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Sedimentation of river-transported particles in the Öre estuary, northern Sweden

Louise Malmgren & Lars Brydsten
Department of Physical Geography, University of Umeå, S-901 87 Umeå, Sweden

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Abstract

Sedimentation of river transported particles in the Öre Estuary was studied during spring flow (April–May, 1989). River input was calculated as the product of discharge and particle concentration in the river water. The concentration of suspended matter in the estuary water was determined with a light-scattering probe at 25 depth profiles throughout the estuary. The sedimentation was measured using sediment traps on 5 stations along a line from the river mouth to the mouth of the estuary. Sampling was carried out on four dates with different water discharge.

The extension of the particle plume varied during the observation period mainly due to variation in river discharge. The maximum extension of the river plume occurred during the peak of the spring flow and covered approximately 70% of the estuary area. The sedimentation rates were generally high and the average retention time for a particle in the water column was less than 1 day which verifies that the river transported fine-grained particles are primary deposited within the estuary. The major part of the river input of suspended matter was deposited near the river mouth. There was a surplus of the total sedimentation compared to the river input which was due to wave-induced resuspension, especially in the eastern part of the estuary.

Introduction

The estuarine sediment dynamics are affected by river inflow, tides, waves, wind, and meteorological forces. To understand these forces, it is necessary to examine the independent influence of each factor and then the combined effect of interacting factors expressed as specific mechanisms (Nichols & Biggs, 1985). This study treats the effects of river inflow of suspended matter to the Öre Estuary, situated in the northern part of the Bothnian Sea (Fig. 1a). In this region, the major part of the annual inflow of suspended matter from the river to the estuary is concentrated into a short period associated with the spring flow. During the spring, the storm frequency is low and as a consequence there are few resuspension events due to wind-driven current or wave action. This means that the river input is the dominating source of the suspended matter in the estuary. The estuarine water circulation driven by salinity differences is weak due to low salinity in the Bothnian Sea (3–5‰), and there are not tides, so the extension of the river particle plume is mainly a function of the river power.

The river input of suspended matter is either permanently accumulated within the estuary or transported to the open sea. Particles are either passing through the estuary in suspension or are primary deposited within the estuary and trans-

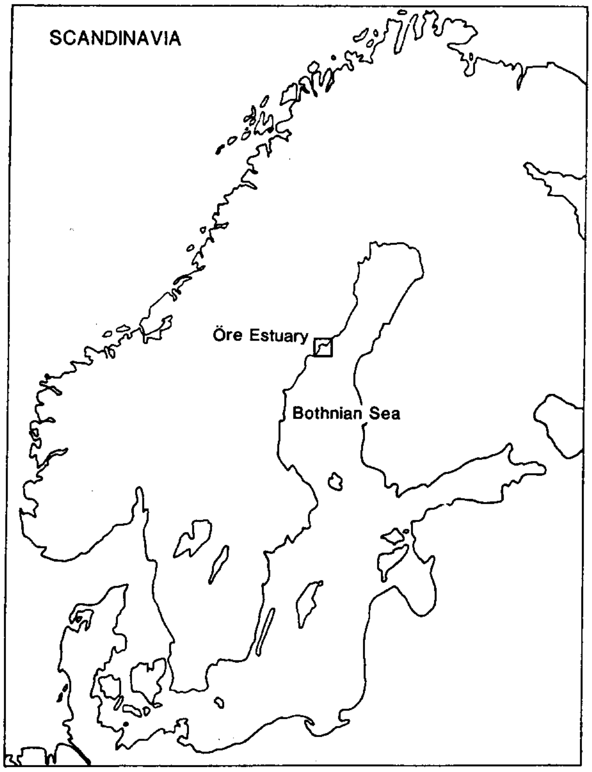

Fig. 1. (a) The location of the investigated area, Öre Estuary, situated in the northern part of Bothnian Sea.

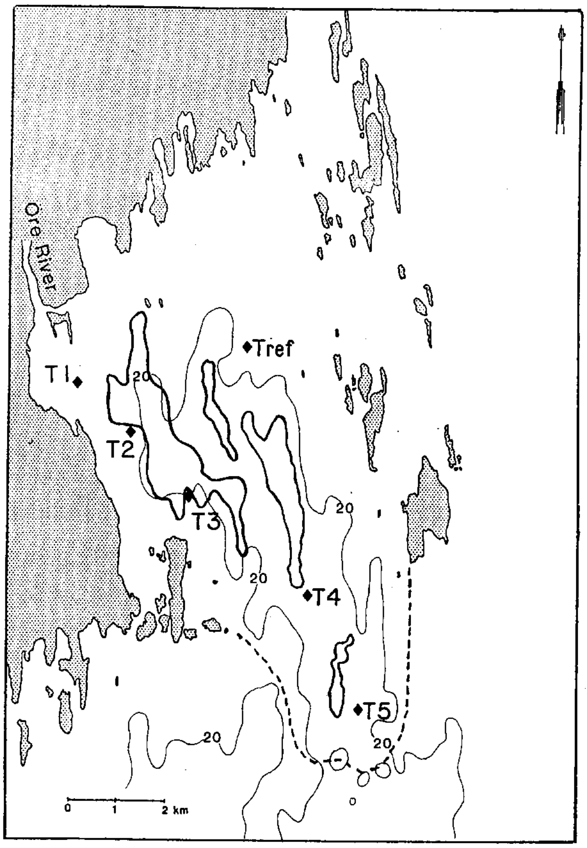

Fig. 1. (b) The morphometry, the locations of the sediment traps and the distribution of fine-grained bottoms within the Öre Estuary. The dashed line show the limit which define the estuary from the sea.

ported out of the estuary in repeated resuspension-redeposition cycles.

Earlier studies of the sediment dynamics in the Öre Estuary (Brydsten & Jansson, 1989) used 137-Cs from the Tjernobyl accident as a tracer. Brydsten & Jansson (1989) showed that during the spring flow 1986, the entire river input of suspended matter was primarily deposited within the estuary and that the internal sediment dynamics, i.e. resuspension – redistribution, within the estuary were much more intense compared to the rates of input and output of particles. If this is a general phenomenon for wind-dominated estuaries, resuspension is necessary for all transport of particles from the estuary towards the open sea.

The aim of this study was to determine the dynamic and behaviour of the suspended particles carried to the Öre Estuary by the river during the spring flow 1989 and to examine the independent effects of the river inflow compared to wind/wave action on the general sediment dynamics.

Study area

The Öre Estuary is partly isolated from the outer sea by a rich archipelago (Fig. 1b). The length of the boundary between the estuary and the open sea is relatively large at the water surface but in deeper water levels (> 20 m) the outlet is narrow. The total area of the estuary is approximately 50 km^2 and the total volume is 1.0 10^9 m^3. The mean depth is 16.4 m.

The main part of suspended particle input to the Öre Estuary is from the Öre River. The mean runoff in the Öre River is 35 m^3 s^{-1} and the annual runoff maximum varies between 200–500 m^3 s^{-1}. The Öre Estuary is dominated by transport bottoms, i.e. bottoms with discontinuous deposition of fine-grained particles (Forsgren *et al.*, unpublished). Erosional bottoms only exist in shallow near-shore areas while accumulation bottoms are found in smaller locations in the deeper parts of the estuary. Extensive areas with accumulation bottoms exist on bottoms with water depths exceeding approximately 65 m, i.e. not within the estuary. Transport bottoms exist in two types; one type where patches with fine-grained sediments are mixed with patches with gravel and stones and one type with solely fine-grained sediments. The solely fine-grained sediment bottoms are situated in the deepest parts of sub-basins within the estuary and are surrounded by the transport bottoms with only patches of fine-grained sediments. Only the general distribution of fine-grained bottoms are illustrated in Fig. 1b which includes the both types of transport bottoms.

Experimental details

The river input of suspended matter, the distribution of suspended matter in the estuary and the net sedimentation rate in the estuary was measured during the spring flow period in May 1989. River input was calculated as the product of the discharge and the particle concentration in the river water. Data of daily river discharge were utilized from a stage recorder situated 25 km upstream of the river mouth and were obtained from the Swedish Meteorological and Hydrological Institute. River water samples were taken at 5 dates: 2, 7, 13, 20 and 29 of May. The particle concentration was determined by weighing of material collected on filters (Whatman GF/C-filter). The particle concentrations between sampling dates were estimated by linear interpolation.

The concentration of suspended matter in the estuary water was determined with a light-scattering probe at 25 depth profiles during 4 dates with different water discharge (3, 11, 18 and 29 May). The light-scattering probe and probes for measuring temperature, conductivity and water depth were connected to a data-logger for rapid processing and storing of data. The light-scattering probe was adjusted to zero in distilled and oxygen-free water. The calibration of the probe was performed from simultaneous water sampling and *in-situ* light-scattering measurements in the estuary. The relationship between light-scattering and particle concentration was obtained from a graph where light-scattering was plotted against particle concentration, measured by weighing material collected on glass fibre filter (Whatman GF/C). The linear relationship between light-scattering and concentration of suspended matter has a standard error of estimation of $0.11\ \mathrm{mg\,l^{-1}}$ (Fig. 2).

At each station the sond was slowly submerged down to the bottom. A typical profile gave three values of suspended matter, temperature and salinity per meter water depth. The concentration of suspended matter has been used for calculation of the total amount of suspended matter in the river plume. Each of the 25 stations represents a sub-area of the estuary. The total quantity of suspended matter in each sub-area was calculated by following equation:

$$\text{Total quantity} = \text{Sum}\,[C_i * (d_{i-1} - d_i)] * Td^{-1} * Sa \qquad (1)$$

where

C_i = Particle concentration at d_i; d_i = Depth at level i; Td = Depth of the particle plume; Sa = Total representative area of station

The total quantity of suspended matter at four dates in the estuary was calculated by summarizing the quantities in each sub-area. The net sedimentation rate was calculated by use of sediment traps. Five sets of sediment traps was placed out along a line from the river mouth to the mouth of the estuary, along the expected extension of the river plume (T1–T5 in Fig. 1b). A reference trap (Tref in Fig. 1b) was placed outside the area expected to be unaffected by the river plume.

The sediment traps were put out on May 3 and drained at three dates (11, 18 and 29 May). The sediment traps were placed at two depths, one near to the water surface and one near the bottom. The surface traps were placed immediately be-

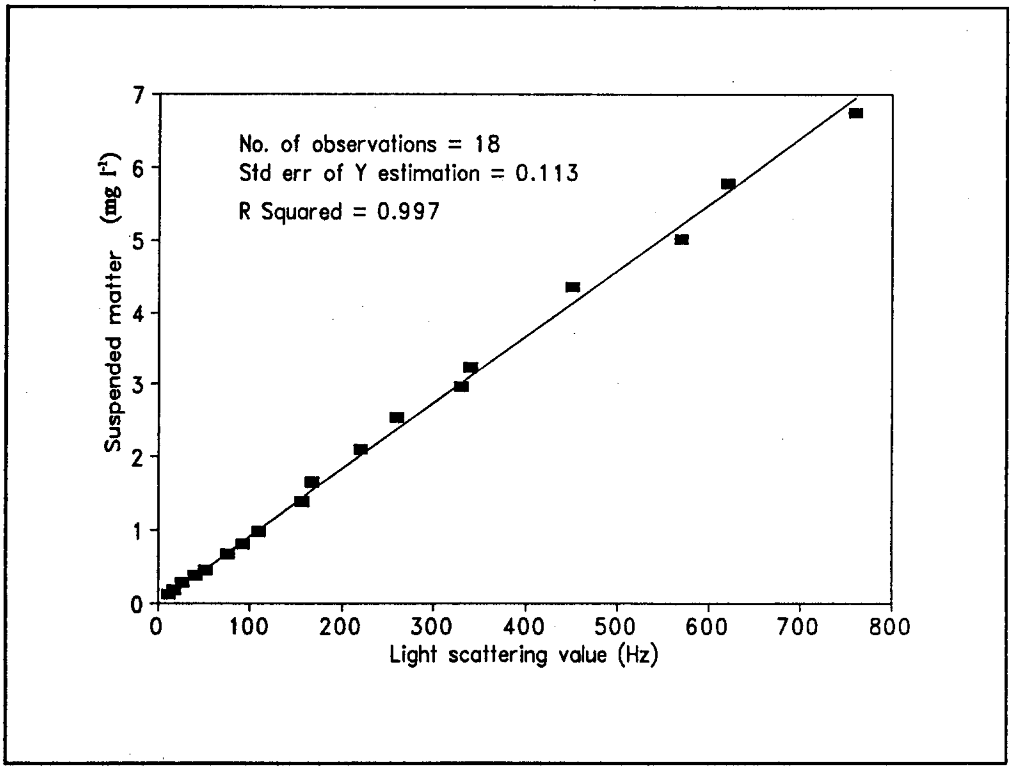

Fig. 2. The linear relationship between light-scattering value and particle concentration, measured by weighing material collected on filter.

neath the level of the halocline on May 3, and were expected to catch the primary sedimentating particles from the river plume. The levels of the surface traps varied between 4–9 m beneath the water surface. The bottom trans were placed approximately 4 m above the bottom. At station one (Fig. 1b), only one sediment trap was placed out, due to the shallow water depth. It was in function only during the two last periods. During the first period, the net sedimentation rate at station one was estimated using the particle content in the water column and the relationship between net sedimentation rates for station one and two during the second and third periods.

The trap samples were centrifuged and dried at 105 °C for 24 h and the total amount of trap yield was determining as dry weight. The total sedimentation rate was calculated by multiplying the sedimentation rates per unit area with the areas of the sub-regions.

Weather data were obtained from the lighthouse Sydostbrotten, situated 10 km southeast of the Öre Estuary, and from the Norrbyn Laboratory, situated in the northern part of the estuary.

Results

It was low wind speeds during the whole investigation period. The wind conditions were associated with the sea breeze, in this area winds from south with the highest speed during mid day. The mean wind speed during the whole period was approximately 4 m s^{-1} and the maximum wind speed was 9 m s^{-1}.

The total river input of suspended matter to the estuary during the study period (May 3–May 31) was approximately 18 000 tonnes. The maximum daily river input occurred on May 4 and reached 2200 tonnes while the maximum river water discharge (300 m^3 s^{-1}) occurred on May 2 (Fig. 3). The mean water discharge during measuring pe-

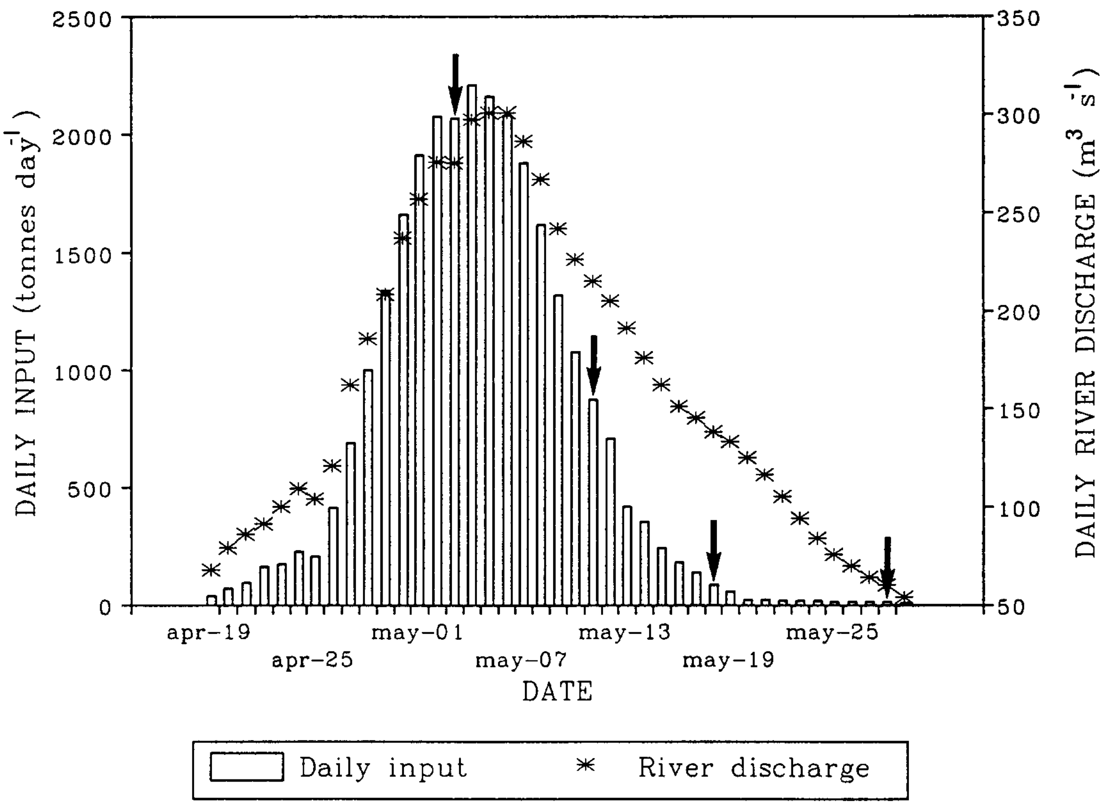

Fig. 3. Daily river input to the Öre Estuary given in tonnes and the daily river discharge from April 19 to May 30. The arrows indicate the four measuring dates when the plume extension was determined.

riod was about 160 $m^3 s^{-1}$. The measurement of the hydrography shows that the estuary is of a salt wedge type where fresh water is spread out on top of brackish water. A brackish bottom layer exist approximately 1 km upstream the river mouth. At the first measurement date (May 3) the bulk of suspended particles was found within the river plume. High concentrations of suspended matter occurred in a thin surface water layer (2–3 m) with a sharp gradient against the deeper water with background values. The salinity has a similar vertical gradient. The depth of the halocline decreased from approximately 3 m near the river mouth to 1 m near the estuary mouth (Fig. 4). No significant increase in particle concentration in near-bottom water was observed, so no turbidity maximum existed.

A great variation in the extension of the particle plume was observed. The greatest extension of the plume (at 0.5 m water depth) was observed on May 4 (Fig. 5), simultaneously with the maximum river discharge and the river input of suspended matter. The tongue-shaped plume then covered approximately 70% of the estuary area and stretched about 10 km from the river mouth with continuously decreasing particle concentration towards the estuary mouth. Outside the estuary the particle concentration was at background level (<0.1 mg l^{-1}) which means that the particle plume never reached beyond the estuary mouth.

As the river discharge and river input of suspended matter decreased, both the horizontal and vertical extension of the particle plume decreased to a similar degree. During periods with winds from the south the estuary is affected by waves generated in the Bothnian Sea and by wind-driven current. This occurred approximately four times during the study period. The surficial wind-driven current is contradictory and stronger than the current driven by the river power. At such con-

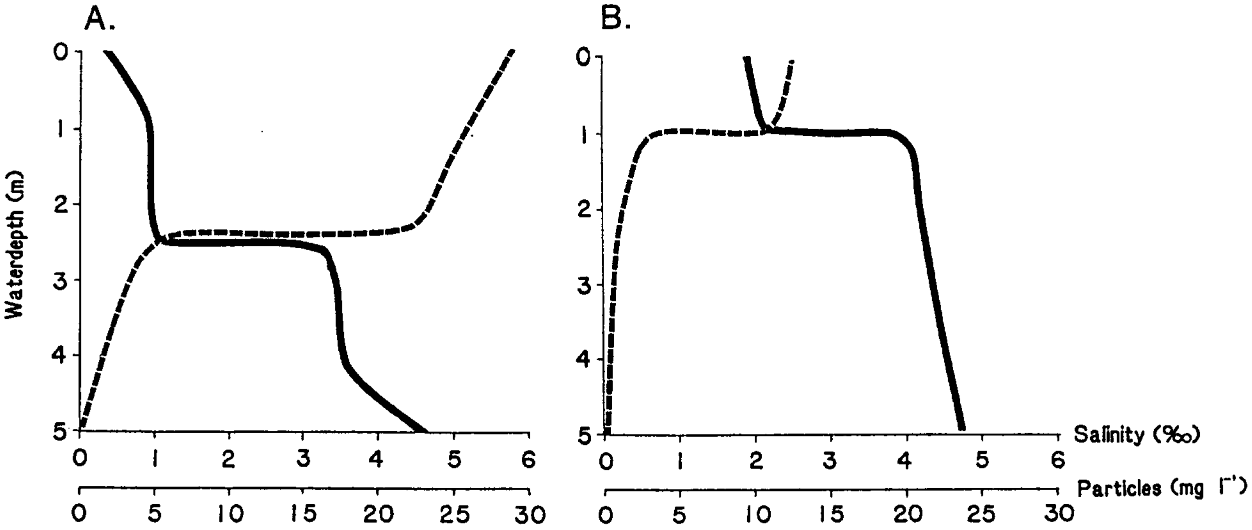

Fig. 4. The vertical gradient which show the depth of the clines for salinity (straight line) and particle concentration (dashed line) at two station; one near the river mouth (a) and one near the estuary mouth (b).

ditions, the halocline and particle cline were broken and the particle plume was dispersed with deeper water with low particle concentrations. This was observed throughout the freshwater plume. The water above the 'wave base', i.e. the 'critical' water depth where the waves affect the bedload, then showed a low homogenous particle concentration. At the same time the horizontal transport of suspended matter due to river power decreased and the river input became distributed in a comparatively thick layer near the river mouth with a horizontal distribution of only approximately 20 percent of the former extension.

The relationship between concentration of suspended matter and salinity is shown in Fig. 6. The dashed line is the theoretical relationship when the river water (0‰ salinity and 30 mg l^{-1} particle concentration) is diluted with estuarine water (4–5‰ salinity and < 0.1 mg l^{-1} particle concentration) and the straight line is the empirical relationship based on data from May 3. The difference between the relationships is due to sedimentation. Sedimentation occurred in water with a salinity lower then 4.5‰, which only exists within the estuary.

Figure 7 shows the total amount of suspended matter in the river plume and the mean daily river input of suspended matter for the four measurement dates. The suspended matter in the plume depends not only on the river suspended matter input of the same day but also of all previous days in the period. Due to that statement the mean daily river input is based on the mean age of the water in the plume. This was estimated by divided the area of the river plume at a mean depth of the particle cline with the river discharge during the four measuring dates. That gives a mean age of fresh water in the plume of 4 days on May 3, 2 days on May 11, 0.4 days on May 18 and 0.5 days on May 29. The input of suspended matter before each sampling date was calculated for a period which length corresponds to the mean age of water in the plume. By comparing this mean daily input of particles with the amounts of particles found in the plume it is possible to achieve an approximate measure of the retention time of particles within the plume. The total amount of suspended matter in the river plume is, on all measurement dates except on May 29, lower than the mean daily river input to the estuary, which means that the mean retention time for particles in the river plume is less than one day.

The sedimentation rates (g day^{-1} m^{-2}) estimated from the sediment trap yields are presented in Table 1. A general decrease in sedimentation rates (based on near-surface traps) occurs with

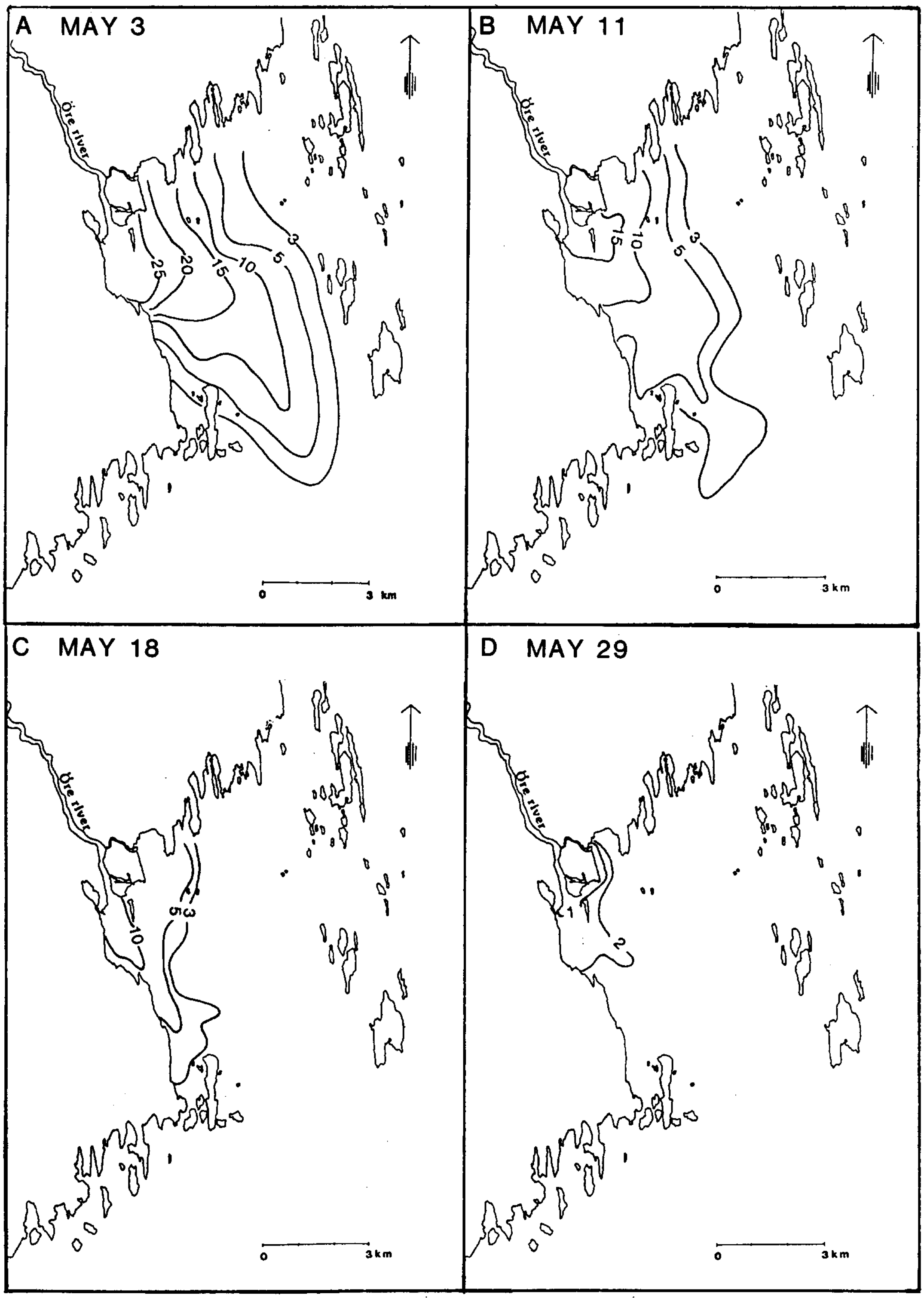

Fig. 5. The extension of the particle plume in the Öre Estuary at a water depth of 0.5 m during four dates (A–D). The concentration of suspended matter are given in mg l^{-1}.

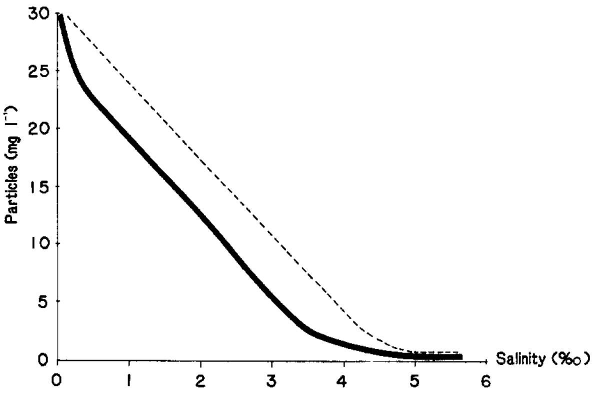

Fig. 6. The empirical relationship between concentration of suspended matter and the salinity, based on data from May 3 (straight line). The dashed line is a theoretical relationship when river water is diluted with estuarine water.

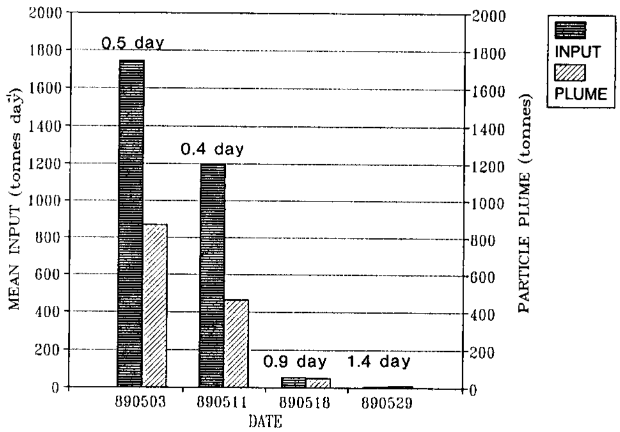

Fig. 7. The quantity of suspended matter in the plume in the Öre Estuary in relation to the mean daily river input for the four measurement dates. The mean residence time for a particle within the estuary are stated above the bars.

time and in a direction towards the estuary mouth. During the first measurement period the yield in the bottom traps and the surface traps are approximately the same at each station, which means that the effect of resuspension on the sediment rate is insignificant. On the other hand, during the second and third periods a higher yield in the bottom traps occurred at stations 4, 5 and at the reference station, despite that the concentration of suspended matter in the water column was near the background value in the beginning and in the end of the measurement periods.

The gross and net sedimentation and the river input of suspended matter for the three measurements periods are presented in Table 2. The short retention time of particles in the plume (see above) makes a direct comparison between input and trap yield possible for the different periods. The calculations of the total net sedimentation are based on the yields in the surface traps while the gross sedimentation are based on the bottom trap yields. During the first period there is a similarity between river input and both gross and net sedimentation, which means that no resuspension occurred and that the major part of the river input was primary deposited within the estuary. During the second and third periods both the net and the gross sedimentation exceed the river input.

The spatial and time distribution of net sedimentation are also shown in Table 2. Approximately 60% of the total net sedimentation oc-

Table 1. Sedimentation rates (g m^{-2} day^{-1}) calculated from the yield in sediment traps

Period	Trap position	Station					
		T1	T2	T3	T4	T5	TREF
May 3–11	Surface	185	112	48	52	16	25
	Bottom	–	96	40	31	16	21
May 11–18	Surface	79	26	13	43	10	16
	Bottom	–	11	15	140	11	32
May 18–29	Surface	49	17	16	14	9	13
	Bottom	–	15	14	33	15	14

Table 2. Total river input of suspended matter (tonnes period^{-1}) and calculated net and gross sedimentation (tonnes period^{-1}) in representative sub-areas. Net sedimentation calculations are based on yield in surface traps while gross sedimentation are based on yield in bottom traps

Station	May 3–11		May 11–18		May 18–29		Total	
River	14000		2900		300		17,200	
	Net	Gross	Net	Gross	Net	Gross	Net	Gross
T1	4,272	4,272	1,140	1,140	837	837	6,249	6,249
T2	3,420	3,040	880	396	513	444	4,813	3,880
T3	2,040	1,530	690	690	731	580	3,461	2,800
T4	2,600	1,300	2,275	7,150	751	1,755	5,626	10,205
T5	532	468	496	558	443	744	1,371	1,770
TREF	1,460	1,241	858	1,650	825	924	3,143	3,815
Total	14,224	11,851	6,339	11,584	4,100	5,284	24,663	28,719

curred near the river mouth (Stations 1, 2 and 3) while the outer region of the estuary only received approximately 5% of the total river input during the measurement period.

Discussion

The results obtained in this study demonstrate that river transported fine-grained particles are primary deposited within the estuary. This is verified by the fact that the maximal extension of the river particle plume do not exceed the estuary limit and that the total net sedimentation within the estuary is the same as the total river input of suspended matter. This is also what could be expected because the distribution of the river input in the estuary is mainly affected by the river power and the river discharge is low compared to the total water volume in the estuary, i.e. a high effective volumetric capacity.

Figure 7 clearly shows that the mean resident time for particles in suspension is short, but when the river action are reduced the resident time increased. In addition the retention time of the water in the plume decreased with time due to the reduced river discharge which result in a thin, limited plume. The short mean resident time for particles in suspension give consequently the main part of the river input of suspended matter deposited near the river mouth (Table 2).

During the first measurement period the calculated net sedimentation is approximately the same as the calculated gross sedimentation, which means that significant resuspensions have not occurred. Consequently, during the first period, the total net sedimentation is approximately equal to the total river input of suspended matter. During the second and third periods, both the total net and total gross sedimentation exceeds the total river input of suspended matter (Table 2). The difference is mainly due to the high amount of material deposited in the eastern part of the estuary (especially station 4), despite that the particle plume not affected this part of the estuary during these periods. Table 1 shows that the yield in the bottom traps are higher compared to the surface traps in this area, which means that resuspension has occurred. If the calculation of total net sedimentation only includes the influence area of the particle plume (Fig. 2, May 11–18 and May 18–29), the total net sedimentation equals the total river input of suspended matter. This means that the differences between total sedimentation and total river input of suspended matter is mainly due to resuspension in the eastern part of the estuary and that the western part of the estuary is not affected by resuspension.

The eastern part of the estuary is more exposed to waves generated in the southern Bothnian Sea compared to the western part of the estuary, which means that during these conditions the resuspension processes are stronger in the eastern part of the estuary (Brydsten, 1991).

Table 3. Chemical composition of suspended matter in the Öre River, material collected i sediment traps in the Öre Estuary and surficial sediments in the Öre Estuary on May 11–18. (R = suspended material, T_S = material collected in surface trap, T_B = material collected in bottom traps, and S = surficial sediment)

Station	Fe (mg g^{-1})		P (mg g^{-1})					
	R	T_S	T_B	S	R	T_S	T_B	S
2	38	37	22	55	1.2	0.88	0.54	1.7
4	27	30	56	57	1.1	1.65	1.75	1.8

The material collected in the traps in the eastern part of the estuary (Stations 4,5 and the reference trap) also have a different chemical composition compared to the traps in the western part (Stations 1,2 and 3). Table 3 shows the concentrations of phosphorus, iron and carbon for surficial sediment, material collected in the traps and suspended particles in the river plume (data from Forsgren & Jansson, 1991). There was similar concentrations of these elements in the surficial sediment and the material collected in the traps for the eastern part of the estuary during the second and third periods, while significant differences were found in the western part. On the other hand, it was a similarity between the chemical composition in the suspended matter in the river plume and the material collected in bottom traps in the western part of the estuary. This means that the major part of the material collected in the eastern bottom traps are derived from the local bottom sediment, while the major part of the material collected in the western traps, are derived from the river input of suspended matter, i.e., the eastern part of the estuary was to a higher degree affected by resuspension.

The gross sedimentation is affected by both the net sedimentation and resuspension so the part of the gross sedimentation that is caused by resuspension, reaches at least the gross sedimentation minus the river input, i.e. approximately 10000 tonnes or approximately 35% of the gross sedimentation.

The total net sediments should not exceed the river input unless the resuspended material also are affecting the near-surface water layers. Studies of wave-induced resuspensions in the area (Brydsten, 1991) has shown that significant amounts of resuspended matter might be transported from the bottom to near-surface water layers by wind-driven current. This is also verified by the chemical composition of material collected in traps at station 4, where the concentrations of phosphorus, iron and carbon are the same in the surface and the bottom trap (Table 3). This means that the net sedimentation based on surface trap yields is overestimated, and the discrepancy between total river input of suspended matter and total net sedimentation (approximately 6500 tonnes) was due to resuspension.

Conclusions

The spring flow in Öre River carries a dominant share of the loading of fine-grained particles to the Öre Estuary. The entire river input of suspended matter is largely deposited within the estuary with most deposited near the river mouth.

The total gross sedimentation exceeds the total river input of suspended matter by approximately 35%. This was found take due to wave-induced resuspension.

Resuspension is necessary for the transport of fine grained particles from the estuary to the open sea.

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