

INFLUENCE OF EROSION ON THE TRANSPORT OF SUSPENDED SEDIMENT AND PHOSPHORUS

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ABSTRACT This investigation is part of the Danish NPO-Project (Nitrogen, Phosphorus and Organic Matter). The part of the project described here aims to evaluate the impact of soil erosion on the transport of phosphorus in selected Danish water courses. Sediment transport was monitored by use of automatic water samplers and indirect measurements of concentration by IR transmission sensors. Simultaneous measurements of erosion were carried out. The impact of erosion was estimated by sedigraph analysis and comparison with recorded rainfall and erosion events. The contribution from total erosion is approximately 45-75% of total suspended sediment transport in the Langvad basin and 25-30% in the Rabis basin. Due to the absence of frost and snow the contribution from soil erosion accounts for only a minor part of the total erosion. The higher values in 1987/88 demonstrate the effect of increased rainfall.

INTRODUCTION AND SCOPE

In recent years eutrophication due to increased nutrient inputs into lakes and coastal waters have caused concern in Denmark. Therefore a large-scale multidisciplinary research project named the Danish NPO-Project was initiated (Nitrogen, Phosphorus and Organic Matter). The overall objective of the project was to study transport and transformation processes in order to develop methods to reduce the flux of nutrients.

The investigations described here are a minor part of the NPO-Project and aimed to evaluate the significance of soil erosion to the transport of phosphorus in water courses. It also aimed to examine the factors that determine the frequency of occurrence and the areal distribution of erosion. Another purpose was to map erosion risk areas in Denmark and to evaluate the representativeness of the investigation areas. The project was carried out as a joint venture between the Institute of Geography, University of Copenhagen (basin- and river erosion), the Danish Society for Land Development (erosion from plots) and the Ministry of Agriculture's Bureau of Land Data (erosion risk areas).

This paper deals mainly with the part of the investigation carried out by the Institute of Geography. The purpose is to describe the transport of sediment and phosphorus in the water courses and its relation to different types of erosion. The methods for specifying and evaluating the contribution by erosion to the transport are described and discussed including results from other investigations.

RESEARCH BASINS

An overview of the environmental and climatological background to erosion and transport processes in Denmark is given in Hasholt (1988a). Due to the position of the ice margin

during the Weichsel glaciation, extensive sandy soils are found in Western Jutland on the outwash plains, while clay soils on young morainic landscapes are found in the eastern part of the country. The two research basins were selected to represent the two main combinations of soil and landscape mentioned above, Rabis (sandy soil on outwash plain) and Langvad (clay soil on young morainic landscape). The climate is a temperate forest climate, Cfb according to Köppen. Water for erosion stems from either convective thunderstorms during summer or rainfall of cyclonic origin during the winter half year when the effects of snowmelt and frozen soil surfaces must also be taken into account. The location of the two basins is shown on Fig. 1.

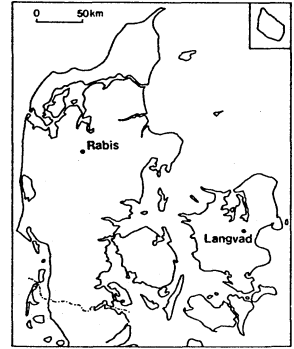
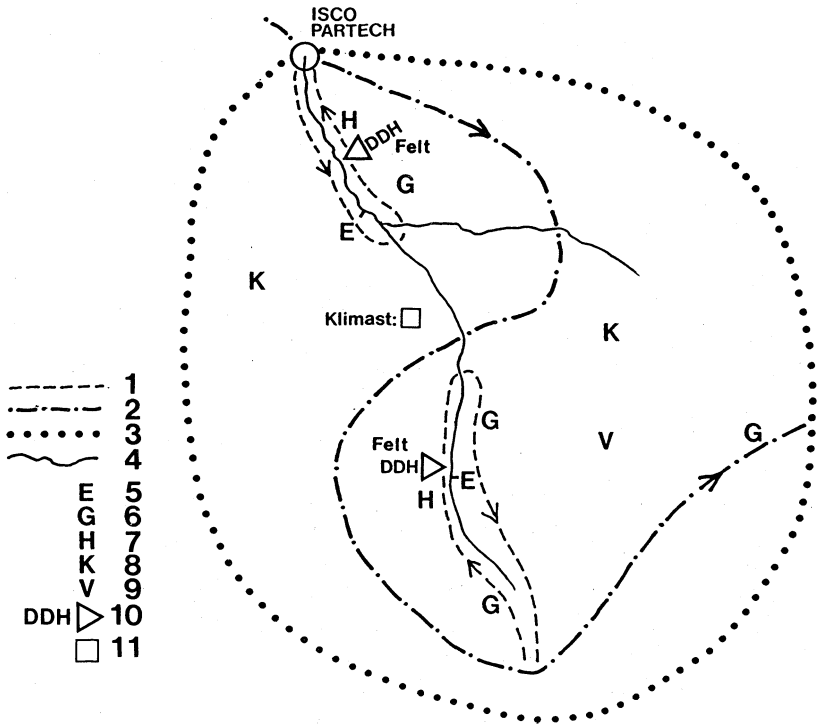


FIG. 1 Survey Map.



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

FIG. 2 Monitoring programme in a hypothetical basin.

The Rabis Basin

The water course named Rabis Brook has a drainage area of 8.7 km² at the monitoring station. The landform is an old outwash plain with two terrace levels within the basin. Except for the slope between the two terrace levels and the valley slopes along the water course the area is extremely flat. The soils are mainly sandy podzols; however, histosols are present in part of the valley bottom. The drainage density is low, 0.3 km km⁻¹ and there is no tile draining due to the well drained sandy and gravelly soils. The discharge is rather high and extremely stable due to a large contribution from upwelling groundwater and springs in the valley bottom. The area of channel bed and banks is 11 000 m².

Approximately 65% of the area is cultivated, the non-cultivated areas are covered with permanent grass, heather and scrub and plantations of conifers. There is cattle grazing in parts of the valley bottom and a small fish farm is situated on the upper part of the water course. The stream is partly realigned and its course is modified by human activities. Weeds are cut, and the water course is cleaned one or two times each summer.

Langvad Basin

The water course, named Syv Brook, has a drainage area of 11.7 km² at the monitoring station. The landscape is gently rolling morainic deposits from the Weichsel glaciation. There is a well developed valley with rather steep slopes in the upper part of the basin, while the area near the gauging station has more gentle slopes. The soils are mostly clayey luvisols, but histosols are also present in the lowest part of the valley where peat was excavated in former times so that small lakes are present today. The drainage density is 0.7 km km⁻¹, but 80% of the area is tile-drained. Discharge varies considerably, the water course dries out for two to three months during summer. The area of bed and banks is 32 000 m².

Approximately 90% of the area is cultivated. The non-cultivated areas are peat bogs often covered with scrub which occur along the upper part of the water course. The streams are totally realigned, weeds are cut and cleaning takes place once or twice each summer or autumn. Some sewage from a small village and individual houses enters the water course.

METHODS

A more detailed description of the soil erosion monitoring program is published in Hasholt (1988a,b). An outline of the measuring programme is, however, shown in Fig.2. The basic principle was to carry out simultaneous measurements/registrations of erosion and transport in the water courses. Due to labor costs and logistics, erosion was only registered or measured once a week. Because of the continuous recording of climatological data and discharge, it is possible to locate the occurrence of erosion more accurately in time. Computations of the transport of sediment and phosphorus are based on recording of discharge and concentration at the monitoring stations. Stage is recorded every 15 minutes and discharge is computed by use of a calibrated relationship between stage and discharge. Here daily values are used. Water samples for determination of the concentration of sediment and phosphorus are collected manually once a week with a depth-integrating sampler (Nilsson, 1969). In order to describe short-term variations in concentration and to secure records under extreme weather conditions, two independent measurement systems were installed. An ISCO automatic water sampler collected two daily samples, at 0300 and 1500 h, thus cov-

ering the daily range of variation. The intake tube was placed so that it was able to swing away from drifting weeds.

The water samples for analysis of sediment concentration were stored cool and dark before analysis, while samples for analysis of phosphorus were immediately sent to the laboratory in an ice box, and the analysis was performed the following day. Sediment concentration was determined by filtering through a Whatman GF/F filter. The filter was dried at 65°C, and subsequently it was combusted at 500°C and the residual determined as a measure of the content of inorganic matter. Total phosphorus was determined before and after filtering by use of the molybdate blue method and photometry. The transport of total phosphorus and particulate phosphorus could then be computed.

A Partech Suspended Solids Monitor was installed in a position where the water was running swiftly. The IR sensor was shielded at the water surface in order to prevent drifting weeds from blocking the measuring gap. The recording interval was 2 minutes. The sensor was cleaned in connection with the weekly inspection. Calibration showed that the range of the sensor was 0 - ca. 300 mg l⁻¹, and the resolution ± 2 mg l⁻¹. The calibration varied considerably through time, and a planned automatic computation of sediment transport based on the indirect concentration values was therefore not carried out as it proved to be too labor-consuming. The transport computation was based on the daily discharge multiplied by the mean of the two daily concentration values. The Partech measurements were used as a control and for removing outliers and filling gaps when the water sampler had been out of action. The resulting yearly transport values vary only $\pm 3\%$ from those computed using a single concentration value of either 0300 or 1500 h.

The observations and measurements of erosion were carried out weekly along the inspection route (see Fig. 2). Occurrence of sheet erosion was registered and its magnitude evaluated visually. The sedimentation in 4 Gerlach troughs was also measured weekly. At two plots (0.5 ha) in each basin the erosion of the surface was recorded continuously (cf. Hansen *et al.*, 1990). The volume of sediment removed by development of rills and the deposition downslope was surveyed in order to determine the amount of sediment that reaches the water course. Erosion of bed and banks was measured at erosion pins on selected stretches.

In order to assess the influence of erosion on the sediment transport in the water course, the daily transport values can be compared day by day with recorded rainfall and temperature. In the case of rising transport, the weekly inspection reports are checked for occurrences of erosion. If found, the contribution to the transport by erosion is computed as the transport on days with rainfall and thaw minus the transport in the preceding dry period. The procedure is analogous to hydrograph analysis and base-flow separation. It is fairly easy to identify increases in sediment transport due to contributions from erosion, but it is more difficult to judge when the contribution has ended. Here it has been assumed that the contribution from erosion has ended when the discharge reaches the same level as before the peak. Although these rules are applied strictly, a certain amount of subjectivity cannot be avoided in case of several erosion events occurring within a short time.

RESULTS

Daily transport values for the two basins are shown in Figs 3 and 4. The transport patterns vary significantly. In the Rabis basin with sandy soil and low relief a very uniform discharge and transport is found. In the Langvad basin with clay soil and moderate relief the distribution is more uneven with a distinct maximum during the winter. The time series shows that the transport was much larger during the sediment transport "year" 1987/88 than

in the following two “years”. The same pattern is seen in Fig. 5, where the part of the monthly transport that can be ascribed to erosion is shown. A much larger erosion component is found in Langvad than in Rabis. The “yearly” values are shown in Table 1, and the transport per km² can be seen to be rather low in both water courses. The erosion component is relatively stable in the Rabis basin, (ca. 25% - 30%), while it varies from ca. 45-75

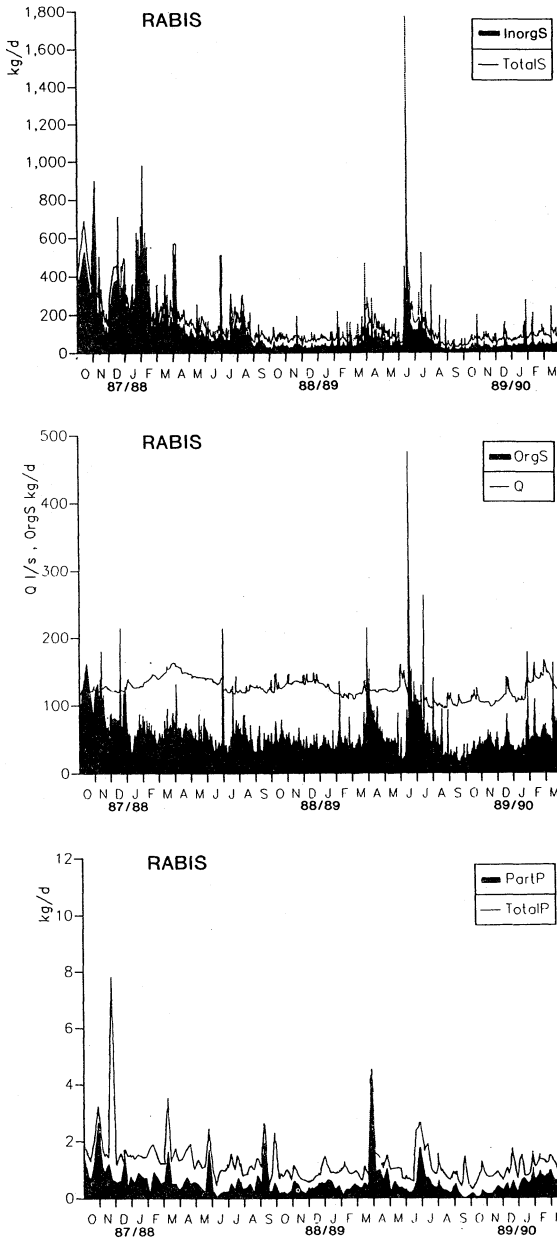


FIG. 3 Daily transport of sediment and phosphorus.

in the Langvad basin. The variation from year to year is a result of climatic variations. In the "year" 1987/88 the precipitation was 1.32 times the normal, while it was 0.86 times the normal in 1988/89. All winters were unusually warm and the absence of frozen soil and snowmelt explains the low transport values. The variation between the years reflects only the effect of rainfall.

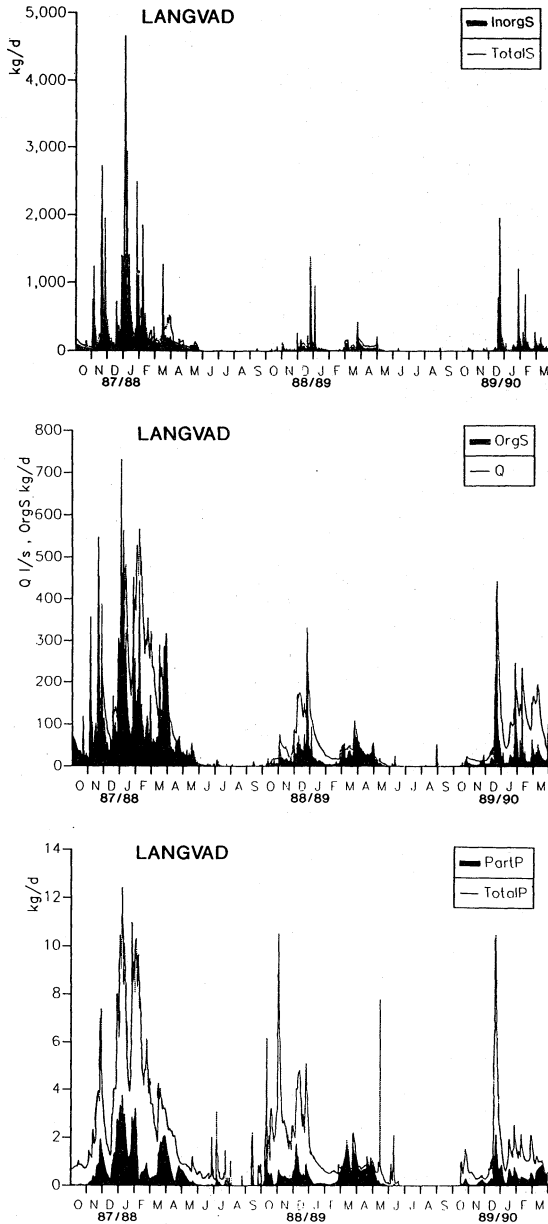


FIG. 4 Daily transport of sediment and phosphorus.

TABLE 1 Annual transport data.

	Rabis			Langvad		
	87/88	88/89	89/90*	87/88	88/89	89/90*
Total susp. t	96	42	15	96	18	18
Total susp. t/km ²	9.9	4.3	1.6	8.2	1.5	1.6
Org. susp. t	25	20	9	27	6	5
Org. susp. t/km ²	2.5	2.0	0.9	2.3	0.5	0.4
Erosion % of total susp.	24	29	17	76	45	82
Basis % of total susp.	76	71	83	24	55	18
Total P kg	584	413	188	853	405	219
Total P kg/km ²	60	43	19	73	35	19
Part. P kg	250	160	49	214	119	63
Part. P kg/km ²	26	16	10	18	10	5

 *) October-March incl.

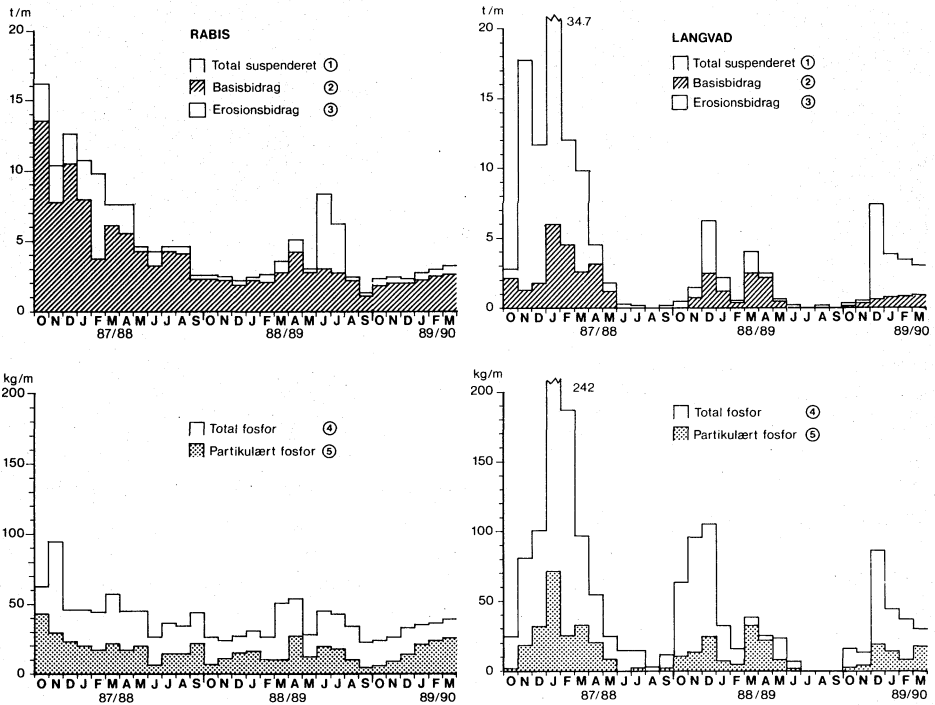


FIG. 5 Monthly transport and erosion: 1 = total suspended load; 2 = basal contribution; 3 = erosion contribution; 4 = total P load; and 5 = particulate P load.

DISCUSSION

A schematic presentation of the sources of transported sediment in a short longitudinal vertical segment of a water course is shown in Fig. 6. The contribution from soil erosion alone is S1, while erosion as a whole also includes S4 and S5, and to some degree also S2 and S3. It is seen that the concentration can be affected by the built-up and degradation of temporary sediment storage by sedimentation, S10, or by resuspension, S9. It is not possible to have S1 alone, because the water that causes soil erosion will also increase the contribution of S4, S5, S9 and possibly also S2 and S3.

The part of the transport that cannot be related to specific erosion events is called the basal, or the stable contribution. A clear delimitation of the basal contribution is not possible; it consists of S6, S7, S8, S11, and part of S2, if sewage enters the pipe drain system, and the "slow" geological erosion from S3. The total transport minus the basal contribution is a measure of the maximal possible contribution from soil erosion. A similar separation of sediment yield into transport components based on sedigraph analysis is described by Schumm et al. (1987 p. 74).

In the Rabis basin there is a significant basal contribution throughout the year. The basal load stems from bed load suspended at the monitoring station, S9, precipitation of iron oxide and phosphorus, S7 and S8, together with some sewage from the farms and the fish farm.

Surface erosion was only visible in 1987/88. The erosion part consists of S1 from a few slopes and the valley bottom together with S4 and S5, but here were no significant net changes in the level of the bed through the 3-year period. The apparent erosion in June-July 88/89 is due to weed-cutting and dredging.

In the Langvad basin there is no constant monthly basal contribution, partly because the water course dries out during the summer. A part of the presumed constant input of sewage and biomass production must be stored temporarily on the channel bottom during low flow. Such storage is in fact observed during late spring and early summer, but there is practically no bed load. Such temporary sediment storage will be flushed out during the autumn if the flow is sufficiently high. This is confirmed by the occurrence of hysteresis loops in the concentration versus discharge relationship. A measure of the basal contribution can be obtained during early winter after a longer period of recession and after the system has been flushed. It is seen that the basal contribution in 1987/88 is larger than the total transport in 1988/89. The erosion contribution in 1988/89 is therefore believed to be derived mainly from temporary storage, S9. Real erosion S1, S4, and S5 occurs nearly exclusively in 1987/88. The approach applied above gives a useful evaluation of the overall influence of erosion, but it is difficult to isolate the effect of soil erosion.

Alternatively the contribution of the different erosion processes to the sediment yield can be measured, or estimated, on the basis of relevant observations. It is very difficult, however, to extrapolate point observations to larger areas and to determine the delivery ratio from diffuse sources. Often the contribution from soil erosion is found by a mass balance computation in which contributions from all other sources are subtracted from the total transport (cf. Hasholt, 1988a). An important precondition for this procedure is that all the sediment released by the different processes passes the monitoring station within the time base of the mass balance.

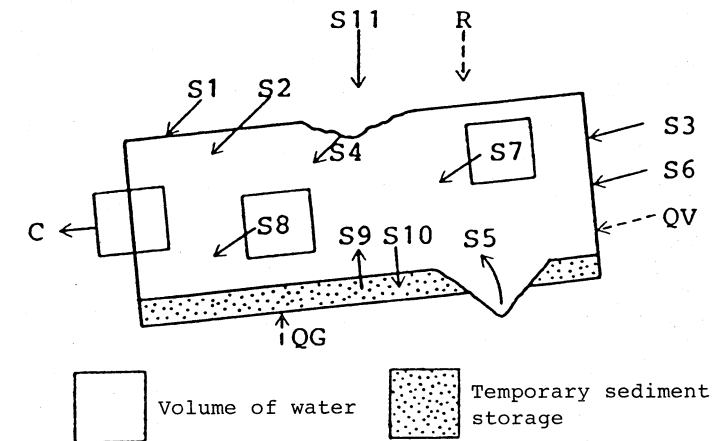
In Table 2 all known contributions of sediment and phosphorus are included according to the nomenclature used in Fig. 6. Except for the total suspended sediment transport 1988/89 large differences are found between the sum of sources and the total transport. Since the

transport values are thought to be accurate, the explanation is that one or more of the contributions from the different sources have been underestimated. From Table 2, it is seen that chemical precipitation in the Rabis basin and tile drainage and sewage in the Langvad basin may be important factors, although it is difficult to imagine that they can explain the variation between the two years.

Bed and bank erosion values are based on point measurements extrapolated to the whole length of the water course, and an underestimation of more than 100% is therefore possible. Sheet erosion values in Table 2 are based on results from the plot studies multiplied by the area that is estimated from field observations to contribute to the water course. Although the plots are so near the water courses that the delivery ratio should be at a maximum and the locations were selected as being representative, field observations indicate that less erosion took place on the plots than on the nearby slopes. The underestimation is probably due to the fact that the conditions on the plots are not representative of the basins as a whole.

The mapping of erosion risk in Denmark showed that the results from the Rabis basin are representative of areas with the lowest erosion in Denmark, while the results from the Langvad basin are representative of areas with moderate erosion.

As the year 1988/89 was practically without any soil erosion the transport this year could be considered a measure of the basal contribution. A comparison with the results



Definitions:

Sources of sediment and water:

S1	Soil erosion	S9	Resuspension
S2	Tile drains and ditches	S10	Sedimentation
S3	Water course upstream	S11	Airborne sediment
S4	Bank erosion	R	Rainfall
S5	Bed erosion	QV	Surface water
S6	Sewage	QG	Groundwater
S7	Chemical precipitation	C	Concentration
S8	Production of biomass		

FIG. 6 Factors that determine the concentration of sediment in a segment of a water course.

TABLE 2. Contribution from sources compared with measured transport.

	Rabis 87/88		88/89		Langvad 87/88		88/89		Reference
	Tot. susp. t/year	Tot. P kg/y	Tot. susp. t/y	Tot. P. kg/y	Tot. susp. t/y	Tot. P kg/y	Tot. susp. t/y	Tot. P kg/y	
S11 Dry/wet deposition	1.6	1	1.6	1	0.8	0.5	0.8	0.5	Hasholt 1988a
S9 Dredging/ weed cutting	2	1	9	6	4	2	2	1	NPO C12
S4, S5 Bed- and bank erosion	5-10	3-6	5-10	3-6	10	9	4	4	NPO C12
S1 Sheet erosion	0	0.5-1	0	0.1- 0.2	0.6- 1.1	14-41	1.3-14	14-21	NPO C12
S1 Rill erosion	0	0	0	0	<0.7	0.4	0	0	NPO C12
S2, S6 Tile drains, sewage	-	-	-	-	-	170- 494	-	66- 228	Hansen, NPO, B9
S7 Chemical pre- cipitation	-	-	9.6	15-80	-	-	-	-	Brüsch, NPO C15
S8 Production of biomass	3	-	3	-	4	-	4	-	NPO C12
Sum of sources	>12- 17	>5.5- 9	>28- 33	>25- 93	>20- 21	>196- 547	>12- 25	>86- 255	
Total transport in water course	96	584	42	413	96	853	18	405	table 1
Difference	<84- 79	<578- 575	<14- 9	<388- 320	<76- 75	<657- 306	<6- -7	<319- 150	

from 1987/88 shows the effect of increasing rainfall only, because frozen soil and snow only occurred a few days.

The variation shown in longer time series of either sediment or phosphorous transport can only be explained in terms of variation in the erosion contribution; there is, however, still a need for a more exact determination of the different components of erosion and the role of temporary sediment storage.

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