Deposition of organic matter and particulate nitrogen and phosphorus at the North Sea – Baltic Sea transition – a GIS study

OCEANOLOGIA, 45 (1), 2003.
pp. 283–303.

KEYWORDS
Sediments
Nutrients
Deposition
GIS
North Sea
Baltic Sea

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Manuscript received 24 March 2003, reviewed 16 April 2003, accepted 5 May 2003.

Abstract

A GIS (Geographical Information System) based study on deposition in the North Sea – Baltic Sea transition area has been carried out. The study is based on (i) a digital bathymetry model, (ii) 93 available $^{210}Pb/^{137}Cs$ sedimentation rate estimations, (iii) grain-size distributions, organic matter, C, N and P content of 64 top 1 cm sediment samples from the study area, and (iv) GIS-based modelling of resuspension potentials based on wind statistics. With the use of regression statistics on depth, resuspension potential and sediment characteristics, results

The complete text of the paper is available in PDF format at http://www.iopan.gda.pl/oceanologia/index.html

are extrapolated area-wide from the 64 sampling positions. The area is divided into sediment types and classified as accumulation or erosion/transport bottoms. Model results show good agreement with existing maps of sediment distributions, indicating that the sediment distribution is governed to a large extent by wind-induced waves. Correlations of sediment types, their deposition rates and their N and P contents were used to estimate spatial deposition rates. In all, the yearly deposition in the study area amounts to 2.8 million tons of organic matter, 0.14 million tons of total nitrogen, and 0.035 million tons of total phosphorus. Correlations of sediment types and dry bulk densities were used to infer spatial inventories of organic matter and total nitrogen and phosphorus in the top 1 cm of the sediments. A total of 100 million tons of organic matter, 4 million tons of total nitrogen, and 0.019 million tons of total phosphorus are contained in the top 1 cm of the sediments in the study area. In general, the deep parts of the study area with low resuspension potentials act as sinks for the fine-grained sediments and their associated particulate nutrients.

1. Introduction

It is well known that unconsolidated, fine-grained sediments and their organic matter content do not remain long on the sea-floor in high-energy shallow water environments. Frequent wave- (Weir & McManus 1987, Sandford 1994) and/or current- (Sandford et al. 1991) induced resuspension entrains such material and ultimately transports it to its final deposition in sheltered or deep waters (Floderus & Håkanson 1989, Laursen et al. 1992, Christiansen et al. 1997, Lund-Hansen et al. 1999, Eckhell et al. 2000, Christiansen et al. 2002). As a consequence of resuspension and transport, sediments making up the sea floor are often observed to become finer in shallow-water to deep-water depth profiles (e.g. Christiansen et al. 1997). Knowledge of erosion, transport, deposition and consolidation of cohesive material is essential, as pollutant dynamics are closely linked to the distribution of particulate matter (Wiltshire et al. 1994, Emeis et al. 2002).

An additional effect of high shear stresses on the bottom is that resuspension affects and changes sediment-to-water fluxes of various nutrients and redox-sensitive species (Laima et al. 2001) as well as oxygen penetration depths into the sediment (Christiansen et al. 1997). Resuspension may thus enrich the water column with nutrients from the sediment. The input is related both to desorption from resuspended particles and to mixing of pore water nutrients into the water column (Simon 1989). Another ecological consequence of resuspension is the potential enhancement of phytoplankton growth, since algae cells are periodically carried back into the euphotic zone (Garcia-Soto et al. 1990). The resuspension process is thus one of the mechanisms that provide a link between the benthic and the pelagic ecosystems. Resuspension may, on the other hand, also reduce algal growth through light attenuation, leading to increased turbidity in the water column.

As a result of resuspension, major parts of areas with water depths less than 40–50 m in the western (Christiansen & Emelyanov 1995) and less than 70–80 m in the central Baltic Sea (Jonsson et al. 1990) are generally considered non-depositional, and it has therefore been estimated that 80% of the organic matter and nutrients deposited in the deep-water basins of the central and northern Baltic Sea originate from erosion of shallow-water sediments (Jonsson et al. 1990).

A GIS-based study on deposition in the North Sea – Baltic Sea transition area has been carried out using ArcView (3.2a) with 3-D Analyst and Spatial Analyst extensions. The purposes of the present study were: (i) to use the GIS-based tools to describe and quantify the role of waves in the sediment type distribution, and (ii) to determine the area-wide accumulation rates, as well as (iii) to compile an inventory of organic matter and nutrients in the North Sea – Baltic Sea transition.

2. Study area

The Kattegat (mean depth 23 m, surface area 22 000 km^2) and the Skagerrak (mean depth 210 m, surface area 32 000 km^2) together form a transition area between the brackish Baltic Sea and the nearly oceanic, saline North Sea (Fig. 1). Both areas, but especially the Kattegat, are strongly influenced by water flowing out from the Baltic Sea. This forms a surface layer with a mean annual salinity increasing from about 8–10 PSU in the south-western Baltic to $>$ 25 PSU in the northern Kattegat (Stigebrandt 1983, Møller 1996). The mean annual salinity in the inflowing bottom water decreases from 34 PSU in the Skagerrak to 13 PSU in the western Baltic (Christensen et al. 1998).

The mean hydrographic conditions in the study area are governed mainly by two processes: (1) the outflow of low saline water from the Baltic Sea towards the Kattegat and Skagerrak, and the inflow of bottom water from the North Sea induced by the high saline estuarine circulation; (2) the large-scale meteorological conditions, which can set up water level differences between the Baltic Sea and the North Sea (Stigebrandt 1983, Anderson & Rydberg 1993). In general, westerly winds force dense bottom water into the Skagerrak and the Kattegat raising the level of the pycnocline. In contrast, easterly winds force low-density surface water from the Baltic Sea towards the Kattegat, where the pycnocline is lowered. The frequency of inflows from the North Sea to the study area may have increased in recent years owing to more episodes with strong westerly winds (Christiansen et al. 1996).

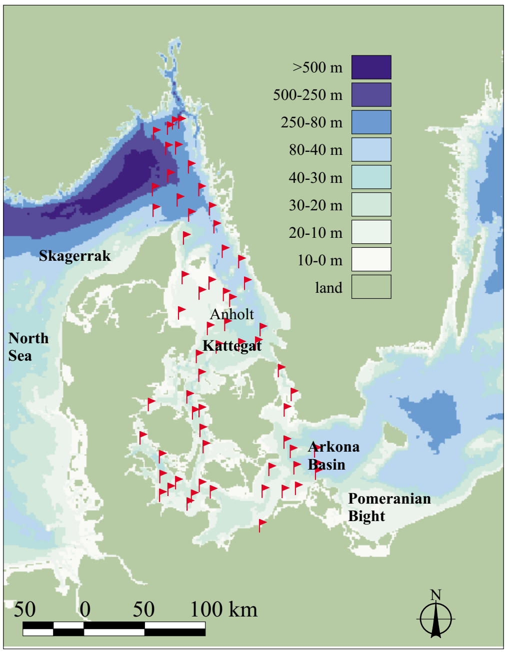

Fig. 1. Bathymetric map of the study area. The locations of the sediment sampling positions are shown by flags

Suspended matter concentrations vary from 5 to 15 mg l^{-1} in the surface and bottom waters in the Kattegat, and preliminary results have indicated that their settling fluxes were highest when North Sea dominated water was present in the study area (Lund-Hansen et al. 1993). The composition of suspended matter depends to some degree on the water circulation. In the Kattegat there is a north to south decreasing gradient in the suspended matter content of calcium (Bernard & Van Grieken 1989, Christiansen et al. 1995). On the other hand, Ingri et al. (1990) observed an increase in barium in the suspended matter from the Baltic Sea towards the Danish Belt area. Regional trends in the surface sediment content of some other elements have also been observed. For instance, Christiansen et al. (1993) noted a north to south decrease in the sediment content of calcium, and Gingele & Leipe (2001) observed a similar trend for the kaolinite/chlorite ratio.

An outline of bottom sediment distribution in the study area was given by Kuijpers et al. (1992), who showed that shallow-water areas are dominated by sand and coarse silt with low organic matter content, whereas deep-water areas have postglacial clayey sediments with a high organic content. Owing to frequent resuspension in shallow-water areas, permanent deposition takes place only in deeper waters (Christiansen & Emelyanov 1995, Christiansen et al. 1997). The Skagerrak is generally considered to be a natural trap for fine-grained sediments and associated organic matter, nutrients and heavy minerals. The highest sedimentation rates in the

Skagerrak (> 4 mm y^{-1}) are found in the north-eastern part (Van Weering et al. 1987). Sedimentation rates may reach 3–4 mm y^{-1} in the Kattegat (Christiansen et al. 1993). An increase in the concentration of organic matter in the youngest sediments is commonly observed in cores from the area (Nordberg & Bergsten 1988, Christiansen et al. 1993). Seidenkrantz (1993) explained the organic matter increase as the result of anthropogenic activity, and found that the distribution of foraminifera was also affected. A number of authors (e.g. Madsen & Larsen 1986 and Cato 1997) have shown that surface sediments, when compared to pre-1850 samples, are generally richer in trace metals by a factor of 2–30. For some elements, enrichment factors near urban areas may be as high as 30–1000 (Cato 1997).

3. Methods

Sampling and grain size distributions

Sediment sampling was carried out by the use of a conventional box-corer (Kanneworf & Nicolaisen 1973). Fig. 2 shows a typical sediment sample, though collected with a new video-controlled and hydraulic damped corer (Lund-Hansen et al. 2002). The top 1 cm of the core material was used for further analyses. After sample splitting by the use of wet sieving (180 μm), the size distribution of the coarse part of each sample was determined by the settling tube (Macrogranometer^{TM}) technique (Syvitski et al. 1991). The uncertainty on triplicates was 0.4–4.9%. The size distribution of the fine part of the samples was determined by the use of the laser diffraction (Malvern Mastersizer/E) technique (Agrawal et al. 1991). The uncertainty on triplicates was $< 2\%$. Sediment type classification was carried out using the Flemming (2000) ternary diagram. Where the sample density was not available, it was estimated empirically from density-organic matter correlations in available samples.

Fig. 2. Photograph of a sediment core from the central Kattegat showing the intact fluffy layer on top of the sandy sediment

Chemical analysis

The organic matter content was determined by weight-loss on ignition at 550°C for two hours. The temperature of combustion is sufficient to oxidise all organic matter, as well as to drive off hygroscopic water and convert pyrite to ferric oxide. According to Ball (1964) these two latter losses can be assumed minimal. Total nitrogen (TN) was determined using a LECO FP-428 2.03. Total phosphorus (TP) was determined after ignition (Andersen 1976) by the ascorbic reduction method on a Milton Roy Spectronic 1201 spectrophotometer. Total carbon (TC) was determined on a Dohrmann DC-190 analyser. The uncertainty on duplicates of chemical analyses was 4–8% for nitrogen and $< 3\%$ for phosphorus.

Waves and resuspension

In order to model a map of sediments based on sea depths and estimations of wave-induced resuspension of sediments a theme representing the fetch had to be elaborated. The calculation of this was coded in the Arc Model Language for ESRI's ArcInfo Grid module ver. 8.1. For every cell representing 1 nautical square mile the maximum fetch in 8 compass directions was calculated using a visibility function for the whole area of investigation. For a detailed description of the algorithm used, the reader is referred to Lundqvist et al. (2003b).

Wave-induced resuspension was calculated in three steps: (1) Wave height, period and length were estimated using the formulas in Beach Erosion Board (1975); (2) the maximum orbital velocity at the bottom was found using the Airy wave theory; (3) the threshold grain-size for resuspension for the calculated velocities was found according to Komar & Miller (1973). Resuspension frequencies were based on a wave base criterion of $0.25 \times$ wavelength, in accordance with Flemming (1999). For each of the 39 346 cells in the grid system with assigned depths (D), the wavelength (L), L/4, and L/4-D were calculated for 104 wind situations (8 wind directions $\times$ 13 wind forces). The resuspension frequency was then calculated for each cell by summing the number of situations during a year which fulfilled the specified resuspension criterion. Wind statistics obtained at Røsnæs Lighthouse in the central part of the study area and covering the period 1978–88 were taken from Kristensen & Frydendahl (1991). Areas with resuspension frequencies $< 0.01\%$ were classified as accumulation areas. Floderus & Pihl (1989) also inferred that accumulation takes place when resuspension is insignificant.

Other GIS-applications

All spatial data relating to the study area were stored as thematic maps and DBase compatible attribute tables in ESRI's ArcView GIS ver. 3.2a. The common geographic reference for all data was the Universal Transversal Mercator Projection (UTM) zone 32, European Datum 1950 (Western Europe). All basic information was stored primarily as point features. However, the bathymetry model, the results from the fetch calculations and the derived maps of sediment types were all stored and manipulated as grids using ESRI's Spatial Analyst and 3D Analyst extensions. The grid-based bathymetry-model was created from the conversion of 57 243 depth observations (1 observation per 1 nautical square mile) made available from the Danish Hydraulic Institute.

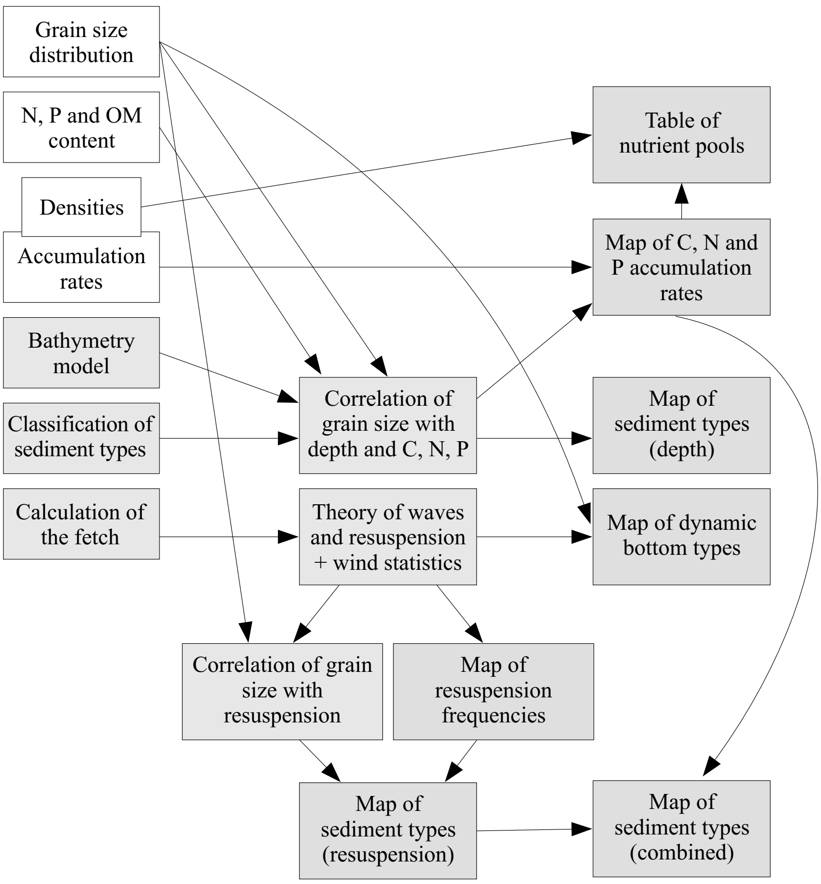

Fig. 3. Work-flow of components involved in the GIS model. Raw data, processed data and output maps and tables are distinguished by the use of grey tones

In the following, the various data involved leading to the derivation of estimated maps of sediment distributions are presented briefly. Most calculations (e.g. regression of grain-size fractions on resuspension potential and on depth) were carried out in the Microsoft Excel environment by importing the DBase-files from ArcView into Excel and exporting them back after the modifications had been completed.

Fig. 3 shows the workflow of the components involved. The map of sediment types was based on a combination of the grain size distributions for the 64 sampled locations, the bathymetry model, fetch, theory of wind-based wave evolution and wind statistics (leading to a map of resuspension frequencies). Accumulation rates of sediments and nutrients were based on combinations of sediment types, their deposition rates and their C,N,P-contents. Furthermore, sediment types, their C,N,P-contents and estimates of the samples' densities were combined to produce a map of nutrient pools. All the results are given for the 56 806 km^2 study area shown in Fig. 1.

4. Results

Resuspension frequencies

One third of the study area is located in sheltered and deep waters where wave-induced resuspension is insignificant: these areas are found mainly in the Skagerrak and in the deep, northern parts of the Kattegat (Fig. 4). Areas exposed to resuspension only about once per year (> 0% to 0.27% of the year; 25% of the area) are situated in the central and eastern parts of the Kattegat and in the Arkona Basin. The average depth of these areas is 33 m. With a monthly frequency (> 0.27% to 3.29% of the year; 19% of the area), resuspension occurs in the central part of the Kattegat (west of Anholt). These areas have a mean depth of 19 m. Resuspension occurs weekly (> 3.29% to <14.25%) primarily in the north-western parts of the Kattegat and in the Pomeranian Bight. Such areas have a mean depth of 11 m. In coastal waters, especially those exposed to the west and in very shallow waters (6% of the area; mean depth 6 m), resuspension occurs with a higher than weekly frequency.

5. Bottom types

Empirical relationships for grain size distribution, i.e. size fractions < 2 μm, 2–63 μm, and 63–2000 μm, and resuspension potential for the 64 sediment sample positions show that the two parameters are very well correlated. Grain size is significantly correlated to resuspension potential at the 99.95% level in all three fractions.

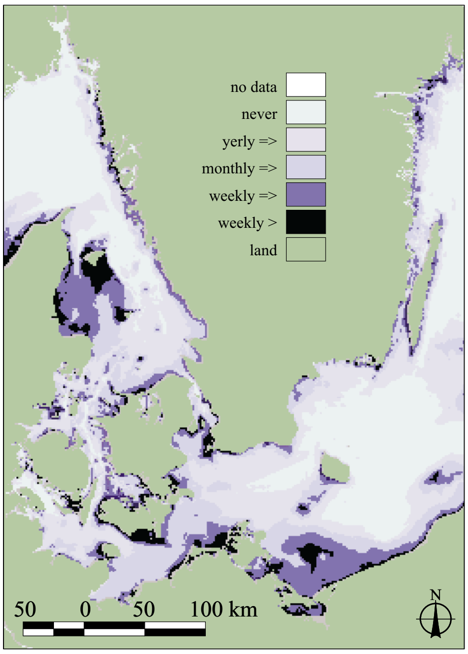

Fig. 4. Spatial distribution of annual resuspension frequencies

In the estimation of sediment type based on depth, the GIS model predicts the existence of 6 different sediment types in the area. In most of the area the sediments are relatively coarse, dominated as they are by the Very Silty Sand sediment type. In the coastal waters of the inner Danish Waters, where depths are relatively shallow, the sediment type is even coarser, consisting of Slightly Silty Sand and Sand. In the Skagerrak area, the deep trough west of Sweden, and in the western Baltic Sea the sediments are finer, composed mainly of Extremely Silty Sandy Mud and to a lesser extent of Silt. As expected, the sediment borders to a great extent follow the isobaths (Table 1).

The GIS-based model based on the wave resuspension potential predicts the presence of 5 different sediment types in the area. Overall, the sediments here are also relatively coarse – even coarser than in the depth model – and are dominated by the sediment types Slightly Silty Sand and Very Silty Sand. The coarsest sediment type – Sand – is found in the Jammer Bight and the Pomeranian Bight. The sediments of the inner Danish Waters are dominated by the Slightly Silty Sand and Very Silty Sand sediment types, the exceptions being the belts and the deep eastern part of the Kattegat, where sediments are finer. The finest grained sediment type – Extremely Silty, Slightly Sandy Mud – is found in the Skagerrak and the western Baltic Sea. Here too, the sediment borders to some degree follow the depth curves, but they are not as pronounced as in the depth model.

Table 1. Depth intervals for sediment types according to the resuspension model (u-max-classification) and the depth model. The letter code for each sediment type refers to the Flemming (2000) classification system

Sediment types	No. of sediment samples	Depth-interval	
		u-max-classification [m]	depth classification [m]
Sand (S)	5	6–25	0–6
Slightly silty sand (A1)	10	1–25	6–15
Very silty sand (B1)	25	0–68	15–42
Extremely silty sandy mud (C1)	16	2–127	42–120
Extremely silty slightly sandy mud (D1)	7	6–104	120–177
Silt (E1)	1		278–325

Overall, there is good agreement between the two models. While the general pattern is the same, the prediction of sediment types based on wave energy shows that the sediments are coarser in most of the shallow-water areas of the Baltic Sea and the coastal waters in the Skagerrak than in the depth-based model. In the belts the sediments are finer in the model, based on wave resuspension potentials, than in the depth model. A combination of the two models is shown in Fig. 5. This combination also allows classification of sediments in areas where depths are greater than the wave base. Here, transport or erosion bottoms (see Fig. 6) are mainly classified as sand or slightly silty sand. The model is unable to predict the texture of non-marine outcrops in these areas.

Organic matter and nutrient content

The sediment content of organic matter (OM) ranges from 0% to 17%. There is a significant ($p < 0.05$) correlation ($r^2 = 0.87$) between organic matter content and the grain size fraction < 63 μm. Generally, the highest organic matter content is found at deep-water stations with low resuspension frequencies.

The content of total phosphorus (TP) in the sediment falls in the interval 0.013% – 0.136% and the highest content is generally recorded in deep water sediments. Total phosphorus is significantly ($p < 0.05$) correlated ($r^2 = 0.71$) with organic matter content. The correlation is, however, best for organic matter contents of up to 6%. The deviation from the line of regression increases at higher organic matter contents. This indicates that the TP content in shallow water with relatively coarse sediments and low OM content is governed mainly by hydrodynamics, whereas the TP content in deeper water also depends on other factors such as the redox conditions.

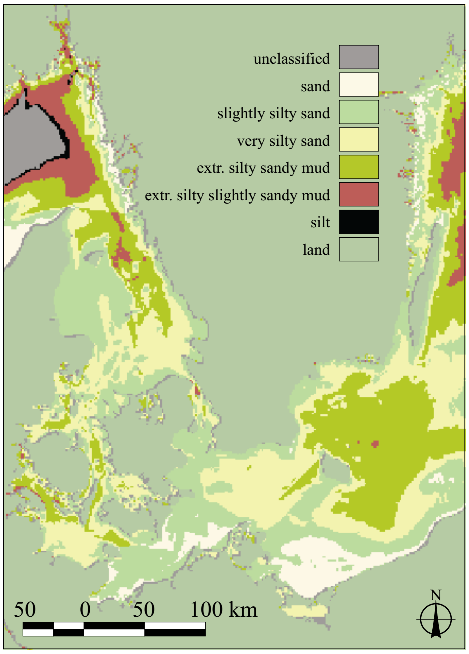

Fig. 5. Spatial distribution of sediment types. Sediment types are inferred from a combination of regression of types on depth and on resuspension potential

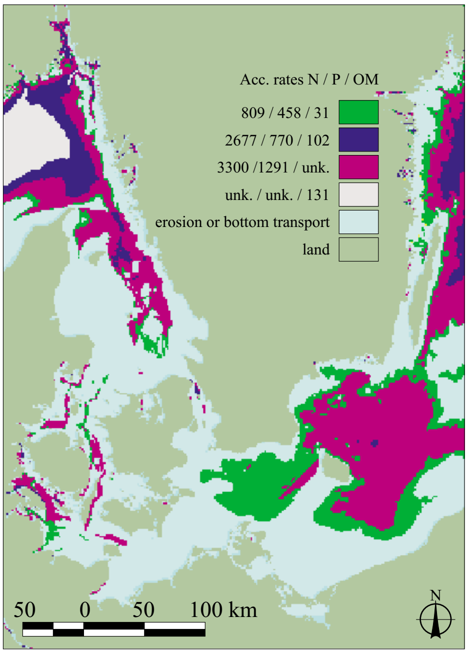

Fig. 6. Average annual accumulation rates of organic matter of nutrients. Rates for organic matter are given in g m^{-2} y^{-1} whereas rates for nutrients are given in mg m^{-2} y^{-1}

The sediment content in the total nitrogen (TN) content ranges from 0% to 0.66% and is significantly ($p < 0.05$) correlated ($r^2 = 0.59$) with the organic matter content. Similarly, the total nitrogen content shows the best correlation with a low organic matter content. For stations in very deep water (> 50 m) the content is in fact moderate and varies around the mean value for all stations (0.185%). The highest TN content is recorded in sediments from water depths between 25 m and 50 m with low resuspension frequencies and fine grain-size distributions.

Nutrient and organic matter deposition

Table 2 summarises the 93 determinations of sediment accumulation rates from the study area given by Lundqvist et al. (2003a) according to sediment type. The accumulation rates range from 25 g m^{-2} y^{-1} to 13 351 g m^{-2} y^{-1}. It is clear from Table 2 that accumulation rates generally increase with increasing depth and with increasingly fine-grained sediment type.

The spatial distribution of average yearly OM, TN and TP deposition rates are shown in Fig. 6 and summarised according to sediment type in Table 3. About 55% of the study area is non-depositional. The largest sinks for organic matter and nutrients are located in the Skagerrak, the deep northern parts of the Kattegat, and in the deep Arkona Basin in the western Baltic Sea. Smaller sinks are located in sheltered parts of the inner Danish waters. In total the yearly deposition in the study area consists of 2.8×10^6 tons of OM, 1.4×10^5 tons of TN, and 3.5×10^4 tons of TP.

Nutrient and organic matter inventory

Table 4 shows the content of nutrients and organic matter in the top 1 cm of the sediments in the study area. The largest TN and OM pools are contained in the relatively deep-water sediment type C1 (extremely silty, very sandy mud), whereas the largest TP pool is contained in the coarser, shallow-water sediment type A1 (slightly silty sand). In all, 1.0×10^8 tons OM, 4.0×10^6 tons TN and 1.9×10^4 tons TP are contained in the top 1 cm of the sediments in the study area.

Per unit area of shallow water, the sandy sediments (sediment type B1 (very silty sand) and C1) contain more TN (47 and 45 tons km^{-2}, respectively) than the muddy sediments (sediment type D1 (extremely silty slightly sandy mud) and E1 (silt)) in deeper water (31 and 32 tons km^{-2}, respectively). This may reflect higher rates of denitrification in the deep-water parts, which, for a wider area, corroborates the findings by Rysgaard et al. (2001). On the basis of a few stations they showed that denitrification rates were lower in sandy sediments than in clayey mud sediments.

Table 2. Accumulation rates of fine sediment [g m^{-2} $year^{-1}$] in relation to sediment type, the area as a percentage of the total area, and depth [m]. The letter code for each sediment type refers to the Flemming (2000) classification system

Sediment types	Accumulation of fine sediment (mean) [g m^{-2} $year^{-1}$]	Min./max. accumulation of fine sediment [g m^{-2} $year^{-1}$]	Area size in relation to total area [%]	Min. depth [m]	Max. depth [m]	Mean depth [m]
Slightly silty sand (A1)	515	200/662	0.03	14	33	30
Very silty sand (B1)	570	25/4.200	12.5	13	68	42
Extremely silty sandy mud (C1)	962	50/6.200	23.2	6	128	64
Extremely silty slightly sandy mud (D1)	1.058	250/4.045	5.9	6	279	143
Silt (E1)	13.351	13.351	0.5	279	325	301

Table 3. Yearly accumulation of fine sediment. TN, TP and OM [ton year^{-1}] in relation to sediment type in the classified area. The letter code for each sediment type refers to the Flemming (2000) classification system

Sediment types	Number of cells	Area [km^2]	Accumulation of			
			fine sediment [ton year^{-1}]	TN [ton year^{-1}]	TP [ton year^{-1}]	OM [ton year^{-1}]
Slightly silty sand (A1)	10	34	1.8×10^4	7.9	4.8	272
Very silty sand (B1)	4.934	16.923	9.6×10^6	1.4×10^4	7.8×10^3	5.2×10^5
Extremely silty sandy mud (C1)	9.117	31.270	3.0×10^7	1.0×10^5	2.4×10^4	1.2×10^6
Extremely silty slightly sandy mud (D1)	2.320	7.957	8.4×10^6	2.1×10^4	1.0×10^4	1.0×10^6
Silt* (E1)	181	621	8.3×10^6	1.7×10^3	802	8.1×10^4
Total	16.562	56.806	5.6×10^7	1.4×10^5	3.5×10^4	2.8×10^6

*Calculations for this sediment type are based on the D1 concentrations.

Table 4. Modelled total inventory of organic matter and nutrients in the top 1 cm of the sediments in the study area. The inventory is compiled on the basis of average concentrations in the sediment types. The letter code for each sediment type refers to the Flemming (2000) classification system

Sediment type	TN-content top cm (ton)	TP-content top cm (ton)	OM-content top cm (ton)
Sand (S)	2.7×10^4	6	6.7×10^5
Slightly silty sand (A1)	2.8×10^5	1.7×10^4	9.8×10^6
Very silty sand (B1)	8.1×10^5	627	3.1×10^7
Extremely silty very sandy mud (C1)	1.4×10^6	1.210	4.4×10^7
Extremely silty sligthly sandy mud (D1)	2.5×10^5	304	1.2×10^7
Silt * (E1)	2.0×10^4	24	9.6×10^5
Unclassified areas	1.2×10^6	146	6×10^6
Total	4.0×10^6	1.9×10^4	10.4×10^7

*Concentrations for sediment type D1 are used in the compilation of inventories for sediment type E1, as this type was not represented in the 64 sediment samples. D1 type concentrations were also used for unclassified sediments.

6. Discussion

The GIS-based classification of sediment types in the study area shows good agreement with the existing sediment maps (Kuijpers et al. 1992, Emelyanov et al. 1994, Hermansen & Jensen 2000) which, in addition to sediment samples, are based on geophysical methods such as side scan sonar and seismic surveys. This indicates that wave-induced resuspension plays a considerable role in determining the spatial distribution of sediment types. Misclassified areas are generally located either in submarine channels or on relatively steep slopes on the bottom, where currents seem to be the dominant factor determining sediment type.

Resuspension frequencies were based on how often the depth in each grid cell was smaller than $0.25 \times$ wavelength. This criterion for wave-induced resuspension was also used by Floderus (1989) and Flemming (1999), who considered this criterion for wave base to be of morphological and sedimentological importance. At this depth 20% of the wave energy on the sea surface is available for resuspension (Sly 1978). It is clear that use of the wave base criterion of $0.5 \times$ wavelength, applied by oceanographers to distinguish between waves in deep and shallow waters, would have resulted in higher resuspension frequencies covering extensive parts of the study area. This may indicate that the present frequencies are underestimates of the actual frequencies for the very fine-grained sediment types. However, Fig. 4 shows good agreement between areas classified as accumulation areas in the GIS modelling and positions where sedimentation rate measurements actually exist (Lundqvist et al. 2003a).

The present study generally shows higher contents of organic matter in the top sediments when compared to earlier studies (e.g. Van Weering et al. 1987, Kuijpers et al. 1993, Christiansen et al. 1993) covering parts of the present study area. This may be a result of the present stronger eutrophication, where increased levels of nutrient concentrations in the water column lead to a higher primary production, which in turn leads to a higher accumulation of organic matter at the bottom (Richardson 1996, Emeis et al. 2000). However, when compared to earlier studies of nutrient concentrations in the sediment (e.g. Christiansen et al. 1993, Larsen & Brügmann 1992), the present study generally shows that the N and P contents of the top sediment are unchanged, resulting in higher C/N and C/P ratios in the sediment at present. This may be a result of both the present change in the wind regime with increased storminess (Christiansen et al. 1993) and the more widespread occurrence of areas with near-bottom anoxia (Christensen et al. 1998). Increased storminess may lead to more frequent resuspension (Eckhell et al. 2000) and consequently longer transport pathways of the suspended matter before final deposition. Preferential loss of nitrogen compared to carbon has been observed to take place during transport and resuspension of particulate suspended matter (e.g. Valeur et al. 1995). Corroborating these observations, the highest C/N ratios in the present study are found in areas with high resuspension frequencies and at the deepest stations.

In the Baltic Sea Emeis et al. (2000) observed 100% higher C/P ratios in sediments dominated by anoxia than in the suspended matter settling to the bottom, and explained this as a function of liberation of iron-bound phosphorus during anoxia. The present study seems to corroborate these findings, as the highest C/P ratios are located at the spots where Christensen et al. (1998) pointed to the occurrence of frequent oxygen deficits in the water column. Additionally, comparison of Table 3 and Table 4 shows that the top 1 cm of the finest sediments in the study area (deep water) contain less P than the yearly accumulation in spite of annual sedimentation rates of < 1 cm y^{-1}, whereas the sandy sediments in shallow water without oxygen deficits contain more P than is accumulated per year.

It is evident that the nutrient pools depend strongly on the representativeness of the samples collected in each of the sediment types. This is especially the case for sediment type E1 (silt). This sediment type is represented by only 1 sample. However, as this sediment type covers only a small part of the total area (Table 3), its contribution to the total pools of nutrients and organic matter is of less importance.

Acknowledgements

We would like to extend our gratitude to the captain and crew of the r/v 'A. Penck' for their skilful help and assistance during sediment sampling. Sediment data from the present study is available at the Baltic Sea Sediment Data Base (www.io-warnemuende.de). The two anonymous referees provided very helpful comments.

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