Sediment Budgets (Proceedings of the Porto Alegre Symposium, December 1988). IAHS Publ. no. 174, 1988.

On identification of sources of sediment transport in small basins with special reference to particulate phosphorus

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Abstract An increasing oxygen deficiency in Danish lakes and coastal waters has caused great concern about the transport of nutrients to water courses. This study is part of a larger project, sponsored by the Danish Ministry of Environment, that deals with the various aspects of the transport of nutrients to the aquatic environment. The aim of this part is to quantify the contribution from different erosion sources to the total transport of phosphorus. Two basins were selected (approximately 10 km^2), where climatic parameters, discharge and sediment transport are recorded continuously at the outlets. The basins are monitored once a week for occurrences of erosion which, if observed, are quantified. Methods are described and preliminary results from the winter 1987–1988 are presented.

Sur l'identification des sources de sédiments transportés, dans les petits bassins avec un intérêt particulier pour le phosphore

Résumé L'évolution du déficit d'oxygène dans les lacs et mers littorales du Danemark a présenté un caractère inquiétant en ce qui concerne l' importance des flux d'éléments nutritifs en rivière. Cette étude fait part d'un vaste projet (avec l'appui du Ministère de l'Environnement) qui poursuit des recherches sur les différents aspects du transport des éléments nutritifs vers l'énvironnement aquatique. Le but particulier de cette partie du projet est de quantifier les contributions des différents types d'érosion au transport total de phosphore. Deux bassins ont été choisis (chacun d'environ 10 km^2) et, à leur exutoires, les paramètres climatiques, les débits et le transport de sédiments sont mesurés régulièrement. Les bassins sont controlés chaque semaine en ce qui concerne l'érosion et, si elle est observée, elle est mesurée. Les méthodes appliquées sont décrites et les résultats de l'hiver 1987–1988 sont présentés dans cet article.

INTRODUCTION

In studies of landscape evolution it is of great importance to trace the different sources of sediment and to establish sediment budgets. Earlier investigations (Bartholdy & Hasholt, 1986; Hasholt, 1981, 1983) have shown that the transport of sediment in Danish water courses may have different origins and that a substantial portion of the transport can originate from soil erosion.

In recent years fish- and bottom fauna kills due to oxygen deficiency and algae blooms have occurred frequently in Danish lakes and coastal waters. These effects are believed to be the result of an increased transport of nutrients, caused by pollution from both point and diffuse sources, to these waters. The Ministry of Environment therefore initiated a research programme called the NPO Project (Nitrogen, Phosphorus, and Organic matter). The main objective of the project is to study transport and transformation processes in order to find methods to reduce the flux of nutrients. The aim of this part of the project is to quantify the contribution of different types of erosion to the total transport of phosphorus. The project is a joint venture between a group from 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 (evaluation of the representativeness of the findings by use of a soil data base). This paper deals mainly with the research carried out by the Institute of Geography.

PROBLEM AND SCOPE

A brief summary of the environmental and climatological background to erosion and transport processes in Denmark is provided below. The surface deposits are mainly of glacial or glaciofluvial origin. In the western part of the country there are sandy moraines and outwash plains, often with podzolic soils. The eastern part consists mainly of younger morainic deposits with luvisols developed. During the Weichsel glaciation, the western regions were partly ice free, so the slopes here are more gentle than those found in the eastern part. Erodibility measured using the index of Wischmeier & Smith varies between 0.08 and 0.55, and infiltration rates generally vary from 2 to 10 mm min^{-1}.

Since the Iron Age, a large proportion of the country's total area has been used for agricultural purposes and today roughly 70% is cultivated. The human impact has been significant for a considerable time, and during this century the cultivation practice has changed so that large areas are bare during winter, because of the growing of grain crops instead of permanent grass. Ploughing and harrowing are carried out very close to the streams. The natural drainage pattern has been subject to substantial changes due to dredging and tile drainage. Many smaller water courses have been changed into ditches or closed conduits and many larger water courses have been straightened. Today, only about 2% of the total length of the water courses remains in the natural condition. The straightened water courses are often deeper than the natural ones so that there is no flood plain to inundate during floods. In other places small dams were built for the use of water mills, irrigation or for fish farms. In order to convey the water towards the sea as rapidly as possible the water courses are maintained according to strict regulations, i.e. dredging of sand and gravel deposited in the channel and removal of weeds twice a year. The streambanks are often straightened with a scraper and the grass cut. During recent years experiments have been carried out to return the streams to their old courses. The human impact is therefore very significant but it is difficult to judge its overall effect on sediment transport.

According to Köppen, the climate is a temperate forest climate, Cfb, the annual mean temperature is 7°C with a monthly minimum of −0.1°C and a maximum of 17°C. The mean annual rainfall is 770 mm (corrected); during summer, convective thunderstorms occur while during winter the rainfall is mainly of cyclonic origin. High discharge rates occur mainly during the winter when the groundwater table is high and the soil saturated, especially when the surface is frozen, or covered with snow and ice.

In 1985–1986 a pilot study was carried out in a 42 km^2 basin to trace the transport and erosion processes in both space and time (Bojsen, 1987). The results are shown in Table 1.

Table 1 *Erosion processes and sediment sources*

Natural processes: raindrop splash, crusting, loosening by frost action, surface runoff and ponding, washing out sand particles, sheet wash, concentrated sheet wash in furrows and tracks, piping and rill erosion, streambank erosion, undercutting and slumping.
Human activities: dredging, removing of weeds, construction, distribution of manure and waste water disposal.

The scientific objective of this project is to elucidate the processes and to quantify the contributions from the different sediment sources, especially those transporting particulate phosphorus. The practical aim is to evaluate the environmental impact of this pollution from diffuse sources in order to find the best ways to reduce the transport to the aquatic environment.

DESIGN OF THE MEASURING PROGRAMME

The Ministry of Environment has allotted a fixed budget for the investigations. It was therefore important to choose an appropriate strategy to achieve results within the budget. The basins mentioned in the text were selected using the following criteria. The River Susaa provided a large range of slopes and diversity in land-use patterns. Rabis Baek (sandy soils) and Gelbaek (clay soils) had been instrumented for earlier investigations and for ongoing NPO Projects. Langvad (clay soils) was being studied as part of the ongoing NPO research.

In selecting an appropriate basin size, it should be possible to relate the transport measured in the water course to the sediment released in the basin, either by natural processes or by human activities (cf. Table 1). This puts constraints on basin size. In larger streams, pulses from erosion events may be attenuated or obscured downstream of tributary confluences, and the basin must therefore not be too large. Logistic and economic constraints also favour smaller basins. In order to extrapolate the results to other basins there should, on the other hand, be a certain amount of diversity in soil types, landforms, and land-use in the study basin. Those chosen are second- to third-order basins extending to about 10 km^2.

As the objective is to relate erosion processes and climatic events to the transport in the water courses, it is of paramount importance that the monitoring system should be reliable during all weather conditions and that the time resolution should be sufficient to monitor all significant variations. This has been achieved by use of automatic water sampling twice a day and the measurement of IR-transmission (turbidity) every 2 minutes at the stations at the basin outlet. Discharge is recorded every 15 minutes.

The next important step is to be able to measure changes within the water course (bed and banks) and to measure sediment delivery from the surrounding areas. Because of the long walking distances involved, even in a small basin, it is not possible to measure these factors more than once a week. In order to obtain as much information as possible, the routes were chosen so that locations most subceptible to erosion are visited each time, and to minimize the amount of work, a stratified random sampling is applied. The routes follow the main water course, and here the stratification is based on the meander pattern. In the surrounding areas, however, it is based on slope- and land-use categories. Sediment delivery from slopes is quantified by use of macro plots (approximately 1 ha) situated near the water course. Areas more distant from the water courses are visited less frequently (once a month); selected places, however, are equipped with Gerlach troughs which are emptied weekly.

In order to explain the variations in sediment transport, supplementary measurements of climate and soil parameters are needed. Rainfall, temperature and wind velocity are recorded continuously. Snow, soil water, infiltration, roughness, compaction and shear strength are measured when erosional features (e.g. rills) develop.

METHODS

The two monitoring stations at the basin outlets are equipped with an ISCO automatic sampler which takes samples twice a day. These are used for determination of suspended load, analysis of phosphorus and for calibration of the infrared sensors of the Partech Suspended Solids Monitor which records at 2-min intervals. The monitoring equipment is housed in an insulated box which is heated during winter and cooled during summer. Every week the stations are checked and samples collected manually with a depth-integrating sampler for calibration and analysis of phosphorus. The observer follows a route along both stream banks and registers all signs of erosion. Bed and bank erosion are measured by levelling and by use of erosion pins at the randomly selected stretches. Erosion in other parts of the basin is registered, while the observer drives on a fixed route; and the Gerlach troughs are also emptied.

The Danish Society for Land Development also visits the four macro plots every week. The plots are of Norwegian design. From an area of about 1 ha, the surface runoff is led to a tank where the discharge is recorded by a Thompson weir and flow-proportional samples are collected. The observations of erosion made on the weekly field trip are quantified and distributed over time by use of the continuously recorded data.

To study the variations within the basin more closely and also the temporal variation of concentration in the various parts of the drainage system, about four measurement campaigns are carried out during the winter season. The aim of the first campaign is also to register the land-use pattern and other parameters which may influence the transport of sediment, such as fallow, ploughed fields, direction of furrows, roughness and application of manure. During the campaign, water samples are collected more frequently. The next two campaigns are used mainly to describe the transport and to survey fields with well developed erosion features. The initiation of the campaigns is decided by use of a 5-day weather forecast in order to find either incidents of heavy rainfall or thawbreaks, because these are known to cause erosion. The last campaign is used mainly for supplementary measurements and for registration of the overall situation after the winter season.

In the laboratory water samples are filtered through Whatman GF/F filters. Phosphorus is determined by the use of the molybdate blue method and photometry, and organic matter by residue on ignition at 500°C. Preliminary results are computed by use of linear interpolation on timegraphs and daily discharge values. Later, when the software is fully developed the computations will be carried out automatically for smaller time units.

RESULTS

The situation of the water courses mentioned below is shown in Fig. 1. Two of the basins were investigated earlier, Rabis Baek and Gelbaek. In Table 2 the results from the years 1983/1984 and 1984/1985 are shown. The transport of particulate organic matter was very low during 1983/1984, while in 1984/1985 it is in good accordance with results from other investigations (Bartholdy & Hasholt, 1986; Hasholt, 1983). The transport of phosphorus per unit area is surprisingly similar for the two basins in spite of significant differences in morphology and soil type.

Figure 2 depicts the monthly transport of phosphorus for the two drainage basins. Transport of organic matter shows the same pattern with maxima during the winter when discharge is high. The transport is more uniform in Rabis Baek, the maximum in July is caused by weed cutting. The maxima during the winter are explained by storage of sediment throughout the summer and subsequent release in winter combined with contributions

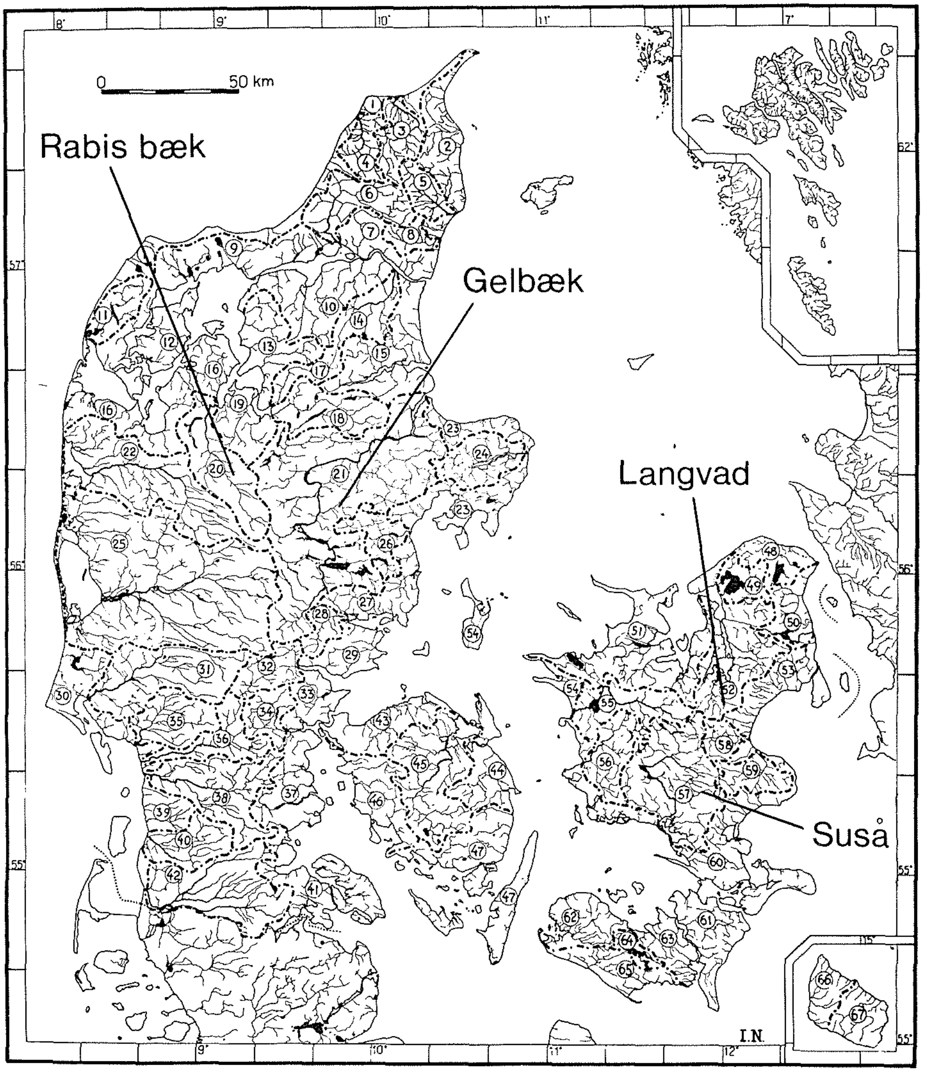

Fig. 1 Survey map.

from erosion.

Results from the pilot study in the 42.2 km^2 River Susa basin are shown in Table 3, where a mass balance of the different transport components has been established in order to find the contribution from soil erosion. It is an important precondition for the mass balance that there is no change of storage in the riverbed, this is checked by visual observations. About 40% of the total suspended load stems from bank erosion and another 40% from soil erosion. For total phosphorus about 60% originates from erosion, and for particulate phosphorus erosion contributes about 80%. The transport of total phosphorus is 137 kg km^{-2} year^{-1}.

Preliminary results from the investigations 1987/1988 are provided in Table 4. The different types of erosion found during the weekly field trips

Table 2 *Annual runoff and transport of phosphorus and particulate organic matter from the Gelbaek and Rabis Baek basins (from Kronvang et al., 1987)*

Basin transport	*Gelbaek (11.8 km²) (kg ha⁻¹ year⁻¹)*		*Rabis Baek (8.2 km²) (kg ha⁻¹ year⁻¹)*	
	1983/84	*1984/85*	*1983/84*	*1984/85*
Total PO_4-P	*0.34*	*0.56*	*0.30*	*0.55*
Total P	*0.51*	*0.70*	*0.36*	*0.68*
Part. org. matter	*6.6*	*18.4*	*9.2*	*10.4*
Runoff	*286 mm*	*266 mm*	*561 mm*	*501 mm*

have been distributed over time by using the continuous records of transport and the sum for the period computed.

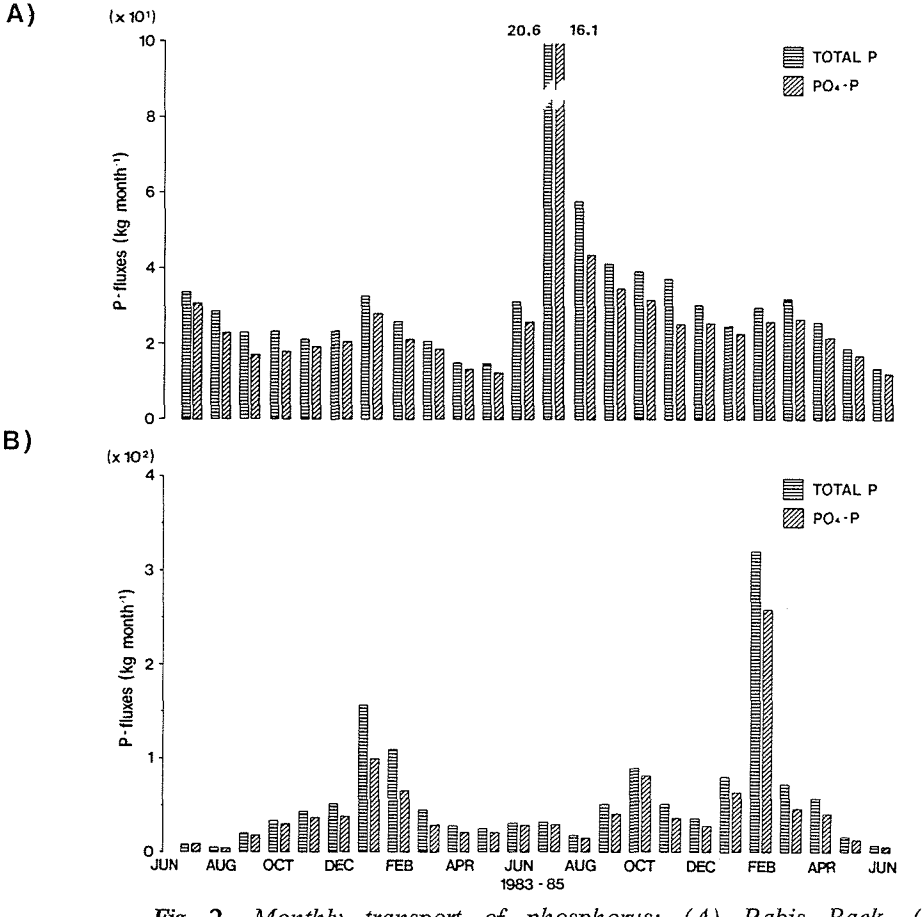

Fig. 2 Monthly transport of phosphorus: (A) Rabis Baek, (B) Gelbaek. From: Kronvang et al. (1987).

Table 3 *Annual transport of suspended solids and phosphorus from different sources within the River Susa basin (based on Hasholt & Bojsen, 1987)*

Source above measuring station	SS (t/year)	PT (kg/year)	PDI (kg/year)	PP (kg/year)	References
Dry deposition	50	min. 30	0	min. 30	Hasholt (1981), Novotny & Chesters (1981)
Wet deposition	0.3	3	?	?	Almér et al. (1974), estimated
Ground Water	small	15	15 (?)	0	Erup (1981), Jacobsen et al. (1981)
Tile drainage	6-18	900	250	600	Brink et al. (1984), Hansen (1981), Uhlen (1978)
Domestic waste-water (towns)	0.6-1.2	1460	1310	150	Løw (1985), own investigation, Miljøstyr. (1984), Løw (1985)
Wastewater from roofs and roads	5-10	60-100	30-50	30-50	Miljøstyr. (1984), VKI (1977), own invest.
Bank erosion	200-300	100-160	0	100-160	Own investigation
Animal farm wastewater	small	360 (?)	180 (?)	0 (?)	Miljøstyr. (1984), DK Statistics (1986)
chemical and bio-logical proces-ses in rivers	50 (?)	0	300 (?)	300 (?)	Estimated
A: subtotal	370 ± 100	2500 ± 600	1400 ± 300	950 ± 400	
B: measured transport at Pindsobro	590 ± 60	5800 ± 600	1430 ± 300	4200 ± 800	Own investigations
B-A: Contribution from soil erosion	220 ± 120	3300 ± 850	30 ± 425	3250 ± 900	

SS = total suspended solids; PT = total-P, PDI = inorganic dissolved-P, PP = particulate-P.

Table 4 Sources of transport winth the Rabis Baek and Langvad basins

	Rabis Baek (1/10/87 to 31/1/88)				Langvad (1/10/87 to 31/1/88)			
	SS(t)	SO(t)	PT(kg)	PP(kg)	SS(t)	SO(t)	PT(kg)	PP(kg)
Wet/dry depos/waste water	9	2	172	17	7	4	120	25
Dredging/weedcutting	0	0	0	0	4	0.8	2	0
Stream bed and banks	41	9	77	100	38	8	27	7
Overland, sheet erosion	0	0	0	0	18	4	300	90
Rill erosion	0	0	0	0	0	0	0	0
Total (t, kg)	50.0	11.0	249	117	67.3	16.1	449	122
Total (t km^{-2})	6.1	1.3	30.3	14.2	5.9	1.4	39.0	10.6

SS = total suspended solids; SO = suspended organic fraction; PT = total-P; PP = particulate-P.

It is seen that sediment transport from sources other than the stream bed and banks and wetlands in the river valley are insignificant for the Rabis Baek. Very little rill erosion occurred during this year and this was not at locations where it could influence transport at the monitoring stations. This is due to the extremely mild and rainy winter during which a large amount of water has been able to infiltrate instead of flowing across the frozen surface.

FUTURE INVESTIGATIONS

The field investigations were planned to extend for two full sediment budget years (October–September) 1987/1988 and 1988/1989. As the winter 1987/1988 was extremely mild, however, it is proposed to continue the field investigations for a further year in order to obtain more data to improve the statistical computations and extrapolation of the findings to other areas. At a later stage it is planned to use the data for testing of soil erosion models.

Acknowledgements Thanks are due to my colleague M. Pejrup for a valuable discussion of the manuscript, to K. Winther for improving the English, and to I. Primstad and J. Ulrich for elaboration of tables and figures.

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