of the snow melted before the frost was gone, and consequently the soil losses in this year were small compared to previous years which had runoff on unfrozen soil.

Rainfall on frozen and snow covered soil Unusually mild winters with heavy rainfall occurred during the measurement period. Rainfall events occurred both on frozen and unfrozen soil, with and without snow cover, producing different runoff conditions and consequently different soil losses. The highest erosion losses were measured in the winter, when rain fell on partially thawed soil (Øygarden, 1994). For example, catchment 108 experienced surface runoff of 9 mm with a soil loss of 760 kg ha^{-1} as a result of rainfall in January, 1990 when a snow cover was absent (Table 5).

Table 5 Precipitation, runoff and soil loss for catchment 108 in the winter of 1990.

Date	Runoff (mm)	Soil loss (kg ha^{-1})	Precipitation (mm)
11-17 January			11.3
17-20 January	9	760	9.5
30-31 January	25	2	81.3
31 January-1 February	77	3050	30.2
1 February-2 February	42	445	4.3
2-4 February	17	150	9.9

Later, conditions became colder and the surface became covered with ice. Snow fell on this ice covered surface and was then followed by milder weather and rain. In a 2-day period, the snow layer and rainfall (total = 112 mm) ran off. On the first day, runoff consisted of melted snow water with few soil particles (25 mm runoff and only 2 kg ha^{-1} soil loss). On the second day, 77 mm of surface runoff led to a soil loss of 3055 kg ha^{-1}. This was attributed to the effects of runoff eroding soil particles from an upper unfrozen soil layer that was underlain with frozen soil. This example shows the large daily fluctuations that may occur in surface runoff. Studies of events with water sampling each day, combined with information about soil conditions and tillage, make it possible to investigate these fluctuations.

Autumn runoff Soil losses in the autumn period depend upon whether the farmers have tilled their soil or not before the occurrence of a rainfall event. On average, for all the catchments during this study, the number of surface runoff events increased from August to October, with the latter month having most events. The autumn period also characteristically had large, infrequent rainfalls. One year had high runoff in September, the other years had no runoff at all in this month.

The 30-year mean precipitation for October in this area is 85 mm. In October 1987, 213 mm of precipitation resulted in five runoff events in all the catchments studied, with runoff coefficients of between 10 and 49.6%. In the period 7-17 October, there was 164.9 mm of precipitation and surface runoff totals varied from 7.0 mm in catchment 101 to 103.1 mm in catchment 106 (Table 6). Soil losses were small in catchments 101,

Table 6 Runoff and soil loss during autumn rainfall for the study catchments.

Date	101		102		106		108	
	Runoff (mm)	Soil loss (kg ha^{-1})	Runoff (mm)	Soil loss (kg ha^{-1})	Runoff (mm)	Soil loss (kg ha^{-1})	Runoff (mm)	Soil loss (kg ha^{-1})
7-9 October	1.9	32.1	6.1	23.7	33.5	104.1	26.5	28.0
9-14 October	4.7	55.1	12.5	114.2	28.1	91.5	15.5	303.8
14-17 October	4.4	61.8	15.6	85.2	41.5	114.5	34.2	414.2

102 and 106 which had stubble. In catchment 108 the soil was ploughed on 10 October. In the runoff period before ploughing, 26.5 mm of runoff resulted in a soil loss of 28 kg ha^{-1}, while after ploughing 15.5 mm of runoff produced a soil loss of 303.8 kg ha^{-1}. These October events were associated with saturated overland flow, which occurred following several rainfall events that produced surface runoff in all catchments. This was the only year when October runoff events were recorded in all catchments. For 1988, 1989, 1990 and 1992, precipitation in October was lower than the mean, and only catchment 106 experienced surface runoff events. Figure 4 illustrates the response of catchment 106 to surface runoff events in October 1988. During the runoff events in October, the soil had not been tilled and soil losses were therefore small. The catchment was ploughed in November and runoff events after tillage resulted in increased soil losses, as occurred in catchment 108 a month earlier. Several runoff events occurred in 1988 following unusually high amounts of precipitation in August and the beginning of September, before the farmers had tilled the soil. There was 150 mm of rainfall in

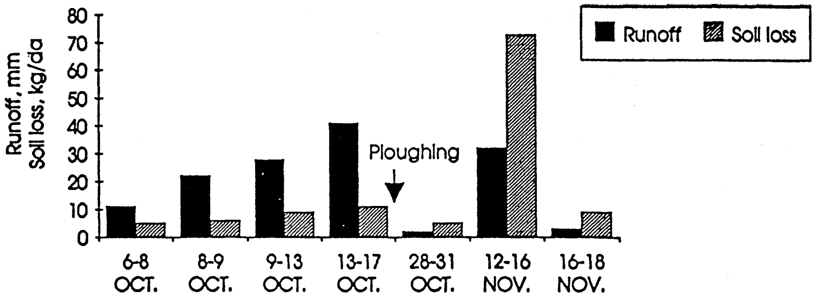

Fig. 4 Runoff and soil loss (1 daa = 0.1 ha) before and after ploughing in autumn 1988 for catchment 106.

August and 131 mm in September (mean values are 95 and 87 mm, respectively). This rainfall occurred in a concentrated pattern. For example, during 1-3 September 102 mm of rain fell and produced surface runoff of between 18 and 52 mm. Soil losses, however, were small because the farmers had not yet begun the autumn tillage. Concentrations of suspended solids in the surface runoff varied between 33 and 776 mg l^{-1}, while after ploughing they increased to between 1000 and 2858 mg l^{-1}, clearly illustrating the importance of the timing of tillage practices. These August and September events accounted for 40-55% of annual surface runoff during 1988 for catchments that also had runoff during snowmelt.

The smallest catchments only experienced autumn surface runoff after several, closely spaced rainfall events had saturated the soil or after unusually high precipitation. Both in 1990 and in 1992, only catchment 106 experienced surface runoff during autumn, mainly due to an unstable soil structure, easy surface sealing and low infiltration capacity. Catchment 106 experienced surface runoff when the soil was unsaturated. In 1991, between 4 and 7 runoff events occurred in catchments 102 to 108, and a single event was recorded in catchment 101. These events occurred after autumn tillage in early and mid November, and were associated with a total precipitation of 124 mm, which was 40 mm higher than normal. The runoff volumes were between 2 and 26.3 mm for catchments 101 to 106.

Runoff intensities were below 1 l s^{-1} ha^{-1} for the majority of the time runoff occurred, but all the catchments had between 13 to 94 h where runoff intensities exceeded 10 l s^{-1} ha^{-1}. This value is often used as a maximum runoff intensity when planning many hydrotechnical measures in agriculture and for dimensioning runoff measuring equipment devices in Norway. Catchment 106 had the highest recorded intensities and the longest durations comprising, 11.9 h higher than 20 l s^{-1} ha^{-1} and 4.2 h higher than 30 l s^{-1} ha^{-1}. Intensities higher than 40 l s^{-1} ha^{-1} were recorded for about 2 h in 1987.

Catchment activities

Catchments with frequent runoff events and high runoff intensities have a higher erosion risk than other catchments. Measurements in the present study have also shown that the winter and the period of snowmelt had the most erosion. Surface conditions and, therefore, tillage activities are important factors. In autumn periods, when several closely spaced rainfall events had saturated the soil, all the catchments experienced surface runoff, but single rainstorms gave surface runoff in only some of the catchments studied. Catchment 106, which has a levelled soil, that is weak and unstable in structure, is susceptible to surface sealing and has a low infiltration capacity, generally had runoff events every autumn. Catchments with valley depressions and possibilities for concentrated waterflow also experienced runoff events. The smallest catchments with even slopes, no concentrated waterflow and high infiltration had runoff events only in autumn, after exceptionally high rainfall intensities or after the topsoil had become saturated.

Catchment activities that reduced erosion include:

- No autumn tillage which reduced erosion significantly and by *c.* 90% in some catchments.
- Grassed waterways and no tillage in valley depressions reduced erosion in topographical depressions.
- Better control of surface runoff, through hydrotechnical measures (including inlets for surface runoff) reduced both surface runoff and erosion.
- Winter wheat cultivation could reduce erosion if a developed plant cover were established early in autumn. Otherwise, this practice constitutes a high erosion risk.

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