Sediment tansport in the drainage area of Ribe Å

Jesper Bartholdy, Bent Hasholt & Morten Pejrup

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The river Ribe Å has a drainage area of 950 km² and a mean annual run-off of 15.6 l/s/km². Supply and deposition of sediment in the drainage area were investigated during the period 1984-86. The denudation based on the measured supply of bed load and suspended bed load is very unevenly distributed in the drainage area and amounts to 26 t/km²/year. The total denudation in Ribe Å's drainage area was calculated to be 34 t/km²/year of which 23 % is wash load, 21 % suspended bed load and 56 % bed load.

Keywords:
Sediment transport, rivers, bed load, fluvial deposits.

Jesper Bartholdy, associate professor, Bent Hasholt, associate professor, Morten Pejrup, associate professor, Institute of Geography, University of Copenhagen, Øster Voldgade 10, DK-1350 Copenhagen K.

Deposition of sand in the lower reaches of rivers running to the Danish Wadden Sea in southwest Jutland is well known (Hasholt 1972, 1984; Bartholdy, 1979, 1980; Jacobsen 1981, and Bartholdy et al. 1983). Deposition in regions like this is natural, but probably also amplified by the presence of sluice gates and by an enlarged sediment transport in the rivers due to realigning of watercourses in the drainage basins.

The outlet of river Ribe Å is protected by a sluice gate, and the channel is dredged in order to keep the river navigable downstream of the town Ribe approximately 5 km inland. Here the river has been dammed to utilize the water power in mills since medieval time. This decreases the slope and therefore sedimentation takes place in low-lying meadows upstream of the town.

An investigation of denudation, based on suspended sediment transport, from drainage basins leading to the Danish Wadden Sea (Bartholdy & Hasholt, 1986) showed 15t/km²/year for river Ribe Å, which is approximately 50 % larger than in two similar major rivers in the region (Vidå and Kongeå).

The present study is based on results from an investigation of the transport and deposition of sediment east of Ribe carried out by the Institute of Geography, University of Copenhagen, for the councils Ribe Amtskommune and Sønderjyllands Amtskommune. The purpose of this applied research project was to survey the sediment transport in the area in order to point out possible solutions to the sedimentation problems in the wetland area.

The objectives of this paper are to quantify the sediment transport leading to the wetland area, to describe the areal variation of transport rates and sediment sources and to establish a sediment balance for the system. Only general remarks on technical solutions of the sedimentation problem are included.

AREA OF STUDY

The drainage system of Ribe Å above Ribe is shown in fig. 1. The total drainage area covers 950 km² of primarily old, flat-topped moraine hills from Saale separated by outwash plains from Weichsel. The valley west of Ribe is primarily covered with salt marsh deposits.

The river springs in the NS-orientated range of hills (terminal moraines from Weichsel) situated in the eastern part of Jutland. In this area the major tributaries to the river drain bogs lying 40-50 m above sea level. These small streams merge into the two main streams of the area, Gram Å/Fladså and Gels Å. The River is named Ribe Å, after the confluence between Fladså and Gels Å, approximately 16 km upstream from the outlet in the Danish Wadden Sea. At the confluence the water is about 5 m above sea level.

The northern main tributary Gram Å is dammed in the town Gram, where a small power plant is situated. Here the sediment from the 290 km² upstream is deposited and dredged regularly. No bed load escapes from here to the downstream reach. Consequently, the remaining part of this northern main tributary (it changes name to Fladså about 5 km upstream the confluence with Gels Å) has lowered its base and is "non-alluvial" with long reaches where the bed consists of very coarse lag-material. This part of the river is almost unregulated and appears wider and more shallow than Gels Å. Downstream of Gram the river drains 62 km² and has three tributaries: Hornsbæk, Fole Bæk, and Harreby Bæk. Near Fole there is a fish farm with a culvert which allows bed load to pass the dam. Downstream of the farm the gradient is 0.9 ‰ and upstream 0.8 ‰.

The southern main tributary, Gels Å, drains 326 km². It starts at the confluence between Nipså and Sønderå. Both streams have been realigned and so has the major part of

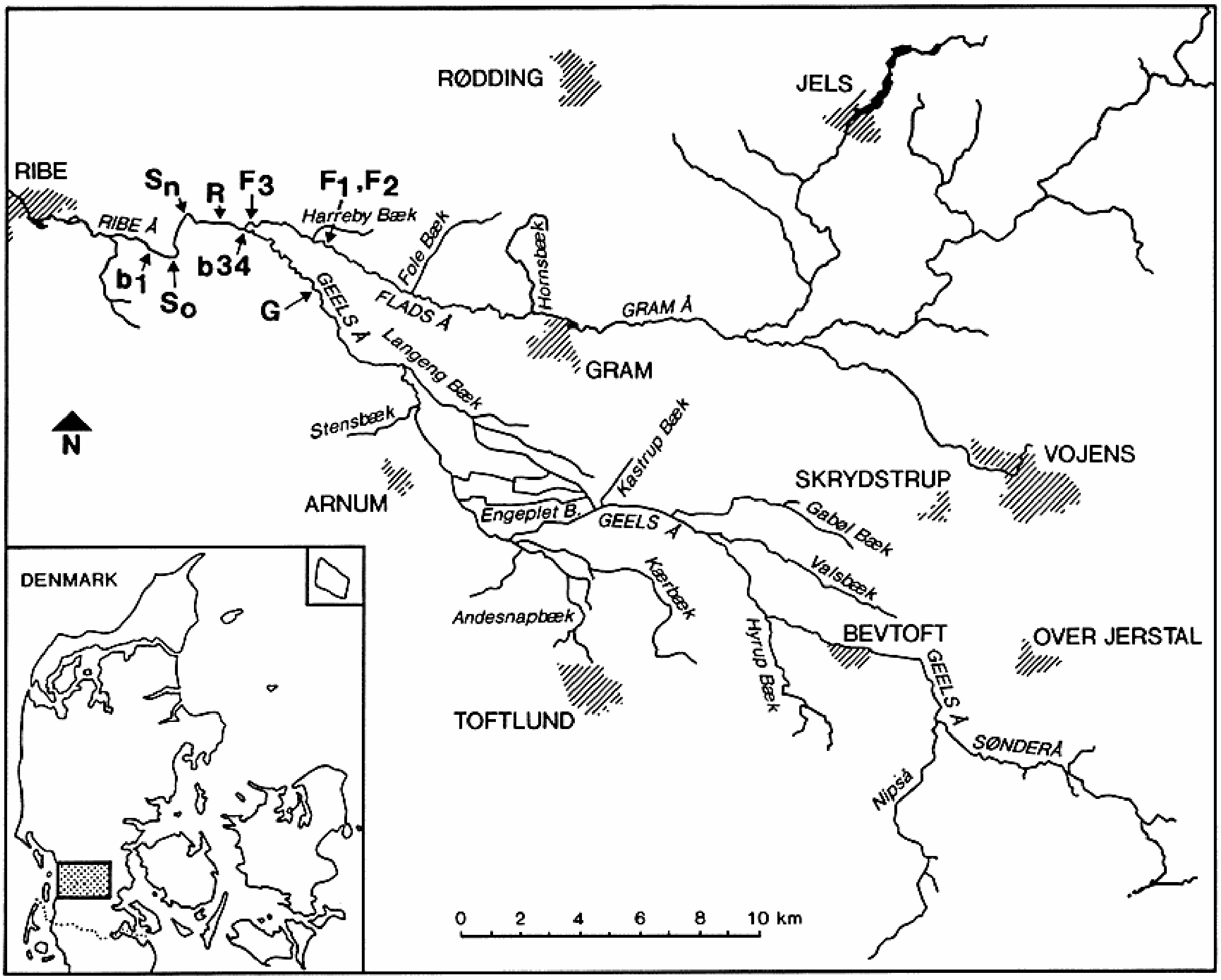

Fig. 1. Survey map of the investigated area. F_1- F_3, G and R indicate the cross-sections where sediment transport was measured, b_1-b_{34} indicate the reach with benchmark poles, Sn shows the location of the new sandtrap and So the delta front from earlier dredging.

Fig. 1. Oversigtskort af undersøgelsesområdet. F_1-F_3, G og R angiver måletværsnit, b_1- b_{34} viser placeringen af strækningen med kantpæle, Sn viser placeringen af det nye sandfang og So placeringen af delta fronten fra tidligere opgravninger.

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Gels Å down to the confluence with Stensbæk. Gels Å receives a number of tributaries supplying bed load to the river, see fig. 1. The degree of realigning is less from the confluence with Stensbæk to Gelsbro. Downstream of a fish farm near Gelsbro to the confluence with Fladså, the river is meandering undisturbed.

The gradient in the southern main tributary system decreases downstream from 1.5 ‰ at the confluence between Nipså and Sønderå to approximately 0.7 ‰ near the confluence with Stensbæk. In between, some reaches have gradients down to 0.5 ‰. Most of the year the bed load is trapped upstream of the sluice at the fish farm near Gelsbro. At high discharges, however, the sluice is opened and the trapped bed load is allowed to pass. In the meandering river reach downstream of the fish farm, the slope is 0.5 ‰ until roughly 1 km upstream of the confluence with the deeper eroded Fladså where it raises to 1.9 ‰.

After the confluence between Fladså and Gels Å, Ribe Å has been realigned and runs through low-lying meadows towards Ribe. An inland delta is formed just upstream of Ribe filling up a former lake system situated here. The last part of this filling is documented by maps, see fig. 2. A number of deltas with names like Lillesand, Nysand, and Storesand (small sand, new sand and big sand) appear on the map showing the old outlets of Ribe Å into the lake. The last delta (Nysand) which eventually grew large enough to fill up the remaining lake (Varming Sø) was artificially located in the eastern part of the lake at the beginning of the eighteenth century by a dredged canal. Today the last part of the lake is prevented from being filled up by an artificial, regularly dredged sand trap.

METHODS

Erosion in the drainage system was investigated by the use of aerial photos and maps of different age and directly measured by means of "erosion pins" in the banks of levelled cross-sections.

Downstream of the confluence between Gelså and Fladså, a system of 1 m long, impregnated benchmark poles was established to mark repeatedly levelled cross-sections (vertical accuracy ± 1 cm, horizontally accuracy ± 5 cm). The location of the poles was determined by triangulation and the level of each pole referred to Danish Ordnance Datum (DNN). The surveyed reach was divided into two parts: the lower part (1700 m) with surveyed cross-sections every 100 m and the upper part (3400 m) with surveyed cross-sections every 200 m. At the delta front, the measuring net was denser (10-50 m).

Discharge was calculated from 10-20 current velocity profiles measured in the cross-sections using an Ott C 31 current meter. Depth-integrated water samples and time-integrated samples of the surface water were collected with a Swedish sampler (Nilsson, 1969) at about 10 positions in the cross-section. They were filtered through

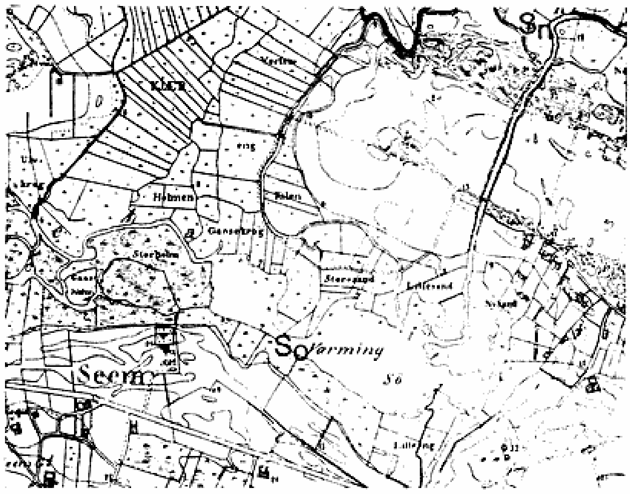

Fig. 2. Part of a map from 1869 (1:20 000) of the wetland area east of Ribe and the former, now filled up lake Varming Sø.

Fig. 2. Udsnit af målebordsblad fra 1869 (1:20 000) over vådområdet øst for Ribe og den nu opfyldte Varming Sø. Copyright Kort og Matrikelstyrelsen (A220-90).

Whatman GF/F filters to determine the suspended sediment concentration. The suspended transport (depth-integrated) and wash load (surface samples) were found by multiplication of the thus determined concentrations with the discharge. The suspended bed load was found by subtracting the wash load from the total suspended transport.

Bed load transport at low discharge was measured with a pressure difference bottom sampler (Hansen, 1966). Measurements were made at 5-10 places in the cross-section. At higher water discharge bed load transport was computed from measurements of the height and migration velocity of the bed forms (dunes and ripples) along three 15 m long wires covering the middle of each third part of the cross- section. On the basis of these measurements mean migration velocity and mean dune height were determined. Dry bulk density of the transported sand was measured with a Kajak tube sampler. Subsequent compu-

	Transport (t)	
Period	Bed load	Total load
1984-85	4300	4800
1985-86	5800	6900

Table 1. The amount of sand transported in Fladså during the investigated period. Each year the terminal date is August 1.

Tabel 1. Transporteret mængde sand i Fladså. Transportåret slutter 1. august.

	Transport (t)	
Period	Bed load	Total load
1984-85	3700	5500
1985-86	9500	18600

Table 2. The amount of sand transported in Gels Å at the gaging station during the investigated period. Each year the terminal date is August 1.

Tabel 2. Transporteret mængde sand i Gelså. Transportåret slutter 1. august.

tation of bottom sediment transport was made according to the method described by Hansen (1966). Results from Thomsen (1980) suggest that the accuracy of such computations of bottom sediment transport is better than ±15 %.

RESULTS

Sediment sources

In order to quantify the sediment sources, they were divided into two categories: sediment brought to the two main streams by tributaries, and sediment released by bank erosion in the main streams.

Supply from tributaries

The sediment transport in the tributaries was measured during two campaigns in 1985: April 1-2, and October 16-17. The results are presented in tables 1 and 2.

The run-off was 28.5 l/s/km^2 in April and 14.0 l/s/km^2 in October. Mean monthly run-off for the last 10 years is 15.6 l/s/km^2, and maximum monthly mean is 31.8 l/s/km^2. Thus, the April campaign represents spring periods with no water weeds and high run-off and the October campaign autumn periods with water weeds and run-off conditions near mean.

As it appears, the supply from the tributaries in Gram Å/Fladså is very limited. Using the Q/Qb relation for Fladså (see later), the two combined supplies correspond to respectively 4 % and 1 % of the total bed load in Fladså. This contribution is therefore regarded as insignificant.

In Gels Å, the supply from the tributaries represents a considerable part of the total bed load in the river. The April campaign's result corresponds to 40 % of the total actual bed load in Gels Å and the October campaign's likewise 23 %.

Figs. 3 and 4 show the spatial distribution of the specific bed load supplied from the tributaries to Gels Å during the two campaigns. In April the mean supply was 0.069 t/day/km^2 and in October 0.008 t/day/km^2. The two figures show the specific bed load for each of the small drainage areas in % of these mean supplies.

In the April campaign, the specific bed loads in Sønder Å (2), Stensbæk (9) and Valsbæk (4) were lower than the

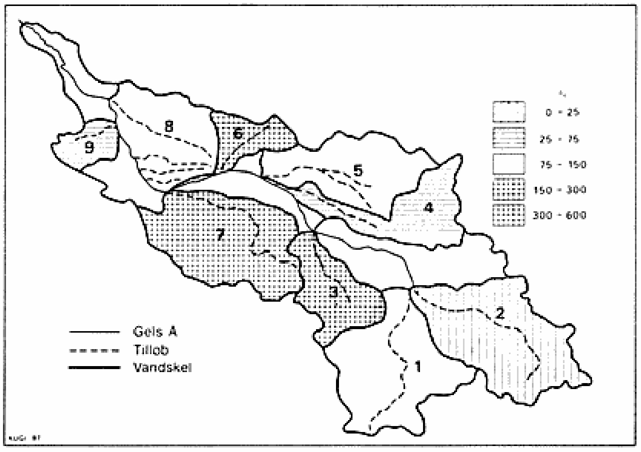

Fig. 3. Spatial distribution of bed load supplied from the tributaries to Gels Å, April 1-2, 1985. The mean specific load was 0.069 t/km^2/d. The tributary contribution is shown in percentage of this mean specific load. The Danish words "tilløb" and "vandskel" mean tributary and watershed respectively. See the text and Fig. 1 for names and location of the drainage area.

Fig. 3. Tilførsel af bundtransporteret sand fra tilløb til Gels Å, 1-2 april 1985. Middeltilførselen var 0.069 t/km^2/døgn. Signaturen angiver de enkelte oplandes tilførsel i % af denne middeltilførsl. Se teksten og Fig. 1 vedr. navne og placering af oplandet.

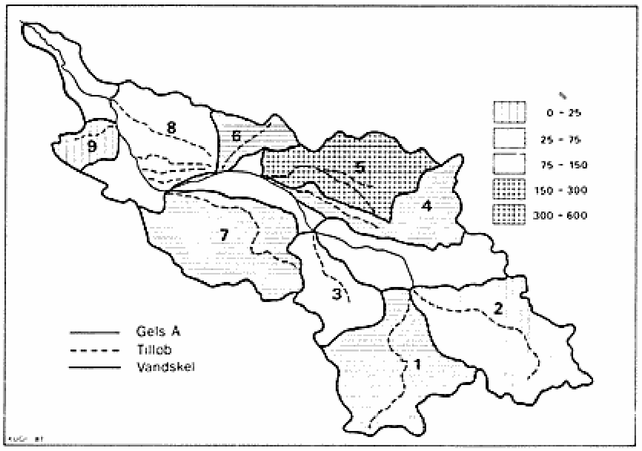

Fig. 4. Spatial distribution of bed load supplied from the tributaries to Gels Å, October 16-17, 1985. The mean specific load was 0.008 t/km^2/d. The tributary contribution is shown in percentage of this mean specific load. The Danish words "tilløb" and "vandskel" mean tributary and watershed, respectively. See the text and Fig. 1 for names and location of the drainage area.

Fig. 4. Tilførsel af bundtransporteret sand fra tilløb til Gels Å, 16-17 oktober 1985. Middeltilførselen var 0.008 t/km^2/døgn. Signaturen angiver de enkelte oplandes tilførsel i % af denne middeltilførsl. Se teksten og Fig. 1 vedr. navne og placering af oplandet.

mean value for the whole area. Nips Å (1), Gabøl bæk (5) and the tributaries draining Tiset Kær (pooled together) (8) had specific bed loads near mean, while Hyrup Bæk (3), Andesnap- /Kærbæk (7) and Kastrup Bæk (6) supplied more bed load per unit area than mean for the whole area.

Like in April, the October campaign showed a specific bed load in Sønder Å (2), Stensbæk (9) and Valsbæk (4) lower than mean, which at this time was also the case for Nipså (1) and Andesnap-/Kærbæk (7). Again the tributaries draining Tiset Kær (8) had specific bed loads near mean, this time followed by Hyrup Bæk (3), while Gabøl Bæk had a specific bed load of more than 400 % of the mean value for the area.

Some of the variations may have been caused by dredging the tributaries in order to maintain a sufficient draining. At least this was the case for Hyrup Bæk, which was dredged just before the October campaign. The spatial variation, however, is fairly consistent. In both campaigns roughly 80 % of the tributary contribution was delivered by 4 tributaries: Nipså (1), Hyrup Bæk (3), Gabøl Bæk (5) and Andesnap-/Kærbæk (7) representing 55% of the total tributary drainage area. The reason for this large variation in sediment yield is not yet investigated.

In order to give a rough estimate of the contribution from the tributaries, the year has been divided into two periods: December to May when the sediment supply from the tributaries in the April campaign as a percentage of the transport in Gels Å is used, and June to November when the similar percentage from the October campaign is used.

Based on the transport in Gels Å at Gels Bro (see later), this estimate showed a contribution from the tributaries

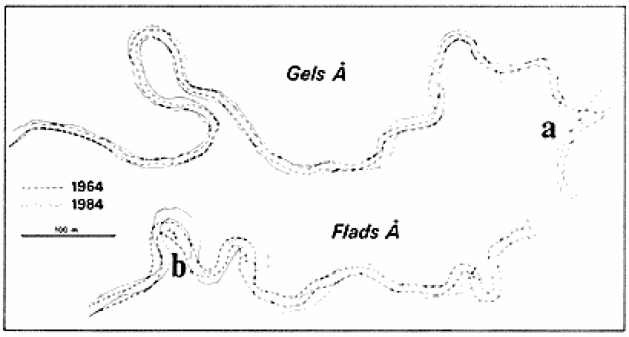

Fig. 5. Location of the river banks in selected reaches of Fladså and Gels Å, based on mathematically corrected aerial photos. The dashed lines indicate the situation September 1, 1964, the full lines the situation April 24, 1984. Detailed measurements were carried out at points a and b.

Fig. 5. Oprettet flyvebilledudtegning af bredderne i Fladså og Gels Å på udvalgte strækninger. De stiplede linier viser beliggenheden af bredderne d. 1/9-1969 og den fuldt optrukne viser situationen d. 24/4-1984. Placeringen af detailmålefelter er angivet med a og b.

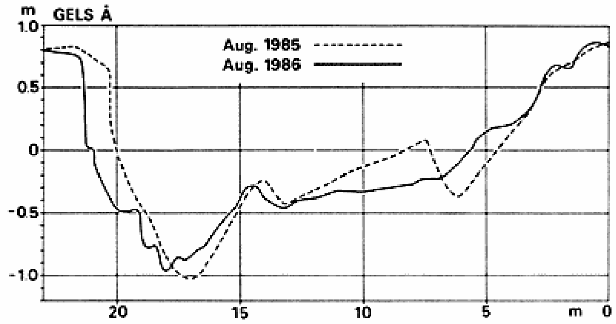

Fig. 6. Cross-profiles from point a in fig. 5. The profiles were sounded at 1-year intervals.

Fig. 6. Tværsnit fra feltet a på fig. 5. Profilerne er målt med et års mellemrum.

to Gels Å from August 1984 to August 1985 of roughly 2000 tons, and from August 1985 to August 1986 roughly 4000 tons corresponding to approximately 50 % and 40 % respectively.

Bank erosion

In the two main streams Gram Å/Fladså downstram of Gram, and Gels Å downstream of Gels Bro, the bank erosion was investigated in two selected typical reaches of these rivers, fig. 5.

This drawing is based on mathematically corrected aerial photos of the banks from 1964 and 1984; the areas marked with "a" and "b" were selected for field measurements of cross profiles. An example of a cross profile from area "a" in Gels Å measured at a 1-year interval is shown in fig. 6.

Eighteen "erosion pins" were mounted in the banks of each of the 2 meanders marked with "a" and "b" on fig. 5. The results from these pins were used to control the analysis based on the aerial photos. The pins showed an erosion of 0.74 m/year (a) and 0.90 m/year (b). In both cases the mean values from the aerial photo analysis were 0.75 m/year. This agreement is considered to be acceptable.

On the basis of the above two figures and levelled profiles, the release of sediments caused by bank erosion in the two river valleys has been calculated to 3500 m^3/year in Gram Å/Fladså downstream of Gram, and 2000 m^3/year in Gels Å downstream of Gels Bro. In addition to this, a minor amount of sediment is released from a few high cliffs where river meanders erode into the old pleistocene landscape. The erosion in these cliffs has been kept under observation by means of a similar combination of erosion pins and analysis of aerial photos. The results show an estimated supply of 400 m^3/year in Gels Å. Together, erosion in the two river reaches releases 3900 m^3/year in Gram Å/Fladså downstream of Gram, and 2500 m^3/year in Gels Å downstream of Gels Bro. With an estimated dry volume weight of 2 t/m^3, these figures correspond to 7800 t and 5000 t, respectively.

Sediment transport in the main channels

Transport relations in Fladså

Discharge and sediment transport are measured in Fladså at the stations shown in fig. 1. The mean grain size of the bed load is approximately 530 μm with a sorting of 0.4-1.1 ϕ and a negatively skewness of approximately -0.3.

It was not possible to fit the data set (Q_b & Q_t = f(Q)) to the traditional power function normally used in alluvial streams. The measured sediment transport rates at high discharge, were too low due to the non- alluvial behavior of the river in such situations. This bed load deficit is primarily caused by the artificial lake in Gram acting as a bed load trap.

The best fit between discharge and sediment transport from this station proved to be a semi-logarithmic regression:

$$Q_b = 51.2 \log Q - 18.4 \ (Q > 0.5) \quad r = 0.77$$
$$Q_t = 73.8 \log Q - 31.1 \ (Q > 0.3) \quad r = 0.90$$

Q_b is bed load in t/day, Q_t is bed load + suspended bed load in t/day, and Q is discharge in m^3/s.

The data and the semi-log regressions are shown graphically in figs. 7 and 8. These regressions are used to calculate the transport in Fladså shown in table 1.

Transport relations in Gels Å

Water and sediment discharge were measured in Gels Å at the gaging station (G) shown in fig. 1. The mean grain size of the bed load is approximately 490 μm with a sorting of

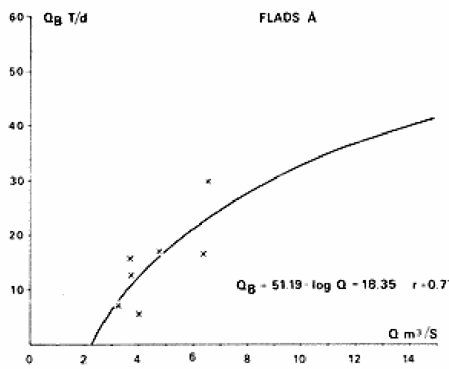

Fig. 7. The relation between discharge (Q) and bed load (Q_B) in Fladså.

Fig. 7. Relationen mellem vandføring (Q) og bundtransport (Q_B) i Fladså.

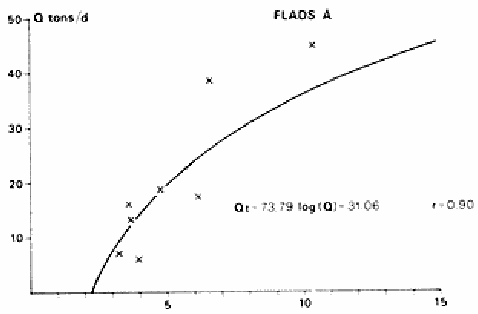

Fig. 8. The relation between discharge (Q) and total load (Q_t) in Fladså.

Fig. 8. Relationen mellem vandføring (Q) og totaltransport (Q_t) i Fladså.

0.6-1.3 ϕ and a negatively skewness of approximately -0.2. In this case it was possible to fit the data set (Q_b & Q_t = f(Q)) to the traditional power function:

$$Q_b = 0.3\,Q^{2.3} \quad r = 0.91$$
$$Q_t = 0.2\,Q^{2.7} \quad r = 0.95$$

Q_b is bed load in t/day, Q_t is bed load + suspended bed load in t/day, and Q is discharge in m^3/s.

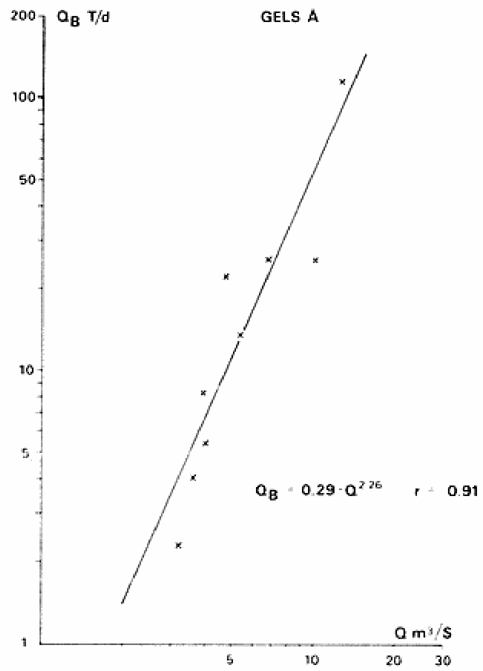

Fig. 9. The relation between discharge (Q) and bed load (Q_B) in Gels Å.

Fig. 9. Relationen mellem vandføring (Q) og bundtransport (Q_B) i Gels Å.

The data and the power functions are shown graphically in figs. 9 and 10. These regressions are used to calculate the transport in Gels Å at station G (fig. 1) shown in table 2.

Transport relations in Ribe Å

The investigated cross-section in Ribe Å is situated about 1 km downstream of the confluence between Fladså and Gels Å (fig. 1). The mean grain size of the bed load is 350-850 μm with a sorting of approximately 0.9 and a negatively skewnes of approximately -0.3. Because the sediment transport through this cross-section is the sum of the transport rates in these two rivers, a relation between sediment transport and water discharge like the one found for Fladså might be expected. The relation found was:

$$Q_b = 66.6 \log Q - 32.0 \quad r = 0.91$$

The data and the semi-log relation are shown graphically in fig. 11.

For this station more data was available on the suspended bed load from Bartholdy and Hasholt (1986) (weekly samples over 1 year). These data showed a linear relation between discharge and suspended bed load (Q_{sb}):

$$Q_{sb} = 1.38\, Q - 4.43 \quad r = 0.67$$

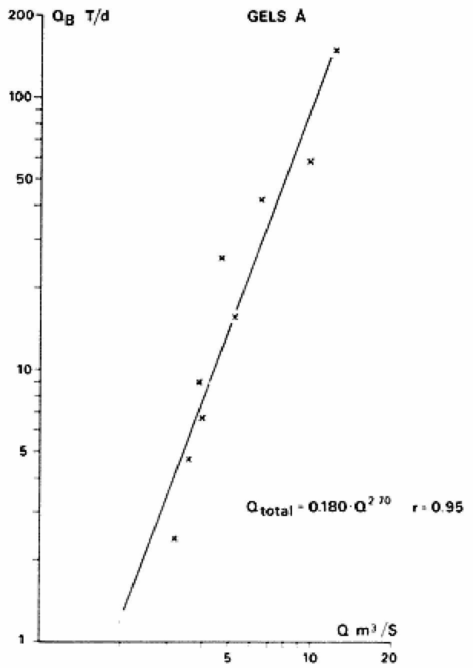

Fig. 10. The relation between discharge (Q) and total load (Q_t) in Gels Å.

Fig. 10. Relationen mellem vandføring (Q) og totaltransport (Q_t) i Gels Å.

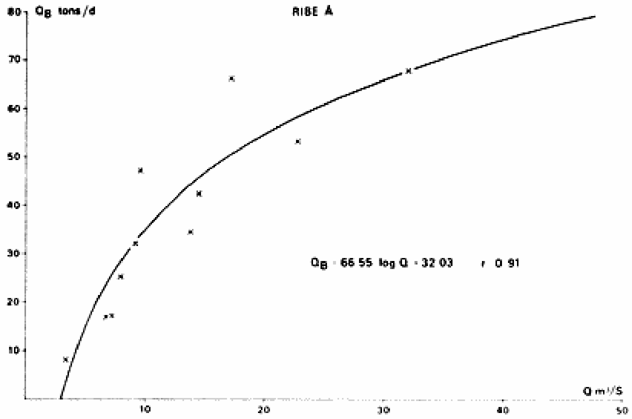

Fig. 11. The relation between discharge (Q) and bed load (Q_B) in Ribe Å.

Fig. 11. Relationen mellem vandføring (Q) og bundtransport (Q_B) i Ribe Å.

This and the Q/Q_b regression are used to calculate the transport in Ribe Å at station R (fig. 1) shown in Table 3.

Period	Transport (t) Bed load	Total load
1984-85	10,000	13,100
1985-86	11,800	19,500

Table 3. The amount of sand transported in Ribe Å at station R during the investigated period. Each year the terminal date is August 1.

Tabel 3. Transporteret mængde sand i Ribe Å ved station R. Transportdret slutter 1. august.

Sediment balance

In a hydrological context the two investigated periods are classified as "dry" and "wet" respectively. Mean annual run off for the period 1975-1985 was 15.6 l/s/km^2 while 1984-85 had a mean run off of 12.9 l/s/km^2 and 1985-86 of 16.7 l/s/km^2.

The sediment transport values in Fladså and Gels Å for the period 1984-85 are rather similar in size; 4800 tons in Fladså and 5500 tons in Gels Å. If the estimated 5000 tons of sediment eroded in Gels Å from the station at Gels Bro to the confluence with Fladså are taken into account, the total sediment supply from these two rivers to Ribe Å is 15,300 tons. Within the uncertainties this figure corresponds with the transport in Ribe Å based on the Q/Q_b relation, showing a total of 13,100 tons. Thus, in dry years such as 1984-85 about one third of the sediment supplied to Ribe Å originates from Fladså and the remaining two thirds from Gelså.

For the period 1985-86 the calculated total supply of sediment to Ribe Å from the two main tributaries was 30 % higher than the transport in Ribe Å. Most likely, this

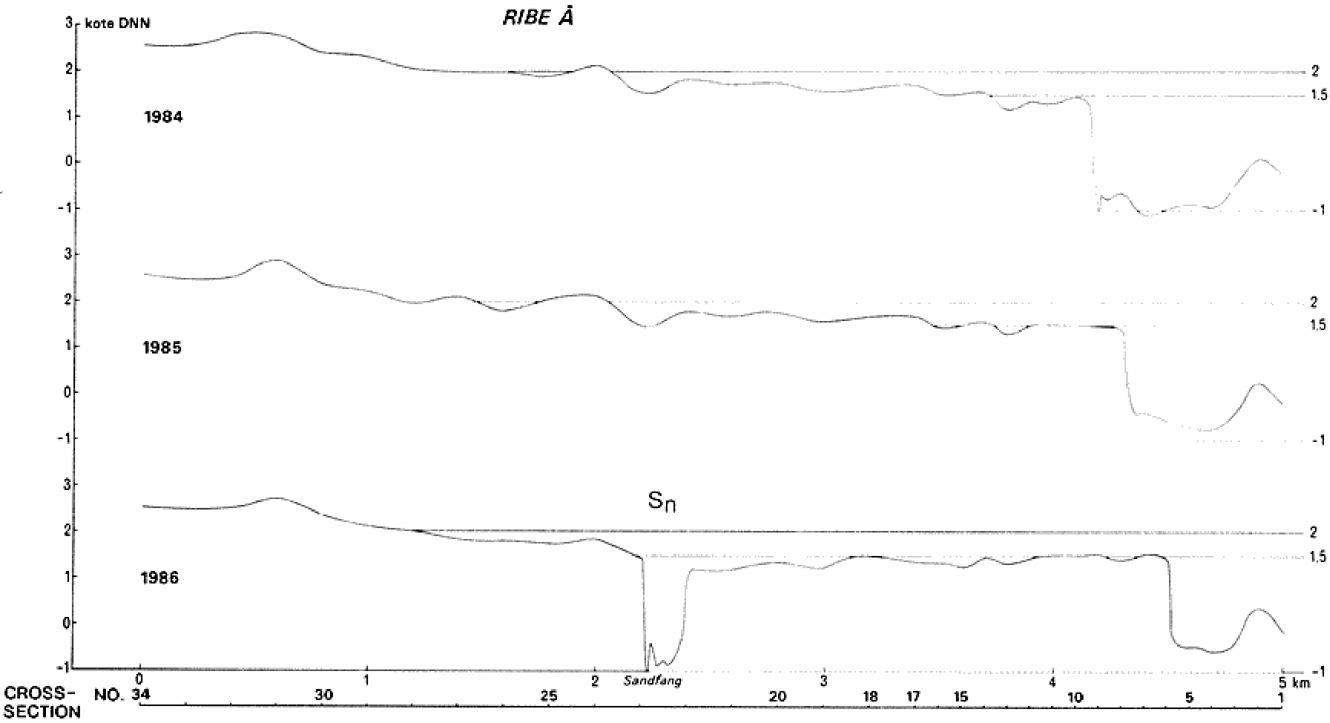

Fig. 12. Length profiles of Ribe Å from benchmark 1 to 34. The location of the river reach is shown in Fig. 1. DNN is the Danish reference level.

Fig. 12. Længdeprofiler af strækningen fra kantpæl 1 til 34 i Ribe Å. Placeringen af strækningen er vist pd Fig. 1.

discrepancy is due to a non-alluvial response in Gels Å during unsurveyed periods of extremely high discharge, i.e. higher than the highest value on figs 9 and 10. If, alternatively, the sediment supply from Gels Å is estimated as the difference between the sediment transported in Ribe Å (19,500 t) and Fladså (6900 t), subtracted the contribution from erosion downstream of the station in Gels Å (5000 t), the result is 7600 t which keeps the relative contribution from the two tributaries at the same level as in dry years. This way of interpreting the results is also justified by the measured non-alluvial conditions at low discharge in Fladså.

Deposition and redistribution of sediments in Ribe Å

The detailed soundings below the confluence makes it possible to follow the bed load from the two tributaries to the accumulation zone and to observe the changing depositional conditions in this area. Three soundings were carried out at yearly intervals in August or September (minimum transport periods) covering the transport years 1984-85 and 1985-86.

The transport year 1984-85

In order to give an overview of the area, length profiles of the bottom level in the middle of the cross-sections are shown in fig. 12. From cross-section 34 to 10 (fig. 1) there are only minor changes in volumes, the corresponding rising and lowering of stream-bed is only ±3 cm. There is a large accumulation of sediment between cross-profiles 10 and 7 and between 7 and 3, in some cross-sections the bed level increased up to 2.3 m. Downstream of cross-section 3 there is only a minor accumulation. The total volume-change is roughly 12,300 m^3, and the net deposition 11,300 m^3. The sediment load is carried through the watercourse from the confluence to cross-section 10 with only a slight rising of the bottom level. Most of the load is deposited as a delta, as shown by Hasholt (1984), with a foreset zone situated near cross-section 8.

The transport year 1985-86

After the sounding in September 1985, a sand trap (wider and deeper channel) was constructed between section 22 and 23. The changes caused by this operation are clearly seen in fig. 12. The pattern is completely different from the situation the previous year. The total volume change is now roughly 29,000 m^3, but the net deposition only 10,700 m^3. Above the sand trap there is a slight lowering of the bed due to headward erosion. The sand trap is almost filled up. Part of the stretch below the sand trap also exhibits erosion because of the surplus transport capacity after the trap. This sediment is carried down towards the former delta and deposited here. In this way the former delta is able to continue its downstream development in spite of the fact that most of the supplied sediment is caught in the sand trap.

The delta

In 1984 the water depth near cross-section 10 changed 2.5 m within 30 m; this reach was identified as the delta front. In 1985, the front zone moved to a position about 30 m below cross-section 8. A detailed view of the delta front movement is shown in fig. 13. It appears that the front moves about 150-190 m per year, or 0.4-0.5 m/day. Fig. 13 also shows bottomset deposits in front of the delta roughly 300-400 m downstream of the delta front, the amount deposited here is less after the excavation of the sand trap.

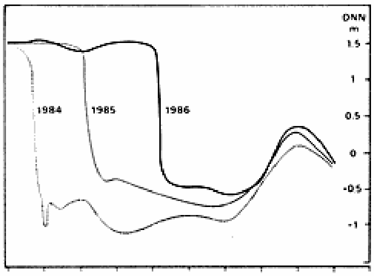

Fig. 13. Length profiles of the delta front (So) in Ribe Å. The location of the delta front is shown in Fig. 1. DNN is the Danish reference level. The benchmark numbers are shown beneath. In this area there are 100 m between each benchmark.

Fig. 13. Længdeprofiler af deltafronten (So) i Ribe Å. Placeringen af deltafronten er vist på Fig. 1. Kantpælenes nummer er angivet forneden på figuren. Der er 100 m mellem kantpælene.

The new sand trap

The trap was established by deepening the river about 2.5 m and widening the cross-profile from some 15 m to 30-40 m. The trap was sounded in 1985 (autumn) and in 1986 (spring), see fig. 12. The net deposition in the trap was roughly 11,000 m^3 with a mean grain diameter of 480 μm nearly the same as the grain size in Gels Å which delivers about 2/3 of the supply.

Comparison between sediment load and deposition

The dry density of deposited material in Ribe Å was determined to approximately 1.7 t/m^3. In order to compare the deposited volumes with the sediment load, the former is converted into tons using this dry density.

The net deposition in 1984-85 was about 19,000 t, and the total transport in Ribe Å (cross-section 31) approximately 13,000 t. In 1985-86 the net deposition was about 18,000 t and the transport about 19,500 t. The discrepancy between deposited and transported material is probably a result of inaccuracy in the soundings of the delta front in 1985. Because of very high water stage and an at that time obliquely developed frontal zone, the accuracy of the measurements was hampered. In order to overcome this inaccuracy of the 1985 soundings, the sum of the transported and deposited material for both periods were calculated to 32,500 t and 37,000 t, respectively. The deviation of less than 15 % between these two figures is considered to be acceptable, and thus to confirm the reliability of the empirical transport-calculations.

SUMMARY AND CONCLUSION

This paper analyzes the amount of sediment (bed load and suspended bed load) transported in the drainage area of Ribe Å in south-west Jutland, Denmark.

The paper comprises: identification and quantification of sediment sources, quantification of the yearly sediment transport through selected cross-sections and quantification of deposited material in the lower part of the investigated drainage area.

The drainage area consists of two main tributaries Gram Å/Fladså (north) and Gels Å (south) running east/west in old outwash plains from the last glaciation (Weichel) bordered with moraine from the second last glaciation (Saale). 16 km upstream of the outlet in the Wadden Sea, these rivers merge into Ribe Å about 5 m above sea level.

The measurements were carried out during the 2 transport years 1984-85 and 1985-86. The size of the run-off in these periods are on both sides of the last 10 years' mean run-off (low in the first and high in the last period). In the following, the mean transport of these two periods are referred to as a measure of the mean transport conditions in the area.

Practically all bed load in Gram Å is trapped in a lake at the town Gram. The delivery of sediment to the main channel from tributaries below Gram is negligible, and the river's sediment supply to Ribe Å of approx. 5900 t is released by erosion downstream of Gram. The bank erosion in this region is estimated to 7800 t primarily based on aerial photos (1964 and 1984). The discrepancy between these two figures is accounted for by an inaccuracy of ± 10 % on the sediment transport and ± 15 % on the erosion estimate. The long-term effect of the detained bed load has caused this river to erode into its base with the result that the lower part (Fladså) is approximately 1 m lower than the adjacent Gels Å near their confluence. This causes net erosion and the down cutting is extended to the lower part of Gels Å.

In Gels Å approximately 3000 t/year originates from smaller tributaries and about 3500 t/year, from the main channel above Gelsbro. From Gelsbro to the confluence with Fladså about 5000 t/year is delivered by bed- and bank erosion.

The total amount of 11,500 t/year supplied to Ribe Å from Gels Å (based on transport at the station in Gels Å, 6500 t/year + the erosion downstream of the station, 5000 t/year) is regarded as relatively accurate. The approximation of the supply from the tributaries has a higher uncertainty because this figure is based on the percentage tributary supply in only two situations. The specific sediment yield (see figs 3 and 4) in these two situations showed an unexpected large variation from sub- basin to sub-basin, which remains unexplained in this investigation.

The analyzed Q/Q_b relations show that at high discharge values the sediment load is lower than expected by the power relations normally used in alluvial rivers. This is interpreted as non-alluvial behavior due to lack of sediment compared with the transport capacity. A semi- logarithmic Q/Q_b-relation described the measured data from such stations fairly well.

The survey of Ribe Å below the confluence of Fladså and Gels Å showed that in 1984-85 the reach was probably in a state of dynamic equilibrium and practically all sediment from above was routed through the reach to the delta in an old sand trap constructed as a deepening of the river some 4-5 km downstream of the confluence.

In 1985 a new sand trap was established approximately 2.5 km downstream of the confluence. This changed the dynamic equilibrium, and erosion occurred upstream as well as downstream of the trap. The erosion upstream of the trap is expected to cease quickly after a new equilibrium is established. Below the new sand trap the watercourse has a surplus transport capacity and therefore scours the bottom. The released sediment is carried forward and deposited in the old sand trap, where the delta continues its migration. This development is expected to continue with a gradually lower and elongated sand body between the new trap and the delta. If the new trap is dredged regularly, the prospective stage of equilibrium for this part of the river, is a deep armored channel with a gentle slope.

The predicted yearly mean supply of sand from the drainage area to Ribe Å is 17,400 t, which is in good agreement with the measured yearly mean deposition upstream the old sand trap of 18,500 t. This indicates the applicability of the used empirical relations between discharge and sediment transport.

The denudation based on this sediment supply amounts to 26 t/km^2/year. The similar figures based on wash load and total suspended load from Bartholdy and Hasholt (1986) is 8 t/km^2/year and 15 t/km^2/year respectively. Thus, the total denudation in Ribe Å's drainage area can be calculated to 34 t/km^2/year of which 23 % is wash load, 21 % suspended bed load and 56 % bed load.

ACKNOWLEDGEMENTS

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Resumé

Aflejring af materiale er konstateret i en række vandløb i det sydvestlige Jylland (Hasholt, 1984). Ribe er beliggende ved et gammelt overgangssted over Ribe Å. I byen er der bygget dæmninger, som har opstemmet vand til mølledrift siden middelalderen. Øst for Ribe findes et lavtliggende eng- og søsystem (indlandsdelta). Den østlige del, Varming Sø, se fig. 2, er efterhånden fyldt op med sediment fra åen, kortet viser, at aflejringsproblemerne har eksisteret i lang tid. For at forhindre tilsandingen af vådområdet, som er fredet, foretages der opgravning af sedimentet ved et sandfang i den tidligere Varming Sø. Det opgravede materiale hæver imidlertid terrænoverfladen og ødelægger dermed den østlige del af vådområdet. Den her beskrevne undersøgelse er iværksat for at vurdere den fremtidige udvikling og finde eventuelle alternative løsninger på tilsandingsproblemet. Som et forsøg på en alternativ løsning er der i 1985 etableret et nyt sandfang ca. 2 km opstrøms det gamle, se fig. 2.

Den nedre del af Ribe Å, som er reguleret, modtager sediment fra to hovedtilløb, Gram Å/Fladså og Gels Å, se fig. 1. I Fladså findes der ved Gram en sø, som opfanger alt bundtransporteret materiale fra det ovenfor liggende opland. Det materiale, som fra Fladså tilføres Ribe Å, stammer derfor fra erosion på strækningen nedenfor Gram, idet åen her kun har få og små tilløb. For Gels Å's vedkommende stammer det tilførte materiale fra en række tilløb og fra selve hovedløbet. En opstemning ved et dambrug nær Gelsbro opsamler det tilførte materiale i perioder med lav vandføring og sender det videre gennem stigbordet ved store vandføringer, transportens fordeling i tid ændres derved.

Sedimenttransportforholdene er undersøgt med anvendelse af flere uafhængige metoder. Erosion er målt ved hjælp af kort og flyfotos i stor skala, resultaterne er kontrolleret ved direkte måling i udvalgte tværprofiler. Materialetransporten i de mindre tilløb er målt kampagnevis ved hjælp af indsamlede vandprøver og bundtransport målt med en prøvetager af trykdifferenstypen.

I Fladså, Gels Å og Ribe Å er sedimenttransporten gennem et tværsnit målt ved hjælp af indsamlede vandprøver og måling af bundformernes vandring; samtidig er vandføringen målt. De sammenhørende målinger af sedimenttransport og vandføring anvendes til etablering af empiriske sammenhænge, således at transporten kan beregnes udfra de dagligt registrerede vandføringsværdier.

Fra sammenløbet af Gels Å og Fladså og til ca. 500 m vest for det gamle sandfang er der etableret et system af kantpæle, som er

indnivelleret i forhold til DNN. Med udgangspunkt i dette system er der foretaget pejlinger af bund og bredder i august 1984, 1985 og 1986. Ved hjælp af disse pejlinger er det muligt at vurdere omsætning og aflejring af sediment i denne del af åen nøjagtigt og dermed også at vurdere mængden af fordelingen af det sediment, som tilføres fra tilløbene.

I Gram Å/Fladså systemet har undersøgelsen vist, at Gram Sø opfanger alt tilført bundmateriale, og at tilførsel fra tilløb nedstrøms Gram sø er negligibel; de ca. 5900 t/år der tilføres Ribe Å fra Gram Å/Fladså stammer således fra ero- sion i vandløb og ånære skrænter nedenfor Gram. I Gelså stammer ca. 3000 t/år fra tilløb, medens ca. 3500 t/år stammer fra hovedløbet opstrøms for Gelsbro. Området neden- for Gelsbro tilfører årligt ca. 5000 t til Ribe Å.

Den beregnede totale tilførsel fra Fladså var 4800 t i 1984-85 og 6900 t i 1985-86. Fra Gelså er den tilsvarende totale tilførsel 5500 t i 1984-85 og 7600 t i 1985-86. Den empiriske sammenhæng mellem vandføring og sedimenttransport i Fladså og Ribe Å viste sig at være semi-logaritmisk. Dette tolkes som et resultat af, at vandløbene ikke er alluviale, således at transporten ved store vandføringer er begrænset som følge af mangel på sediment, vandløbet kan transportere.

Gels Å udviser alluviale træk i hele det interval af transportværdier, som er målt; men en sammenligning med transporten i Ribe Å og Fladså viser, at man også her må regne med, at transporten er begrænset af mangel på sediment ved store vandføringer.

Den specifikke transport i Ribe Å's opland er 34 t/km^2/år fordelt med 23 % som wash load, 21 % som suspenderet bundmateriale og 56 % som bundtransport. Der forekommer ligeledes en stor variation mellem de enkelte deloplande, som ikke umiddelbart kan forklares.

Opmålingerne af den årlige nettoerosion og aflejring nedenfor sammenløbet i perioden 1984-86 (18.500 t) svarer til den målte tilførsel (17.400 t). Dette opfattes som en bekræftelse af de empiriske transportrelationers gyldighed og den hermed forbundne tolkning af vandløbenes ikke- alluviale reaktion.

I perioden 1984-85 sker der overvejende en transport af materiale gennem Ribe Å nedenfor sammenløbet uden at bundforholdene ændres, materialet aflejres som et delta i det gamle sandfang. Dette bekræfter, at åens morfologi på dette tidspunkt er i dynamisk ligevægt med sedimenttransporten. Pejlingen i 1986 viser, at opgravningen af det nye sandfang ændrer ligevægtstilstanden radikalt. Det nye sandfang forårsager erosion såvel opstrøms som nedstrøms for sandfanget. Opstrøms for sandfanget vil der hurtigt blive genskabt en ny ligevægtssituation. Nedenfor sandfanget optager vandløbet materiale svarende til den tiloversblevne transportkapacitet. Dette materiale vandrer nedad og aflejres i det gamle sandfang. Det sandlegeme, der befinder sig mellem det nye sandfang og deltaet, vil derfor, under forudsætning af fortsat opgravning af sand i sandfanget, blive gradvist lavere og længere. Når en ny ligevægt har instillet sig i dette område, vil åen således være blevet dybere med et mindre vandspejlsfald.

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M.B. Nielsen, Sønderjyllands Amt and S.C.K. Svendsen, Ribe Amt, are thanked for interesting discussions of the sediment transport problems. We are thankful to a number of students at the Institute of Geography, University of Copenhagen for their participation in the field work during all kinds of weather. A special thank is due to J. Kisling- Møller and T. Nielsen for tireless levelling and sounding, the former likewise for his participation in the work up of the field data. K. Simonsen, Skalling-Laboratoriet, is thanked for careful analyses of the water and sediment samples. Thanks are also due to J. Jønsson and J. Ulrich for drawing the figures, and to K. Winther for improving the English manuscript.

Resumé

Aflejring af materiale er konstateret i en række vandløb i det sydvestlige Jylland (Hasholt, 1984). Ribe er beliggende ved et gammelt overgangssted over Ribe Å. I byen er der bygget dæmninger, som har opstemmet vand til mølledrift siden middelalderen. Øst for Ribe findes et lavtliggende eng- og søsystem (indlandsdelta). Den østlige del, Varming Sø, se fig. 2, er efterhånden fyldt op med sediment fra åen, kortet viser, at aflejringsproblemerne har eksisteret i lang tid. For at forhindre tilsandingen af vådområdet, som er fredet, foretages der opgravning af sedimentet ved et sandfang i den tidligere Varming Sø. Det opgravede materiale hæver imidlertid terrænoverfladen og ødelægger dermed den østlige del af vådområdet. Den her beskrevne undersøgelse er iværksat for at vurdere den fremtidige udvikling og finde eventuelle alternative løsninger på tilsandingsproblemet. Som et forsøg på en alternativ løsning er der i 1985 etableret et nyt sandfang ca. 2 km opstrøms det gamle, se fig. 2.

Den nedre del af Ribe Å, som er reguleret, modtager sediment fra to hovedtilløb, Gram Å/Fladså og Gels Å, se fig. 1. I Fladså findes der ved Gram en sø, som opfanger alt bundtransporteret materiale fra det ovenfor liggende opland. Det materiale, som fra Fladså tilføres Ribe Å, stammer derfor fra erosion på strækningen nedenfor Gram, idet åen her kun har få og små tilløb. For Gels Å's vedkommende stammer det tilførte materiale fra en række tilløb og fra selve hovedløbet. En opstemning ved et dambrug nær Gelsbro opsamler det tilførte materiale i perioder med lav vandføring og sender det videre gennem stigbordet ved store vandføringer, transportens fordeling i tid ændres derved.

Sedimenttransportforholdene er undersøgt med anvendelse af flere uafhængige metoder. Erosion er målt ved hjælp af kort og flyfotos i stor skala, resultaterne er kontrolleret ved direkte måling i udvalgte tværprofiler. Materialetransporten i de mindre tilløb er målt kampagnevis ved hjælp af indsamlede vandprøver og bundtransport målt med en prøvetager af trykdifferenstypen.

I Fladså, Gels Å og Ribe Å er sedimenttransporten gennem et tværsnit målt ved hjælp af indsamlede vandprøver og måling af bundformernes vandring; samtidig er vandføringen målt. De sammenhørende målinger af sedimenttransport og vandføring anvendes til etablering af empiriske sammenhænge, således at transporten kan beregnes udfra de dagligt registrerede vandføringsværdier.

Fra sammenløbet af Gels Å og Fladså og til ca. 500 m vest for det gamle sandfang er der etableret et system af kantpæle, som er