A Fine-grained Sediment Budget for a small Tidal Area, Königshafen, Sylt, Germany

Michael Larsen, Morten Pejrup & Karen Edelvang

Abstract

A net budget for fine-grained sediment (<63 μm) has been computed for the Königshafen tidal area; a small tidal bay covering an area of some 4 km^2, located in the Wadden Sea at the north-eastern end of Sylt. The net budget for fine-grained sediment has been separated into the following sediment sources: (1) Supply from the North Sea, (2) Salt marsh erosion, (3) biological primary production and (4) atmospheric deposition. The total net accumulation within the area has been calculated by geomorphological mapping combined with estimates of fine-grained accumulation rates determined from ^{210}Pb core dating. The net accumulation was calculated to 1400 t/y based on ^{210}Pb dating. The salt marsh erosion is measured to supply 16% of this sediment, and from literature studies primary production and atmospheric deposition are estimated to supply 7% and 1%, respectively. The remaining 76 % between the three above mentioned sediment sources and the total net accumulation originates from the North Sea and from fluvial input to the adjacent tidal area. A minimum of 70 % of the total supply of fine-grained sediment accumulated in Königshafen originates from the North Sea. It is shown that on a yearly basis an average of 0.5 g/m^3 is filtered out of the water exchanged between Königshafen and the North Sea. Although this is a small quantity compared to other tidal areas, the trapping efficiency is shown to be relatively high compared to other areas. It is suggested that this difference may be explained by the influence of benthic organisms on the aggregation of fine-grained suspended sediment.

Keywords

^{210}Pb dating, fine-grained sediment, sediment budget, salt marsh erosion, turbidity, trapping efficiency.

Michael Larsen, Morten Pejrup & Karen Edelvang: Institute of Geography, University of Copenhagen, Øster Voldgade 10, 1350 Copenhagen K., Denmark.

Danish Journal of Geography 96: 1-10, 1996.

Normally, the concentration of fine-grained sediment suspended in the Wadden Sea region increases from the North Sea through the tidal inlets reaching a maximum in the inner part of the tidal area. Typical concentrations of fine-grained suspended sediment in the North Sea are 0-2 mg/l (Eisma 1981), in the tidal inlets of the Wadden Sea about 10 mg/l (Postma 1981), and in the inner parts of the Wadden sea 50-600 mg/l (Pejrup 1980; de Haas & Eisma 1993). This longitudinal distribution of concentrations may indicate that the fine-grained suspended sediment in the inner part of the Wadden Sea originates from sediment sources within the area. However, Bartholdy & Madsen (1985) found that 85% of the fine-grained sediment deposited in the Grådyb tidal area comes from the North Sea.

Accumulation of cohesive sediment in estuarine environments is influenced by a number of different processes. Van Straaten & Kuenen (1957, 1958), and Postma (1967) showed that fine-grained sediment was concentrated in the inner parts of the Wadden Sea because of the settling- and scour-lag processes creating a turbidity maximum. The amount of suspended sediment settling from the turbidity maximum on the tidal flats and on the salt marshes depends on the trapping efficiency of the area and the amount of sediment available. Trapping efficiency is influenced by the in situ settling velocities of the suspended sediment. Settling velocities in estuaries are increased by salt flocculation of the cohesive sediment (Edzwald & O'Melia 1975; Kranck 1975 and 1981; Owen 1977; Krone 1978; van Leussen 1988; Pejrup 1988 and 1991), and by benthic organisms as mussels and snails producing faecal pellets of the fine-grained suspended sediment (Haven & Morales-Alamo 1968; Briggs & Howell 1984; Edelvang 1996; Edelvang & Austen submitted). On the salt marsh, vegetation plays an important role in the process of retaining fine-grained sediment during inundation periods (Pethick 1984; Frey & Basan 1978).

Based on morphological mapping, ^{210}Pb core dating, and grain size analysis, this paper presents a net budget for fine-grained sediment from a small tidal bay with low concentrations of suspended sediment but relatively high accumulation rates of fine-grained sediment.

Study Area

The island of Sylt is situated in the northern part of the Wadden Sea. Königshafen is a small tide-influenced bay located at the northern end of Sylt (fig.1). The morphology of the area as it appears today was formed from the middle of the 17th century to the end of the 18th, according to old maps and geological findings (Bayerl & Higelke, 1994).

Figure 2 shows the geomorphology of the bay. To the west and north it is protected from the North Sea and the prevailing westerly winds by sand dunes. To the south it is protected by the core of the island, making it exposed only to the east. The tide in the area is semi-diurnal with a mean tidal range of 1.8 m. The total area potentially influenced by the tide is approximately 4 km^2, of which the sandy tidal flats cover 2.9 km^2, and muddy tidal flats and tidal channels 0.2 km^2 each. The supratidal salt marsh areas cover the remaining 0.7 km^2.

The surface sediments in Königshafen are described by Austen I., (1994). She found that the sandy tidal flats contain less than 10% of fine-grained sediment and that the muddy tidal flats contain 10 - 50% fine-grained sediment. The salt marsh contains 93 - 95% fine-grained sediment.

Methods

^{210}*Pb Core Dating*

The net accumulation of fine-grained sediment can be determined by using the ^{210}Pb dating technique validated on fine-grained sediment by e.g. Madsen & Sørensen (1979). This dating method has been used in earlier studies on the accumulation of fine-grained sediment in the Grådyb tidal area (e. g. Madsen 1981; Bartholdy & Madsen 1985).

Along the profile-line in figure 2, three sediment cores were collected. On the salt marsh two sediment cores were taken. One core was taken close to mean high tide level, and another was taken at a slightly higher level in the

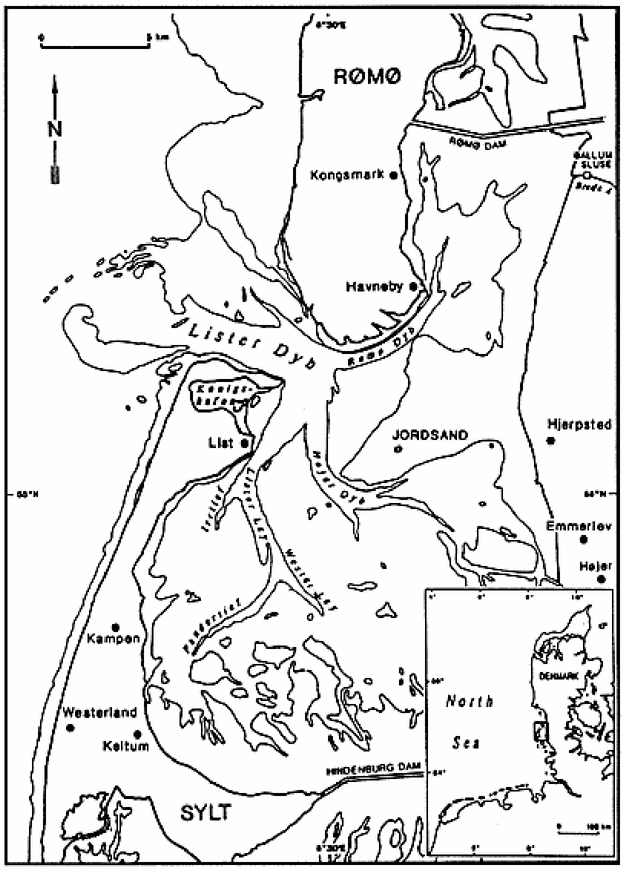

Figure 1: Map of the investigation area. Königshafen is located at the northern end of Sylt.

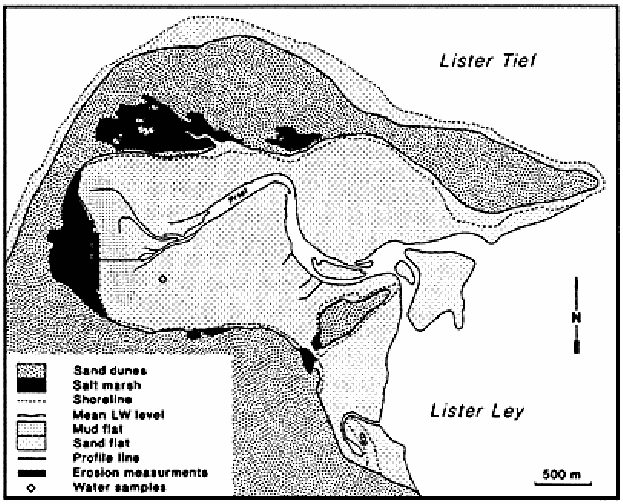

Figure 2: Geomorphological map of Königshafen (after Pejrup & Bartholdy, (1991)).

Figure 3: Sampling of a sediment core on the tidal flat (photo M. Larsen).

central part of the salt marsh. To avoid compaction, these cores were cut out of the side of a hole digged in the salt marsh. The core on the tidal mud flat was taken by penetrating an aluminium tube into the sediment (figure 3). Before pulling out the tube, it was filled with water and sealed with an expandable rubber plug. The plug creates a vacuum within the tube thus enabling it to be pulled out leaving the sediment almost undisturbed inside the tube.

The cores from the salt marsh were 30-40 cm long, which is about the maximum depth possible for ^{210}Pb-dating with an average deposition rate of 1-2 mm/year. The core from the tidal mud flat was 68 cm long with a compaction of 4 cm. By averaging the compaction throughout the whole core each cm represents 72/68 cm = 1.06 cm, which makes the error made by the compaction insignificant.

The three cores were divided vertically into equal halves. Each half was cut horizontally into 1 cm pieces. One half was archived for grain-size analyses. The activity of ^{210}Pb was measured on selected subsamples from the other half. ^{210}Pb is a natural, radioactive isotope. The content of ^{210}Pb in the sediment can be divided into two different parts; supported and unsupported ^{210}Pb. Both parts originate from the decay of ^{226}Ra, which is a natural component of the sediment. The supported ^{210}Pb originates from the decay of ^{226}Ra within the sediment. The unsupported ^{210}Pb originates from the decay of the gas ^{222}Rn, which is a daughter isotope of ^{226}Ra emitted from the continental crust. The unsupported ^{210}Pb is washed out of the atmosphere with precipitation. When introduced into the marine environment it adheres to the surface of cohesive sediment particles. When the sediment is deposited, further adhesion of ^{210}Pb stops. The age of different levels in the sediment can then be calculated by measuring the vertical activity profile of the unsupported ^{210}Pb, knowing the half-life of ^{210}Pb to be 22.3 years. The background activity of the supported ^{210}Pb was determined by measuring the activity deep in the core, where the unsupported ^{210}Pb had decayed totally.

To calculate the age of different levels in the cores, the constant rate of supply method (C.R.S.) was used. This method assumes that the flux of unsupported ^{210}Pb is constant in time. Even in cases where this condition is not strictly fulfilled, the C.R.S. method can be used (e.g. Appleby & Oldfield 1978; Madsen & Sørensen 1979; and El-Daoushy 1988). This is because mixing caused by physical and biological processes causes differences in the upper part of the sediment core to be levelled out as the contributions from several years are mixed before the vertical profile of the ^{210}Pb is established beneath the mixing layer.

Sediment Analyses

Subsamples from the second half of the core were used for grain-size analyses. The samples were divided into two fractions by wet-sieving the sediment through a 63 μm sieve. The fraction ≥63 μm was weighed and sieved at ¼ Φ intervals.

The fine fraction (< 63 μm) was suspended in 0.002 M $Na_4P_2O_7$ and stirred for 2 minutes with ultrasound. The grain-size analysis was carried out by the use of a Sedigraph Model 5100. The Sedigraph calculates the fine fraction of the sediment in equivalent Stoke diameters. The sediment is suspended in a sedimentation cell and the dampening of a soft X-ray beam is measured during sedimentation.

Measurement of Salt Marsh Erosion

Erosion of the salt marsh was measured by use of two different methods. One was to establish iron sticks in the erosional salt marsh cliff. Five iron sticks were established in Königshafen along a representative part of the erosional salt marsh. The measuring site is marked in figure 2.

The iron sticks are 1 m long with a diameter of 12 mm. They were initially driven 0.9 m into the salt marsh cliff. In this way, the erosion of the cliff could be surveyed directly by measuring the length of the stick exposed by erosion. Measurements were carried out every 2-3 months throughout the year. The average height of the salt marsh cliff was determined, and the total erosion was computed by multiplying the length of the representative cliff, the height of the cliff, the erosion measured by the iron sticks, and the dry bulk density of the salt marsh sediment. The bulk density of the salt marsh was determined by taking an undisturbed sediment sample of 100 cm^3 with an aluminum ring at the same site as the erosion measurements were carried out.

The other method for measuring cliff erosion was to survey the edge of the salt marsh at the measuring site with a theodolite Topcon BS 3. This theodolite uses infrared light to measure the horizontal distance between the optic and a reflector. The reflector was placed at points along the edge of the salt marsh. The distance between two points was at the most 1 m. The edge-lines from 1992, 1993 and 1994 are shown in figure 6. The area between the lines was measured, and the erosion volume between two measurements could be calculated when knowing the average height, length, and dry bulk density of the cliff.

Results

Net Accumulation

The dating of different levels in the cores is shown in figure 4a-c, and the vertical distribution of sand, silt, and clay in the profiles is shown in figure 5a-c. These figures are based on results from Pejrup & Bartholdy (1991). Figure 5c shows a marked break in the grain-size distribution between 12 and 15 cm, the age of this layer is dated back to 1870 ± 68 years. This is approximately the age of the formation of the present Königshafen (Bayerl & Higelke 1994).

The total accumulation rate shown in table 1 refers to all grain-size fractions and includes organic matter as well. The average accumulation rate (mm/y) corresponds to the linear deposition rate in the top layer (0-1 cm) computed

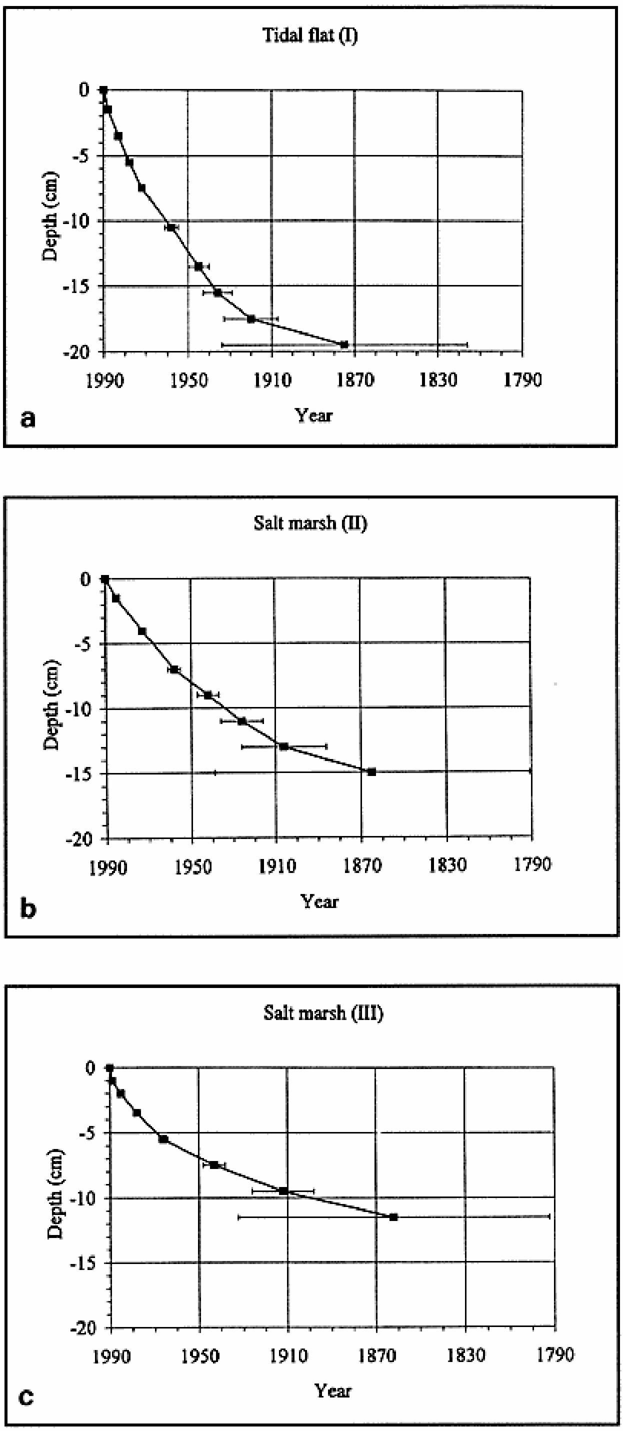

Figure 4 a-c: ^{210}Pb dating profiles of the sediment cores. Error bars indicate 68 % prediction interval. a: Profile from the mud tidal flat. b: Profile from the salt marsh close to the mean high tide level. c: Profile from the central part of the salt marsh. (Modified after Pejrup and Bartholdy (1991)).

from the bulk density at this level. The mixing depth is the thickness of the top layer that is regularly mixed, either due to resuspension caused by wave activity or mixing caused by animals living in the sediment. By dividing the mixing depth with the linear accumulation rate, it appears that it will take about 4 years at an average to get the sediment buried beneath the mixing layer on the tidal mud flat and 9 to 16 years on the salt marsh.

The percentage of silt and clay in table 1 also corresponds to the top layer values (0-1 cm). When the sediment is compressed, the linear accumulation rate will be much smaller than indicated. To avoid this problem, the accumulation rate in kg/m^2/y is used instead. The accumulation of fine-grained sediment is obtained by multiplying the total accumulation rate by the percentage of fine-grained particles in the sediment. The fairly constant content of clay and silt within the topmost 10-15 cm of the cores, as appears from figures 5a-c, justifies this computation.

The accumulation rates of fine-grained sediment in the different geomorphological units are listed in table 2. The areas of the units were measured on the geomorphological map (figure 2). The accumulation rates of the salt marsh area are taken as the average value of core II and III. This is justified by the apparent one-dimensional distribution of the accumulation rate along the profile line, with the highest values close to the high-water line decreasing with increasing level of the salt marsh surface away from the erosional salt marsh cliff. Core I is taken as representative for the muddy tidal flats. In this way, the total accumulation of fine-grained sediment in Königshafen was determined to 1400 t/y. This figure is about one third lower than the total accumulation for the area presented by Pejrup and Bartholdy (1991). The higher value from the latter investigation is caused by a relatively rough estimate of the area of accumulation and furthermore, accumulation rates were not corrected for content of fine-grained sediment in the collected sediment samples.

Salt Marsh Erosion

The map of the edge-lines from the survey is shown in figure 6. The retreat of the salt marsh is clear, the average retreat of the coast line being approx. 0.25 m/y, at selected places up to 1 m/y.

The amounts of eroded material computed by the two methods are listed in table 3. It appears that the iron stick method underestimates the erosion rate 3-4 times, taking the survey method to be the most reliable. This underesti-

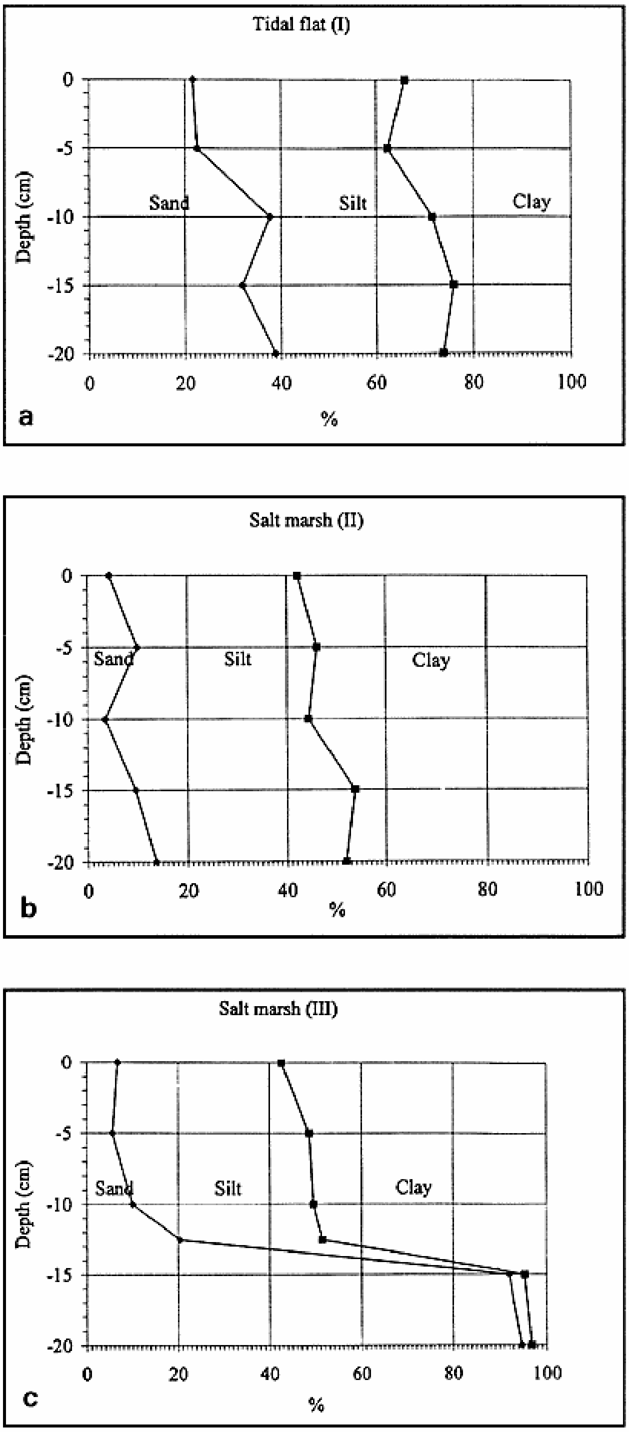

Figure 5 a-c: Grain-size distribution in the three cores.
a: Profile from the tidal mud flat. b: Profile from the salt marsh close to the mean high tide level. c: Profile from the central part of the salt marsh. (Based on results from Pejrup and Bartholdy (1991)).

Table 1: Average accumulation rates from the geomorphological units. The numbers (I, II, III) refer to the same unit as in figure 5. Based on results from Pejrup & Bartholdy (1991).

Geomorphological unit	*Accumulation Total* kg/m^2/y	*Average* mm/y	*Mixing depth* mm	*Silt + clay* % dw	*Accumulation Fine-grained* kg/m^2/y
Tidal mud flat (I)	5.1 ± 0.3	5.9	25	78.3	4.0
Salt marsh (II)	1.2 ± 0.1	2.2	20	95.6	1.2
Salt marsh (III)	0.5 ± 0.04	1.2	20	93.2	0.5

Table 2: Total accumulation rate from the tidal mud flat and the salt marsh.

Accumulation area	*Area* km^2	*Accumulation< 63 µm* t/y
Mud flat	0.2	800
Salt marsh	0.7	600
Total	0.9	1400

Table 3: Eroded material from the salt marsh computed by the two methods. The amount is given as m^3 per unit width.

	Iron stick m^3/m/y	*Survey* m^3/m/y
1992 - 1993	0.070	0.293
1993 - 1994	0.071	0.218
Average	0.071	0.256

mation is due to the different numbers of points measured by the two methods. The iron sticks have caused problems because each stick has disappeared once during the two years of investigation leaving a gap in the sequence of measurements. However, this error can not account for the underestimation alone. The underestimation by a factor 3-4 by the iron stick method is also found in other areas with salt marsh erosion in the Lister Tief area (Larsen et al. 1994).

The theodolite surveys were only carried out once a year, whereas the iron sticks were measured every 2-3 months or just after major storm events. Therefore, the iron sticks are suitable to describe the seasonal variation in erosion, whereas the surveys give a much more exact quantitative measure because of the larger number of measuring points. The results from the successive surveys were used to determine the yearly erosion rate.

The investigated salt marsh to the south is 600 m long with an average height of 0.61 m, the erosional part of the salt marsh to the west is 1300 m long with an average height of 0.15 m, the salt marsh to the north is protected from erosion by sand dunes.

The content of fine-grained sediment in the salt marsh is 94% and the bulk density of the salt marsh is 1010 kg/m^3.

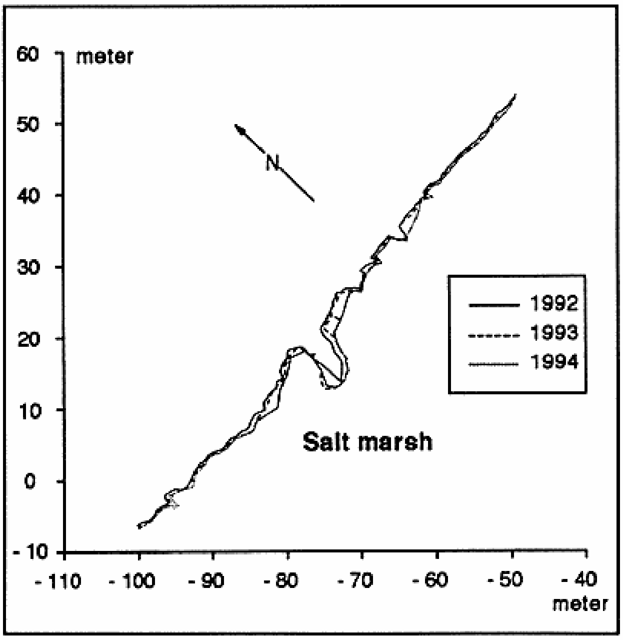

Figure 6: Map of the salt marsh erosion surveyed with theodolite.

According to table 3 the mean erosion rate of the southern cliff was 0.256 m^3/m/y; the mean erosion rate of the eastern cliff is computed as 0.15/0.61 · 0.256 = 0.063 $m^3/m/y$. The erosion was calculated as:

(length)·(mean erosion)·(bulk density)·(percentage of fines)

This gives a total erosion volume of the southern cliff of 146 t/y and a total erosion volume of the eastern cliff of 78 t/y giving a total salt marsh cliff erosion of 224 t/y. This corresponds to about 16 % of the total accumulation of fine-grained sediment within the area of investigation.

Primary Production

In the Königshafen tidal area, Asmus & Asmus (1985) distinguished 3 types of bottom communities: The Neireis-Corophium-belt, the seagrass bed, and the Arenicola-flat. They measured gross primary production rates for these 3 communities to be 148, 473 and 152 g $C/m^2/y$ respectively.

In the Dollard estuary van Es (1977) estimated the pelagic primary production to be 7.5 g C $/m^2/y$ and values for the benthic primary production on the tidal flats to be 116 g C $/m^2/y$. Thus, the total gross primary production was estimated to 123.5 g C $/m^2/y$, of which at least 90% is mineralized (van Es, 1977) before final burial beneath the benthic mixing layer. This leaves a maximum value of 12 g C $/m^2/y$ to contribute to the net accumulation of fine-grained sediment. This is equivalent to about 24 $g/m^2/y$ of organic matter.

In the Grådyb tidal area, Bartholdy & Madsen (1985) used a value of net primary production in the Grådyb tidal area of 6000 t/y, equivalent to 44 $g/m^2/y$. This value was based on unpublished data and on the assumption that 90 % of the gross primary production was mineralized. Information on the relative distribution between benthic and pelagic contribution was not offered.

Today, the Königshafen tidal area is mostly characterized by the Neireis-Corophium-belt and the Arenicola-flats. Therefore, a mean value of the gross primary production of 150 g $C/m^2/y$ from these two biotopes has been used in this study. A minimum of 82 % of this productivity is caused by microbenthos and microphytobenthos (Asmus & Asmus 1985). On the assumption that 90 % is mineralized, this will give a net input of organic matter of 30 $g/m^2/y$. This value is fairly consistent with the findings by van Es (1977). Taking the whole intertidal and subtidal area of 3.3 km^2 as potentially productive, this will give a net input of organic matter of 99 t/y to the Köninghafen tidal area.

According to results from the Dollard estuary (van Es, 1977) the supply from biological production on the salt marsh only amounts to 0.6 % of the total supply of organic C, and this contribution is therefore considered insignificant.

Atmospheric Deposition

The supply from the atmosphere to the net sediment budget originates primarily from aerosols of insoluble matter. These primarily originate from clay minerals and combustion of coal. The primary chemical constituents are Al, Ca, Fe, and Mg. Schulz (1993) presented results on the concentrations in rainwater of such chemical compounds, measured throughout the year, from Westerhever Lighthouse on Eiderstedt some 50 km south of the Königshafen area. Based on these results, a wet deposition rate of about 1.7 $t/km^2/y$ can be estimated. To this figure should be added dry deposition equivalent to a maximum of 30 % of the wet deposition (Schulz 1993). In this way a maximum value of total atmospheric input of 2.2 $t/km^2/y$ can be estimated.

These new figures can be compared to older ones presented by McCave (1973), estimating a net atmospheric deposition for the whole North Sea area to be $1.6*10^6$ t/y. The total North Sea is $575*10^3$ km^2 (McCave, 1973), which gives an atmospheric deposition rate of 2.8 $t/km^2/y$. When using the values from Schulz (1993), an atmospheric deposition of about 9 t/y can be estimated for the Königshafen area amounting to about 1 % of the total net budget of fine-grained sediment.

Discussion

The net budget of fine-grained sediment for the Königshafen tidal area is shown in table 4. Local erosion of salt marsh is seen to contribute 16 %, whereas primary production is estimated to contribute 7 % of the net budget. Atmospheric deposition is of little significance, contributing only about 1% . The remaining 76 % originates from the North Sea. However, it cannot be excluded that a minor part of this contribution stems from river input to the Sylt-Rømø tidal area. According to Pejrup et al. (1995) the net fluvial input of fine-grained sediment to the Sylt - Rømø tidal area is about 8000 t/y. If this is evenly distributed over the tidal area, about 1/100 or 80 t/y would deposit in the Königshafen area. This is only about 6 % of the total net budget, and it can therefore be concluded that at least 70 % of the fine-grained sediment accumulating in the investigated area originates from the North Sea.

Table 4: Net budget of fine-grained sediment for Königshafen given as total amount and as percentage of the total. The supply from the North Sea is calculated as the residual between total accumulation and contribution from other sediment sources.

Sediment source	*total supply t/y*	*% of total supply*
Salt marsh erosion	224	16
Primary production	99	7
Atmospheric input	9	1
North Sea	1068	76
Total	1400	100

The mean tidal volume in Königshafen is obtained from the hypsographic curve in figure 7, the mean tidal range is 1.8 m, mean low water is -1.0 m and mean high water is 0.8 m giving a mean tidal prism of $3.6*10^6$ m^3. Averaged over a year, the amount of sediment settling out of each m^3 of water exchanged between Königshafen and the adjacent North Sea can thus be calculated to 0.5 g/m^3.

An investigation of the turbidity in Königshafen made by Austen G. (1994) shows that in weather conditions with strong westerly winds, the turbidity is low and varies between 5-20 mg/l. Austen G. (1994) found that the tidal variation in hydrodynamics and turbidity in Königshafen show the same pattern as in most other tidal areas in the Wadden Sea. Therefore, the low turbidity values described in Königshafen must be caused by its position close to the Lister Tief tidal inlet. Based on the above mentioned typical suspended concentrations it can be concluded that maximum values of filtering efficiency of the water flowing in and out of the Köningshafen area will be in the range of 3-10 % of the total fine-grained suspended sediment transport.

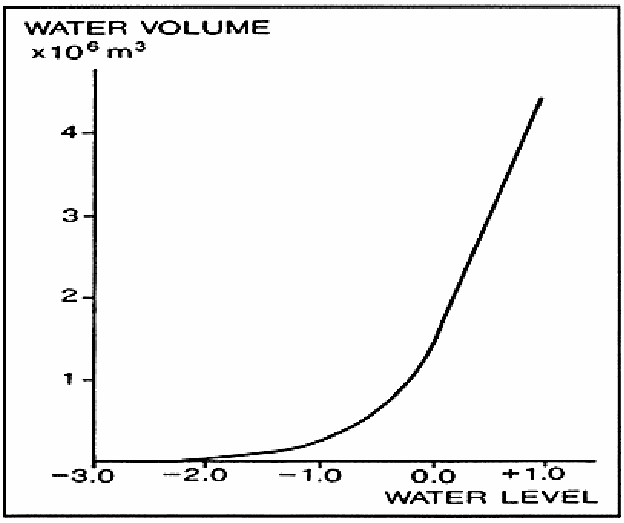

Figure 7: Hypsographic curve from Königshafen tidal bay. (After Pejrup and Bartholdy (1991)).

To compare the filtering efficiency in absolute values for different tidal areas in the Wadden Sea, a relation between yearly accumulation of fine-grained sediment and yearly total tidal volume was suggested by Bartholdy & Madsen (1985):

$$C\ (g/m^3) = \frac{\text{Accumulated fine-grained sediment (g/y)}}{\sum \text{mean tidal volume } (m^3/y)}$$

In table 5 values of the C index from Jade, Dollard, and Grådyb are compared with the value for Königshafen. It appears that the C value for Königshafen is low compared with other areas. Although these other areas are much larger, the relative distribution between areas covered by salt marsh, intertidal flats and tidal channels are comparable. Therefore, the low C value for Königshafen is probably explained by the generally low values of suspended sediment in the bay caused by its position close to the Lister Tief tidal inlet, because the actual percentage of sediment deposited from water entering the bay is fairly high.

Königshafen is densely inhabited by benthic filter feeders and deposit feeders (Reise et al. 1994). Briggs & Howell (1984) stated that the trapping efficiency of estuaries is connected to benthic filter feeders forming faecal pellets of the fine-grained material and thereby enhancing the settling velocity of the fine-grained sediment. The measured accumulation rates of fine-grained sediment in Königshafen are comparable to accumulation rates from the Grådyb tidal area reported by Bartholdy and Madsen (1985). The comparison between C values and accumulation rates for Königshafen and Grådyb suggests that the impact of benthic organisms on the net accumulation of fine-grained sediment is much larger in Königshafen than in Grådyb.

Table 5: Average amount of sediment settling out from each m^3 of water from different tidal areas. (*) indicate that the values are taken from Postma (1982).

Tidal area	*Mean tidal volume (10^6 m^3)*	*Fine-grained sediment accumulation 10^3 t/y*	*C g/m^3*	*References*
Jade	400 (*)	500	1.8	Eisma (1981)
Dollard	250 (*)	700	4.0	Van Es (1977)
Grådyb	138	142	1.5	Bartholdy & Madsen (1985)
Königshafen	3.6	1.37	0.5	This work

Conclusion

Based on morphological mapping and ^{210}Pb core dating, the net accumulation of fine-grained sediment in the Königshafen tidal area was determined to be 1400 t/y.

The contribution from the North Sea amounts to 70-76 % of the total supply, whereas local salt marsh erosion is estimated to account for 16 % and primary production and atmospheric depositon for 7 % and 1 %, respectively.

In spite of low turbidity values, the accumulation rates in Königshafen are comparable to other tidal areas in the Wadden Sea. This is explained by a high trapping efficiency in the bay that may be caused by the dense populations of benthic organisms.

Acknowledgements

This study was carried out as part of the large inter-disciplinary project "Sylter Wattenmeer Austaush Prozesse". We are deeply indebted to the Ministerium für Forschnung und Technologie (BMFT), Bonn, for providing the funds for this project. The authors thank Jesper Bartholdy for sampling the two cores on the salt marsh used for ^{210}Pb dating and grain size analysis and one core on the tidal flat used for grain-size analysis. Furthermore we wish to thank Michael Ansbak Petersen, Mette Bradam Hansen, Anette Lützen Møller and Thorbjørn Andersen for helping with the field work and Charlotte Bak for doing the major part of the grain-size analyses.

References

Appleby, P. G. & Oldfield, F., (1978): The Calculation of Lead 210 Dates Assuming a Constant Rate of Supply of Unsupported ^{210}Pb to the Sediment. Catena, 5: 1-8.

Asmus, H. & Asmus, R., (1985): The Importance of Grazing Food Chain for Energy Flow and Production in Three Intertidal Sand Bottom Communities of the Northern Wadden Sea. Helgoländer Meeresuntersuchungen, 39: 273-301.

Austen, I., (1994): The Surficial Sediment of Königshafen - Variations over the Past 50 Years. Helgoländer Meeresunters., 48: 163-171.

Austen, G., (1994): Hydrodynamics and Particulate Matter Budget of Königshafen, southeastern North Sea. Helgoländer Meeresunters, 48: 183-200.

Bartholdy, J. & Madsen, P., (1985): Accumulation of Fine-grained Material in a Danish Tidal Area. Marine Geology, 67: 121-137.

Bayerl, K. -A. & Higelke, B., (1994): The Development of Northern Sylt During the Latest Holocene. Helgoländer Meeresunters, 48: 145-162.

Briggs, R. B. & Howell, B. A., (1984): The Estuary as a Sediment Trap: Alternate Approaches to Estimating its Filtering Efficiency. p.107-129 in Kennedy V.S.(ed.): The Estuary as a Filter

de Haas, H. & Eisma, D., (1993): Suspended-sediment transport in the Dollard estuary. Neth. Jour. of Sea Res. 31: 37-42.

Edelvang, K. (1996): The significance of aggregation in an estuarine environment. Phd. thesis, Institute of Geography, University of Copenhagen, Geographica Hafniensia.

Edelvang, K. & Austen, I.(submitted): The temporal variation of flocs and fecal peellets in a tidal channel. Estuarine, Coastal & Shelf Science.

Table 5: Average amount of sediment settling out from each m^3 of water from different tidal areas. (*) indicate that the values are taken from Postma (1982).

Tidal area	*Mean tidal volume (10^6 m^3)*	*Fine-grained sediment accumulation 10^3 t/y*	*C* g/m^3	*References*
Jade	400 (*)	500	1.8	Eisma (1981)
Dollard	250 (*)	700	4.0	Van Es (1977)
Grådyb	138	142	1.5	Bartholdy & Madsen (1985)
Königshafen	3.6	1.37	0.5	This work

Conclusion

Based on morphological mapping and ^{210}Pb core dating, the net accumulation of fine-grained sediment in the Königshafen tidal area was determined to be 1400 t/y.

The contribution from the North Sea amounts to 70-76 % of the total supply, whereas local salt marsh erosion is estimated to account for 16 % and primary production and atmospheric depositon for 7 % and 1 %, respectively.

In spite of low turbidity values, the accumulation rates in Königshafen are comparable to other tidal areas in the Wadden Sea. This is explained by a high trapping efficiency in the bay that may be caused by the dense populations of benthic organisms.

Acknowledgements

This study was carried out as part of the large interdisciplinary project "Sylter Wattenmeer Austaush Prozesse". We are deeply indebted to the Ministerium für Forschnung und Technologie (BMFT), Bonn, for providing the funds for this project. The authors thank Jesper Bartholdy for sampling the two cores on the salt marsh used for ^{210}Pb dating and grain size analysis and one core on the tidal flat used for grain-size analysis. Furthermore we wish to thank Michael Ansbak Petersen, Mette Bradam Hansen, Anette Lützen Møller and Thorbjørn Andersen for helping with the field work and Charlotte Bak for doing the major part of the grain-size analyses.

References

Appleby, P. G. & Oldfield, F., (1978): The Calculation of Lead 210 Dates Assuming a Constant Rate of Supply of Unsupported ^{210}Pb to the Sediment. Catena, 5: 1-8.

Asmus, H. & Asmus, R., (1985): The Importance of Grazing Food Chain for Energy Flow and Production in Three Intertidal Sand Bottom Communities of the Northern Wadden Sea. Helgoländer Meeresuntersuchungen, 39: 273-301.

Austen, I., (1994): The Surficial Sediment of Königshafen - Variations over the Past 50 Years. Helgoländer Meeresunters., 48: 163-171.

Austen, G., (1994): Hydrodynamics and Particulate Matter Budget of Königshafen, southeastern North Sea. Helgoländer Meeresunters, 48: 183-200.

Bartholdy, J. & Madsen, P., (1985): Accumulation of Fine-grained Material in a Danish Tidal Area. Marine Geology, 67: 121-137.

Bayerl, K. -A. & Higelke, B., (1994): The Development of Northern Sylt During the Latest Holocene. Helgoländer Meeresunters, 48: 145-162.

Briggs, R. B. & Howell, B. A., (1984): The Estuary as a Sediment Trap: Alternate Approaches to Estimating its Filtering Efficiency. p.107-129 in Kennedy V.S.(ed.): The Estuary as a Filter

de Haas, H. & Eisma, D., (1993): Suspended-sediment transport in the Dollard estuary. Neth. Jour. of Sea Res. 31: 37-42.

Edelvang, K. (1996): The significance of aggregation in an estuarine environment. Phd. thesis, Institute of Geography, University of Copenhagen, Geographica Hafniensia.

Edelvang, K. & Austen, I.(submitted): The temporal variation of flocs and fecal peellets in a tidal channel. Estuarine, Coastal & Shelf Science.

Edzwald, J. K. & O'Melia, C. R., (1975): Clay Ditribution in Recent Estuarine Sediments. Clays and Clay Minerals, 23: 39-44.

Eisma, D., (1981): Supply and Deposition of Suspended Matter in the North Sea. Spec. Publs. Int. Ass. Sediment, 5: 415-428.

El-Daoushy, F., (1988): A Summary on the Lead-210 Cycle in Nature and Related Applications in Scandinavia. Environment International, 14: 305-319.

van Es, F. B., (1977): Preliminary Carbon Budget for a Part of the Ems Estuary: The Dollard. Helgoländer wiss. Meeresunters, 30: 283-294.

Frey, R. W. & Basan, P. B. (1978): Coastal salt marshes. In: Richard Davis, Jr. Coastal Sedimentary Environments. Springer Verlag, New York.

Haven, D. S. & Morales-Alammo, R. (1968): Occurence and trans0ort of fecal pellets in suspension in a tidal estuary. Sedimentary Geology, 2: 141-151.

Kranck, K., (1975): Sediment Deposition from Flocculated Suspension. Sedimentology, 22:111-123.

Kranck, K., (1981): Particulate Matter Grain-size Characteristics and Flocculation in a Partially Mixed Estuary. Sedimentology, 28: 107-114.

Krone, R. B., (1978): Aggregation of Suspended Particles in Estuaries. In: B. Kjerfve (Editor), Estuarine Transport Processes, Univ. South Carolina Press, USA.

Larsen, M., Edelvang, K. & Pejrup, M., (1994): Deposition of Fine-Grained Sediment in the Rømø - Sylt Tidal Area. Teilprojekt B 4.2; Sylter Wattenmeer Austausch Prozesse. Landesamt Tönning, Germany.

van Leussen, W., (1988): Aggregation of Particles, Settling Velocity of Mud Flocs. A Review. p. 347-403 in: J. Dronkers & W. van Leussen (Eds.), Physical Processes in Estuaries. Springer Verlag, Berlin

Madsen, Ph, P., (1981): Accumulation Rates of Heavy Metals Determined by ^{210}Pb Dating: Experience form a Marsh Area in Ho Bay. Rap. P. -v- Réun. Cons. int. Explor. Mer, 181: 59-63.

Madsen, Ph, P. & Sørensen, J., (1979): Validation of the Lead-210 Dating Method. Journal of Radioanalytical Chemistry, 54, 1/2: 39-48.

McCave, I. N., (1973): Mud in the North Sea. p. 75-100 in: E. D. Goldberg (Ed.), North Sea Science.

Owen, M. W., (1977): Problems in the Modelling of Transport, Erosion and Deposition of Cohesive Sediment. p. 515-537 in: E. D. Goldberg et al. (Eds.), Wiley-Interscience, New York.

Pejrup, M., (1980): The Turbidity Maximum in the Northern Part of Ho Bugt. Geografisk Tidsskrift, 80: 72-77, Copenhagen, Denmark.

Pejrup, M., (1988): Flocculated Suspended Sediment in a Microtidal Environment. Sedimentary Geology, 57: 249-256, Elsevier Science Publ. B.V., Amsterdam.

Pejrup, M., (1991): The Influence of Flocculation on Cohesive Sediment Transport in a Microtidal Estuary. p. 283-290 in: D. G. Smith et al. (Eds.), Clastic Tidal Sedimentology,, Canadian Society of Petroleum Geologists, Memoir no. 16.

Pejrup, M. & Bartholdy, J. (1991): Deposition of Fine-Grained Sediment in the Königshafen Tidal Area. Teilprojekt B 4.2 in Sylter Wattenmeer Austausch Prozesse. Landesamt Tönning, Germany. In: Meddelelser fra Skalling-Laboratoriet, 34: 1-22. Reitzel , København.

Pejrup, M., Larsen, M. & Edelvang, K. (1995): Deposition of Fine-Grained Sediment in the Rømø - Sylt Tidal Area. Teilprojekt B 4.2 ; Sylter Wattenmeer Austausch Prozesse. Landesamt Tönning, Germany.

Pethick, J. (1984): An introduction to Coastal geomorphology. Edward Arnold Pub. ltd., Great Britain.

Postma, H. (1967): Sediment Transport and Sedimentation in Estuarine Environment. In: G. H. Lauff (Ed.), Estuaries. Am. Assoc. Adv. Sci. Publ., 83:158-179.

Postma, H. (1981): Exchange of Materials Between the North Sea and the Wadden Sea. Marine Geology, 40: 199-213.

Postma, H., (1982): Hydrography of the Wadden Sea: Movements and Properties of Water and Particulate Matter. Final report on 'Hydrograpy' of the Wadden Sea Working Group. Report 2, Netherlands.

Reise, K., Herre, E. & Sturm, M. (1994): Biomass and abundance of macrofauna in intertidal sediments of Königshafen in the northern Wadden Sea. Helgoländer Meeresunters, 48: 201-215.

Schulz, M. (1993): Räumliche und zeitliche Verteilung atmosphärischer Einträge von Spurenelementen in die Nordsee. PhD. dissertation. Schriftenreihe Angewandte Analytik. Inst.für Anorganische und Angewandte Chemie der Universität Hamburg.

van Straaten, L. M. J. U. & Kuenen, P. H., (1957): Accumulation of Fine-grained Sediment in the Dutch Wadden Sea. Geologie en Mijnbouw (NW. Ser.) 19: 329-354.

van Straaten, L. M. J. U. & Kuenen, P. H., (1958): Tidal Action as a Cause of Clay Accumulation. Jour. Sed. Pet., 28, 4: 406-413.

Table 5: *Average amount of sediment settling out from each m^3 of water from different tidal areas. (*) indicate that the values are taken from Postma (1982).*

Tidal area	*Mean tidal volume* *(10^6 m^3)*	*Fine-grained sediment accumulation* *10^3 t/y*	*C* *g/m^3*	*References*
Jade	400 (*)	500	1.8	Eisma (1981)
Dollard	250 (*)	700	4.0	Van Es (1977)
Grådyb	138	142	1.5	Bartholdy & Madsen (1985)
Königshafen	3.6	1.37	0.5	This work

Conclusion

Based on morphological mapping and ^{210}Pb core dating, the net accumulation of fine-grained sediment in the Königshafen tidal area was determined to be 1400 t/y.

The contribution from the North Sea amounts to 70-76 % of the total supply, whereas local salt marsh erosion is estimated to account for 16 % and primary production and atmospheric depositon for 7 % and 1 %, respectively.

In spite of low turbidity values, the accumulation rates in Königshafen are comparable to other tidal areas in the Wadden Sea. This is explained by a high trapping efficiency in the bay that may be caused by the dense populations of benthic organisms.

Acknowledgements

This study was carried out as part of the large inter-disciplinary project "Sylter Wattenmeer Austaush Prozesse". We are deeply indebted to the Ministerium für Forschnung und Technologie (BMFT), Bonn, for providing the funds for this project. The authors thank Jesper Bartholdy for sampling the two cores on the salt marsh used for ^{210}Pb dating and grain size analysis and one core on the tidal flat used for grain-size analysis. Furthermore we wish to thank Michael Ansbak Petersen, Mette Bradam Hansen, Anette Lützen Møller and Thorbjørn Andersen for helping with the field work and Charlotte Bak for doing the major part of the grain-size analyses.

References

Appleby, P. G. & Oldfield, F., (1978): The Calculation of Lead 210 Dates Assuming a Constant Rate of Supply of Unsupported ^{210}Pb to the Sediment. Catena, 5: 1-8.

Asmus, H. & Asmus, R., (1985): The Importance of Grazing Food Chain for Energy Flow and Production in Three Intertidal Sand Bottom Communities of the Northern Wadden Sea. Helgoländer Meeresuntersuchungen, 39: 273-301.

Austen, I., (1994): The Surficial Sediment of Königshafen - Variations over the Past 50 Years. Helgoländer Meeresunters., 48: 163-171.

Austen, G., (1994): Hydrodynamics and Particulate Matter Budget of Königshafen, southeastern North Sea. Helgoländer Meeresunters, 48: 183-200.

Bartholdy, J. & Madsen, P., (1985): Accumulation of Fine-grained Material in a Danish Tidal Area. Marine Geology, 67: 121-137.

Bayerl, K. -A. & Higelke, B., (1994): The Development of Northern Sylt During the Latest Holocene. Helgoländer Meeresunters, 48: 145-162.

Briggs, R. B. & Howell, B. A., (1984): The Estuary as a Sediment Trap: Alternate Approaches to Estimating its Filtering Efficiency. p.107-129 in Kennedy V.S.(ed.): The Estuary as a Filter

de Haas, H. & Eisma, D., (1993): Suspended-sediment transport in the Dollard estuary. Neth. Jour. of Sea Res. 31: 37-42.

Edelvang, K. (1996): The significance of aggregation in an estuarine environment. Phd. thesis, Institute of Geography, University of Copenhagen, Geographica Hafniensia.

Edelvang, K. & Austen, I.(submitted): The temporal variation of flocs and fecal peellets in a tidal channel. Estuarine, Coastal & Shelf Science.