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Measurement of sediment transport components in a drainage basin and comparison with sediment delivery computed by a soil erosion model

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Abstract Simultaneous field measurement of sediment transport and erosion are carried out in The Syv Brook basin. The data were used for calibration of the SHE hydrological model and a soil erosion model. Computation shows that the spatial distribution of overland flow and soil erosion is very sensitive to groundwater level. The occurrence of resuspension is also indicated.

INTRODUCTION AND AIMS

Erosion is increasingly being recognized as a hazard in temperate countries of Northern Europe (Morgan, 1986; Chisci, 1986). Concern is often caused by off site effects such as eutrophication of lakes and coastal waters due to the increased nutrient inputs (Hasholt, 1988, 1991).

The research project, which is part of the STEP-programme is partly based on measurements carried out under the Danish Nitrogen-Phosphorous and Organic matter-programme, NPo, 1987-1990 (Hasholt *et al.*, 1990) and partly on new measurements carried out August 1991-March 1992.

The models used for the study are SHE(DK) (Abbot *et al.*, 1986; DHI, 1987), and the erosion model SEM (Nielsen & Styczen, 1986), which has been modified slightly for the present study. The results of the study will be used as a base for evaluating further necessary developments and limitations of the European Soil Erosion Model (EUROSEM), when this is developed to catchment scale.

The results of the NPo-programme (Hasholt *et al.*, 1990; Hasholt, 1991) show that the level of erosion during the investigation period was generally low, mainly due to lack of melting snow and rain on frozen soil. Depending on computation and measuring methods the gross erosion component of the total load in the water course varied from 45-76%. Sediment budget computations showed that bed and bank erosion, together with sheet erosion were important components, while rill erosion was of minor importance in the measuring period. The sheet erosion component based on sediment budget computations for the water course was significantly higher than found from plot studies within the basin.

Aims of study

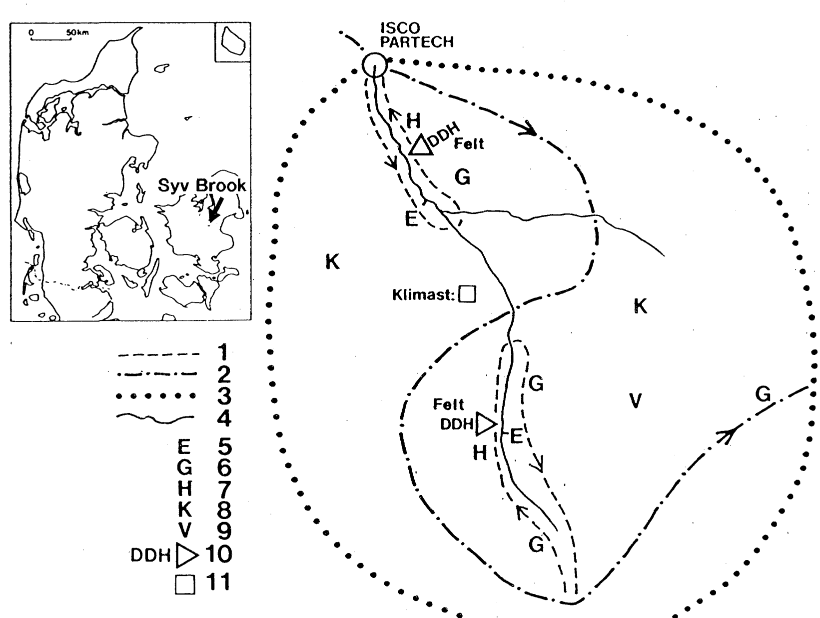
(a) By simultaneous development of models and procedures for field testing, to identify problem areas in monitoring programmes and to develop procedures for data collection for model validation.
(b) To quantify and evaluate the timing and areal distribution of overland flow and sheet erosion and compare the results with field investigations.
(c) To test the performance of a soil erosion model in a catchment and identify problem areas in model building.

This paper reports selected results from field work carried out during the period 1987-1992. Results are used as input and calibration parameters for computations of runoff and sediment transport by the SHE and the modified SEM.

METHODS

The research basin

The Syv Brook basin was chosen for the study because the sampling frequency during the NPo-measurement period was high enough to compute reliable short term variations



1. Inspection route by foot
2. " " " car
3. Topographic divide
4. Water course
5. Bed- and bank erosion
6. Gerlach trough
7. Frost depth
8. Campaigns
9. Wind erosion
10. Erosion plots
11. Climatic station

Fig. 1 Location of Syv Brook and monitoring programme.

of runoff and sediment concentrations during storm events. Furthermore, information about the occurrence of erosion features e.g. bank erosion and rills existed.

The basin, 11.7 km^2, is situated on the island of Zealand approximately 40 km west of Copenhagen, see Fig. 1. The landscape is gently rolling morainic deposits of Weichsel age. Steeper slopes, extending 6°, exist only along a valley in the upper part of the basin. The soils are mainly Luvisols (sandy loams), but Histosols are found in the valley bottom, where the peat was excavated so that small lakes were formed. The drainage density is today 0.7 km^{-1}, but about 50% of the area is tile-drained. The streams are totally realigned. The area of beds and banks are 32 000 m^2, weeds are cut and cleaning takes place once or twice in the summer or in the autumn. Some sewage from a small village and individual houses enters the water course. Discharge varies between zero and 0.6 m^3/s. The water course dries out for two to three months during the summer. Approximately 90% of the area is cultivated, the rest consists of peat bogs covered with scrubs.

Field investigations

A detailed description of the monitoring programme is given in Hasholt (1988). The basic principle was to carry out simultaneous measurements/registrations of erosion phenomena in the basin and sediment transport in the water course. The principles of the field programme are shown in Fig. 1. Stage and discharge are recorded both by an ordinary stage recorder and an established stage/discharge relationship and by an automatic flow recorder based on the Doppler principle. Water samples are collected twice a day by an ISCO automatic sampler. These samples are used for computation of sediment concentration and for calibration of a continuous recording of the concentration by use of a Partech IR light transmission sensor. The inspection routes were visited only once a week due to labour costs and logistics. Information concerning signs of erosion were collected during the inspection routes. Because of the continuous recording of climatological parameters and of the runoff, it is, however, possible to accurately pinpoint the time where the erosion features were formed during the week.

Computation of sediment load and budgets

The daily sediment transport is computed by use of the hourly values of discharge and concentration. The accuracy is sufficient for the computation of monthly and yearly sums of sediment transport.

The sediment budget The different sources of sediment and phosphorous are either measured directly as e.g. bed and bank erosion and rill erosion or estimated by use of information from other investigations or literature as e.g. wet and dry deposition and contribution from sewage. Transport from non-point sources, i.e. sheet erosion is then found as the total load at the outlet from the basin minus the sum of loads from other sources.

The sedigraph/sediment concentration graph approach Two graphs were constructed, discharge versus time and concentration versus time. The graphs were combined to compute sediment transport versus time. As an analogue to base flow separation in unit-graph theory, the transport after longer dry periods was considered as the base transport while peaks occurring after heavy rainfall were examined carefully as potentially caused by erosion. The peaks were considered caused by erosion when erosion features were recorded in connection with the inspection of the basin. The transport during the peak events, after subtraction of the basic contribution, was considered as 'erosion based' transport. This method tends to overestimate the contribution by erosion, especially when resuspension takes place.

Direct measurements Surface erosion was recorded directly at two 0.5 ha erosion plots (Hansen, in Hasholt *et al.*, 1990). Due to the need of a cellar for the measuring equipment, the distance to the groundwater was at least 2 m at the bottom of the slopes. The plots were situated near the water course, on slopes where the erosion was believed to be rather large. It was, however, difficult to estimate the areal representativity of the plot results. Field observations indicate that the erosion on the plots was small, probably due to the distance to the groundwater which diminished the amount of saturated overland flow.

Long term evaluations The only long term record oι transport relating to erosion, that exists for a Danish catchment is a record of transport of phosphorous (Kronvang & Bruun, 1990). This record shows values of transport of up to 3-4 times the transport, of the present measuring period.

The high values coincide with wet years and years with severe winter conditions indicating that erosion is more severe under such circumstances.

The models

SHE(DK) (Système Hydrologique Européen) is deterministic and distributed, and contains all major processes of the hydrological cycle. The precedence of this model compared to most other hydrological models is that the interaction between surface- and groundwater is well described, which is of great importance in this drainage basin.

The soil erosion model used (SEM) is a separate module applied 'on top of' the SHE model and it is assumed in the calculations that the erosion and transport processes do not affect the hydrological processes.

The detachment in each grid square is determined as the sum of part of the splash detachment by rainfall and by overland flow. The sediment leaving each element is limited either by the amount of detached sediment or by the transport capacity of overland flow. If the transport capacity is lower than the available detached soil, deposition will occur. The erosion model contains two calibration parameters, one for the splash erosion (A) and one for the flow erosion (η). The routing of the sediment load is based on the continuity equation of sediment discharge. The present version of SEM include a rill indicator, but rill, bank and bed erosion and resuspension are not included. The routing of sediment in the river model is too simple, and the aim is to use the MIKE 11 river system for modelling of this component in the future.

Preparation of data for the models

The digital terrain model is based on maps from the Geodetic Institute with a scale of 1:25 000 and 2.5 m contour intervals. Due to the long running time for the model a grid size of 100 m was used at this stage. This is, however, bound to introduce some errors because the model is very sensitive to changes in slopes. Data on geology, soils, vegetation, and river cross sections were collected during the NPo-programme or in connection with other investigations (ADK, 1989; Gravesen, 1990; and Hasholt, 1990).

For most of the period, hourly measurements of rainfall from a climatic station in the drainage basin were available from the Research Centre Foulum. The hourly precipitation data are corrected for loss due to wind and wetting. Temperature and potential evaporation have been measured too, and are used within the SHE model.

Daily hydrographs and sedigraphs were used together with meteorological observations to select erosion events for detailed computations. During the events, the hydrograph was split up into 15 minute intervals by use of the continuous stage recordings. The sedigraph was split up to the same time interval by calibration of the IR-light transmission recordings by the concentrations found by the ISCO water samples.

RESULTS AND DISCUSSION

Field investigations

In principle the significance of soil erosion to the total load of sediment and phosphorus measured at a gauging station at the outlet of a basin can be determined by field

Table 1 Syv Brook Basin. Sources of sediment and phosphorus (measured and computed).

	87/88 Total susp. t/year	Total P kg/year	88/89 Total susp. t/year	Total P kg/year	89/90 Total susp. t/year	Total P kg/year
Dry/wet deposition	0.8	0.5	0.8	0.5	0.8	0.5
Dredging / weed cutting	4	2	2	1	2	1
Bed and bank erosion	10	9	4	4	5	5
Rill erosion	<0.7	0.4	0	0	0	0
Tile drains, sewage*)	?	140-655	?	88-544	?	187-538
Chemical precipitation	?	?	?	?	?	?
Production of biomass	4	?	4	?	4	?
Sum of sources above	20	152-667	11	94-550	12	194-544
Total transport	96	853	18	405	21	252
Total - sources above ~ sheet erosion	76	186-701	7	-145-311	9	-292-58
Sheet erosion from plots**)	0.85-<1.6	20-59	1.9-20.9	20-31	0.8-1.1	4-8

*) based on data from Hansen, 1991; **) based on data from Hansen 1990

investigations. Often, however, it is not possible for economical or practical reasons to measure all erosion components of the transport. The sheet erosion, due to its different occurrences, is particular difficult to measure. It is therefore often found by use of sediment budgets. An important precondition for the use of yearly budgets is that all sediment released during the budget year will pass the gauging station, so that there is no storage from year to year. Table 1 represents the state of the art of knowledge of transport components in the basin compiled from different investigations. Computed by the budget method sheet erosion account for 43-79% of the total suspended load, with the largest value in 1987/88, which was a very rainy year. Rill erosion only contributes in 1987/88. Figures for bed and bank erosion are in the right order of magnitude, it is, however, difficult to judge the representativity of measured stretches for an extrapolation to the whole stream.

Results of measurements of the transport of phosphorus indicate a rather large contribution from tile drained areas. The two figures in Table 1 are results from two different sample areas. The sediment concentration in tile drains was not measured, but tile drains may be a possible sediment source. This contribution, however, does not seem to vary much from year to year. The results of measurement of sheet and rill erosion from two plots are used as representative for the whole basin in table 1 below. Except from the year 1988/89 the values are an order of magnitude lower than indicated by stream measurements and do not reflect the yearly variation in sediment transport. A possible explanation is that the plot sites are not representative, which is partly supported by the fact that rills are practically absent on the plots, when they occur on slopes nearby.

The contribution by erosion to the suspended load found by the sedigraph separation approach is shown in Table 2. The erosion accounts for 45-76% of the total suspended load, which is in good accordance with the results of the budget method above. The contribution calculated by this method is gross erosion. The 'basic'

Table 2 Syv Brook Basin. Transport of sediment and phosphorus. Erosion % determined by sedigraph/ sediment concentration approach.

	87/88	88/89	89/90
Total susp. t	96	18	21
Total susp. t/km^2	8.2	1.5	1.8
Org. susp. t.	27	6	6
Org. susp. t/km^2	2.3	0.5	0.5
Erosion % of total susp.	76	45	70
Basis % of total susp.	24	55	30
Total P kg	853	405	252
Total P kg/km^2	73	35	22
Part. P kg	214	119	76
Part. P kg/km^2	18	10	6

contribution consists of production of biomass, chemical precipitation, sewage and probably of some material released by bed and bank erosion.

After long periods without erosion, part of the transport in the beginning of an event can be due to resuspension (storage), this can not be separated from the 'true' erosion. The method therefore tend to overestimate the erosion contribution. During larger runoff events, it can be difficult to separate different sources and certainly some bed and bank erosion will be included in the gross erosion, thus also resulting in an overestimation of the 'pure' soil erosion contribution.

The discrepancy between the direct and indirect determination of soil erosion (sheet) and the contribution to the load in the water course can not be explained on the basis of the available measurements. The SHE and the SEM models can, however, elucidate amount and distribution of surface runoff and soil transport and thereby give valuable information about the question of representativity.

Hydrological simulations

Hydrological simulations were carried out for the period from August 1977 to March 1990. The simulated discharge turned out to be extremely sensitive to the groundwater level, for which limited data are available. With respect to other model inputs, the simulation is mainly based on measured data.

The main problem related to the simulation of ground water levels and discharge to tile drains in this catchment is that the catchment is influenced by a larger regional groundwater regime. There is inflow from and outflow to the surrounding area through the limestone and gravel aquifers at depth. To simulate the in- and outflow, however, it is necessary to fix the potentials at the edge of the catchment during the simulation. In reality it is not constant, it will vary in a wavelike pattern due to seasonal variations in recharge, and furthermore, it is influenced by the Copenhagen water supply companies who are extracting water just north of and at some distance east of the catchment. The groundwater potential fell during the last part of the 80's and the extraction at one of the northern sites were halved in the middle of 1990. Therefore, simulation of the wet year 1987 was done with a higher groundwater table than 1988-90 (Fig. 2).

From comparisons of the surface runoff from a range of simulations, however, it appears that this component is much less sensitive to the changes in groundwater level than the total discharge which is dominated by drainflow. However, errors are to be found for specific grids at specific times, particularly related to the occurrence of a gravel lens aquifer.

Sediment transport simulations

The hydrological data necessary for simulation of the chosen events are taken from the continuous hydrological simulations.

For the wet winter of 1987/88, it was attempted to simulate erosion from November till mid January. The first sediment peaks are clearly resuspension, while the period from 26 November to 15 December can be simulated well. For the last fortnight of December, the simulations cannot be made to fit the data. It is not clear whether this is due to the surface runoff simulation, the simulation of erosion, the routing, or because the measured sediment is due to other processes (bank erosion, waste water or the like) than those included in the model. The fact that the P-content of the transported material, in particular the first of these events, is rather low, could indicate that the peak is due to erosion of the stream bank or bottom.

For the first half of January, the simulations agree better with observations, but problems are observed. The erodibility parameter for flow erosion (η) decreases 36% (0.07-0.045) from November to the second week of January. The erodibility parameter A for splash erosion decreases 40% (from 0.5-0.3) in the same period. The phenomenon may be explained as a result of consolidation of the soil and as a result of the fact that the easiest detachable material is removed first. A reduction in erosion rates from beginning to end of the growing season to half or one third has been observed and described by Meyer (1985).

Errors in the erosion simulations are observed on 7-8 and 11-12 January 1988. Through an analysis of the spatial distribution of surface runoff in the simulation, it became obvious that the errors occur due to incorrect simulation of the groundwater potential in a gravel lens aquifer. This part of the simulation is very sensitive to the boundary conditions, and since no precise data were available, it was not considered possible to correct the problem without including a much larger area in the simulation.

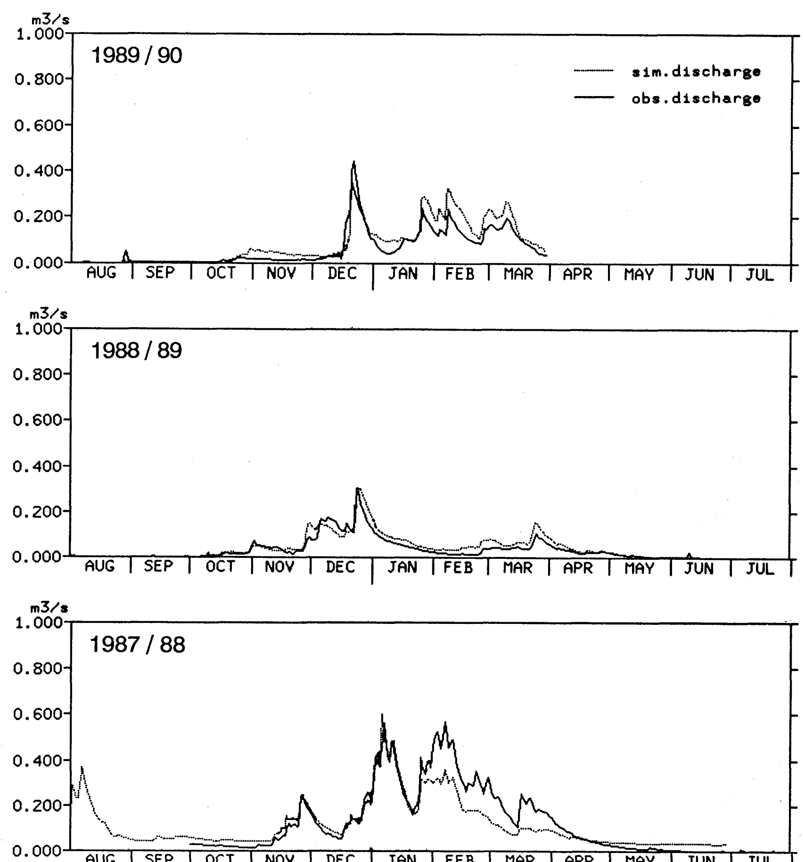


Fig. 2 Hydrograph simulation.

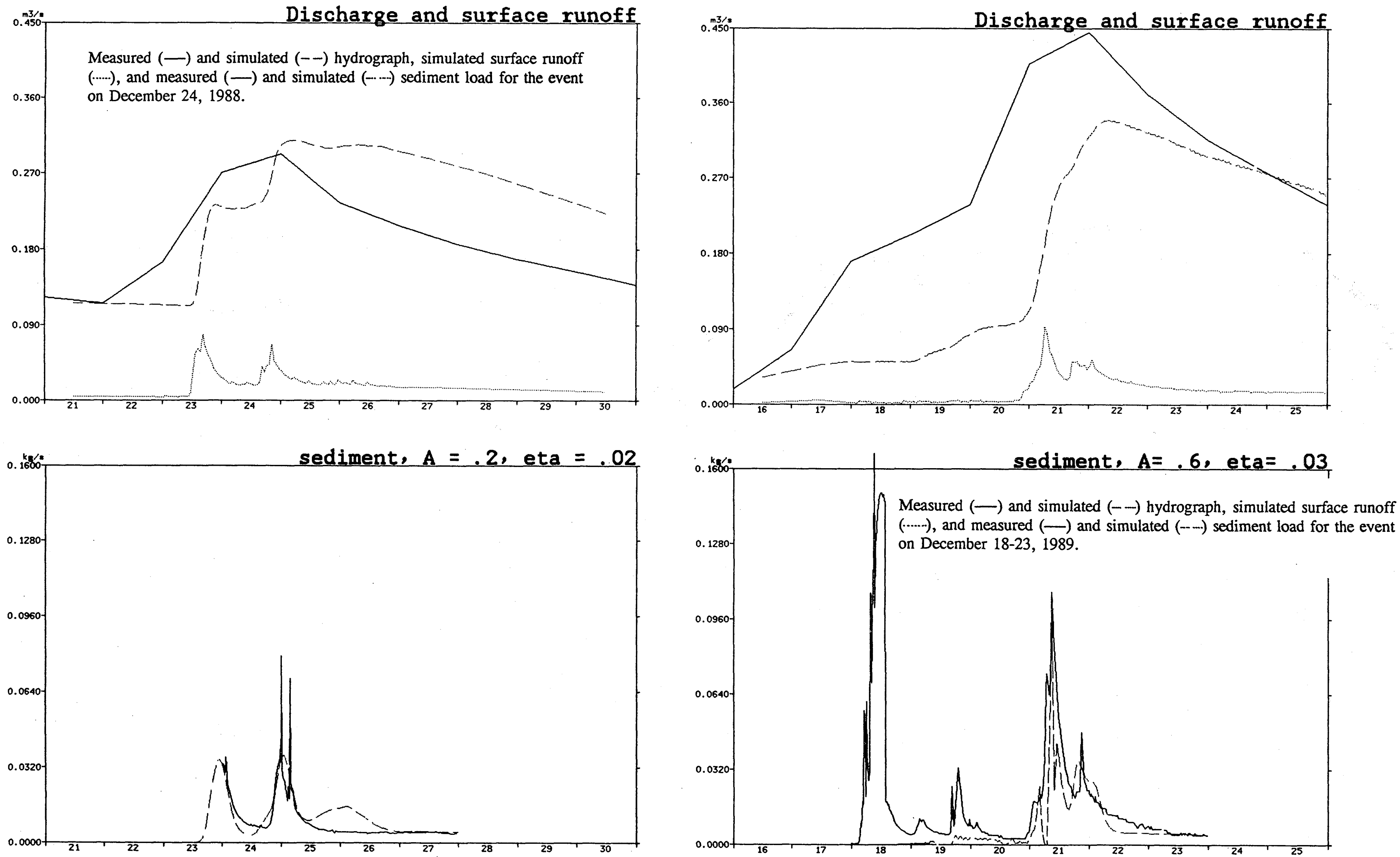


Fig. 3 Measured and simulated hydrographs and sedigraphs for two events in December 1988 and December 1989.

Figure 3 shows the measured and simulated hydrographs and sedigraphs for two events in December 1988 and 1989. In both cases it is obvious that overland flow only makes up a small part of the total hydrograph. Figure 4 indicates where in the catchment erosion has occurred and where the highest probability of rilling was found during the events. Erosion occurs in a limited area of the catchment only. Furthermore, a small error in calculation of surface runoff (25-26 December 1988) can be seen immediately in the simulation of erosion (Fig. 2).

During the event in December 1989, both erosion and resuspension took place. During the first storms every autumn, large peaks of resuspension of biological material occur. Here, the events on 18-20 December cannot be due to erosion as no sheetflow occur. Only on 21 and 22 December can the sediment load be due to sheet erosion.

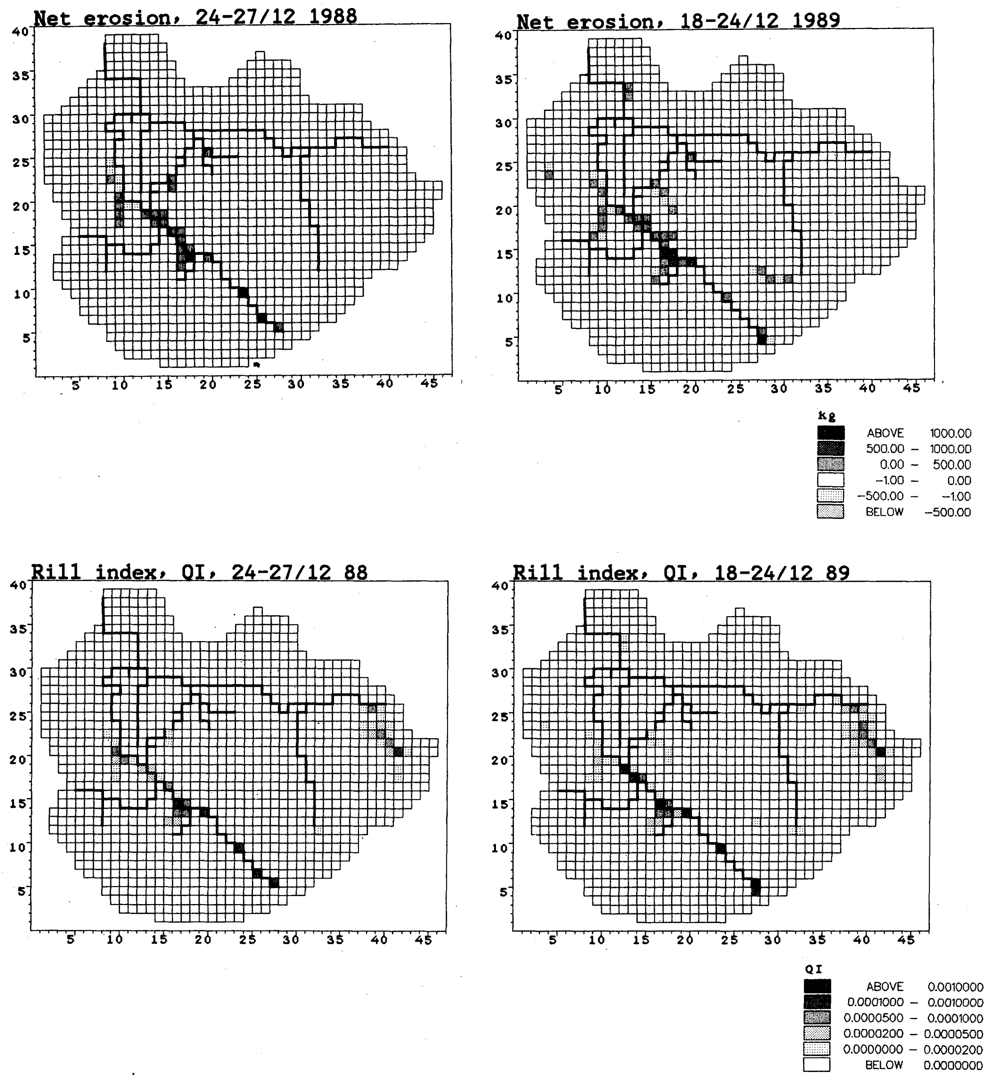


Fig. 4 Net erosion and rill index for events.

Comparison of computed and measured soil erosion contribution

For the events, where the surface runoff simulation could be considered adequate, the simulation of sheet erosion is relatively good, in spite of the fact that it is a very simple erosion model. Table 3 shows the results for the January 1987, December 1988, and December 1989. simulation. With respect to the areal distribution of erosion and overland flow, it is mainly correct (Fig. 3). However, errors occur due to the distortion of the topography as a result of the chosen grid scale (100 m) and where the overland flow simulation is considered incorrect due to boundary conditions.

The major problem is to predict the erodibility parameters, which were not constant throughout a given year or different years. The change observed in a given year seems to be a decrease, probably due to consolidation and removal of easily detachable material first. The differences between the different years is probably due to land use, but the records for the catchment are too incomplete to give a good picture of the changes. However, the wet conditions of the autumn of 1987 could, for example have left the winter wheat in a poorer state due to late sowing, than in 1988 and 1989. When comparing the calibration factors for December 1988 ($A = 0.2$, $\eta = 0.02$) and 1989 ($A = 0.6$ and $\eta = 0.03$), it should be considered that for the 1988 event resuspension has occurred earlier, while for the 1989 event, it is the first event of the winter. This would generally give larger values, and as the model cannot distinguish between resuspended and eroded material, the tendency may be to use too large calibration parameter values. Furthermore, the sensitivity of the model to A is not large.

Table 3 Observed and simulated sediment loads, daily values. Where the simulation of surface runoff is obviously wrong, the error has not been calculated (n.a.).

Date	Observed, kg	Simulated, kg	error, %
31/12 1987	940	1001	+ 6
1/ 1 1988	969	960	0
2/ 1	3764	3668	- 3
3/ 1	3027	3180	+ 5
4/ 1	2779	2637	- 9
5/ 1	1974	2268	+ 14
6/ 1	3691	3429	- 7
7/ 1	3582	11861	n.a.
8/ 1	2078	3771	n.a.
9/ 1	1296	1290	0
10/ 1	1393	1405	+ 1
11/ 1	1836	5577	n.a.
12/ 1	1495	3833	n.a.
24/12 1988	1285	1256	- 2
25/12	1040	1143	+ 10
26/12	386	679	+ 76
27/12	386	415	+ 8
18/12 1989	3744	-	-
19/12	831	115	-
20/12	386	155	- 60
21/12	3240	2219	- 32
22/12	1104	851	- 23
23/12	458	421	- 8

In earlier studies on a silt loam in loose state, η attained values of 0.24, and in compacted state of 0.12 (Nielsen & Styczen, 1986). For two tropical catchments with good forest cover (DHI, 1987), values as low as 0.005 and 0.00076 were obtained for η. The range of η obtained here are thus within the expected range. With respect to A it is difficult to compare to earlier studies, as the former splash component used was not divided into particle sizes as it is now.

IMPLICATIONS AND RECOMMENDATIONS

The Syv Brook basin is by no means an atypical Danish basin, however both the field measurement and the model computations show very complicated patterns of hydrology and sediment transport. The main problem for the model is to verify the surface runoff simulations in time and space, and to find rational ways to predict the persistence of the calibration factors describing erosion A and η. Field studies and laboratory experiments, where effects of groundwater and sediment from tile drains and from bed and bank erosion can be excluded, are helpful in establishing such procedures. Other studies indicate, however, that an erosion model also needs inclusion of rill erosion and of frozen soil routines in order to cope with larger erosion events in a Danish basin.

The result of the present investigation emphasize the fact that a very extensive data set is needed for a complete validation of a model at basin scale. Although the data set from Syv Brook is much more extensive than usually is the case, the following needs are identified:

(a) A more complete knowledge of geology and the groundwater level and its variation through time.

(b) A more complete record of land use and agricultural practice, e.g. direction of drilling.

Investigation are needed of sediment load from tile drained areas, of bed and bank erosion and of occurrence of rill erosion where the model predicts it.

An interesting possibility as shown in Fig. 4 is to run the model 'on line', so that the computed result of a severe rain fall can be investigated in the field immediately after it has occurred. This is probably less expensive than running a large erosion programme continuously.

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