Distribution and cycling of fine-grained sediment in the Eastern Scheldt, Southwest Netherlands

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Abstract

Surface and core samples of sediment were taken from 3 types of mud depositional areas in the Eastern Scheldt in 1985–1986, before the completion of the Storm Surge Barrier. Total accumulation rates of clay and silt were highest (100–200 Gg yr^{-1}) in abandoned channels. Clay and silt were also deposited in large quantities (30–80 Gg yr^{-1}) in salt marshes, and were cycled in large amounts (200–500 Gg yr^{-1}) in mussel banks by deposition of faeces and pseudo-faeces. In the latter habitat no net accumulation occurred, because equal amounts were resuspended by wave agitation and dredging.

The balance of sediment input and accumulation indicated a net seaward flux of 80–1800 Mg day^{-1} of clay + silt and 3–80 Mg day^{-1} of organic carbon through the mouth of the Eastern Scheldt. Most of the sediment probably came from eroding Holocene deposits elsewhere in the Eastern Scheldt, and smaller amounts from fluvial influx. Analysis of their elemental composition indicated that a major source of the sediments was formed by sandy deposits with clayey laminae of subrecent Dunkirk age, and a minor source was older, more clayey Calais deposits.

The sedimentation rates were highest (5–15 cm yr^{-1}) in abandoned channels near dams and dikes. In such environments, seasonal variations in sedimentation rates were clearly reflected in cyclic changes of porosity and organic carbon concentrations in the sediment. Similar seasonal changes were observed in the sediment at the surface of sandy intertidal flats.

Introduction

There have been several recent studies of the input-output balance of dissolved and particulate matter in the Eastern Scheldt, before the completion of the Storm Surge Barrier, the Oesterdam and the Phillipsdam in 1986–1987 (Bigelow et al., 1977; Stortelder et al., 1984; Van den Berg, 1986; Van Geldermalsen, 1985; Dronkers, 1987). These studies are of particular significance with respect to the environmental changes to be expected in the Eastern Scheldt from 1986 onwards (Knoester et al., 1984).

While the relatively small fluviatile discharges of suspended matter are well known (Stortelder et al., 1984), data on the net exchange with the North Sea are conflicting. Some studies (Bigelow et al., 1977; Van Geldermalsen, 1985) pointed to a net import of particulate matter from the North Sea. Other recent studies, however, have indicated a net export of mud (Dronkers, 1987).

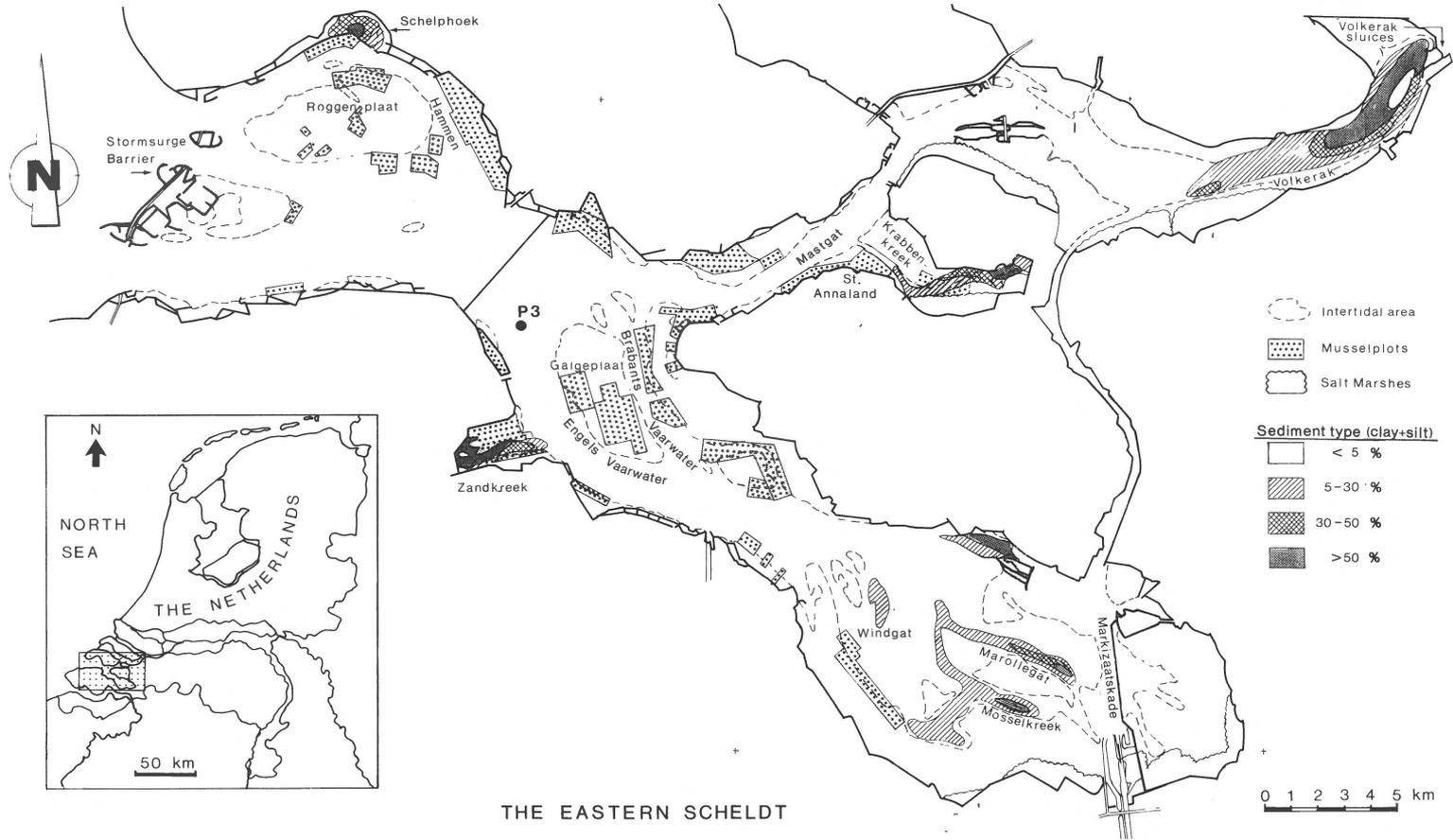The predominantly sandy sediments, with very

Fig. 1. Location of abandoned channels, salt marshes and mussel plots in the Eastern Scheldt.

low organic carbon concentrations (<0.1%) in tidal channels and intertidal flats (Oenema & Slagmaat, 1986; Terwindt, 1965) suggest that during the last decades the fine-grained sediment accumulation has been negligible in these terrains.

However, rapid siltation has occurred in abandoned channels, recently cut off by dikes and dams from most of their tidal discharge (Fig. 1). A second depositional environment of clay + silt is formed by salt marshes, where a steady accretion of 1–1.5 cm yr^{-1} has occurred during the last decades (Oenema & DeLaune, 1988). A third area with recent fine-grained sediments is found in mussel plots within and below the tide range, where the blue mussel, *Mytilus edulis*, deposits its faeces and pseudo-faeces (Smaal et al., 1986).

This paper is concerned with clay + silt and organic carbon deposition in these three depositional areas, and will compare accumulation rates with estimated sediment supply rates in the Eastern Scheldt up to 1986. The composition and possible provenance of the sediments will be discussed.

Methods

Study site

Since the Middle Ages the Eastern Scheldt has gradually lost its function as main distributary of the Scheldt river, until in 1871 it became completely disconnected from the Scheldt by a dam. Major recent changes occurred within the framework of the 'Delta Plan' (Knoester, 1984). The Volkerak dam in the northern branch largely cut off the input from the rivers Rhine and Meuse in 1969. All remaining fluviatile input was essentially cut off by the completion of the Markizaatskade in 1983 and the Philipsdam and Oesterdam in 1986–1987. Smaller branches of the Eastern Scheldt were cut off by dams in the Zandkreek in 1960 and in the Krabbenkreek in 1972.

Before the works were completed in 1986–1987, the Eastern Scheldt had a total surface area of 450 km^2 and an average depth of 8 m. Approximately 30% of the area consists of intertidal flats, and in 1983, before the completion of the Markizaatskade, there were 16 km^2 of salt marshes. The vertical tide is essentially semidiurnal, with a range of 3.0–3.5 m. Only small variations in chlorosity (12 to 17 g l^{-1}) occur, due to the relatively small fresh water input (Stortelder et al., 1984).

Sampling and determination of sedimentation rate

The investigation of the depositional area of fine-grained sediments in abandoned channels (Fig. 1) was limited to surface (0–15 cm) samples. These samples were taken at intervals of 100–500 m by a Van-Veen grab between August 1985 and December 1986. The thickness of the fine-grained sediment layers was determined from undisturbed sediment cores (0–2 m) taken by divers. The mean sedimentation rate was calculated from the thickness of this layer and the number of years since the channel was cut off, and the total annual accumulation was calculated from the sedimentation rate, the clay + silt and organic carbon contents and the area of siltation.

Surface sediment samples (0–3 cm) of the intertidal area were taken at fixed stations on the Galgeplaat and Roggeplaat at regular time intervals in 1983–1986.

Undisturbed sediment cores (0–30 cm) from demarcated mussel plots were taken by slowly twisting PVC tubes (I.D. 10 cm) into the mud. The mean density of mussel banks per plot was estimated from the data of Smaal et al. (1986), and from aerial photographs and observations during field surveys. Rates of biodeposition were also calculated from the data of Smaal et al. (1986). Actual mud accretion rates in mussel banks were measured between April 1985 and December 1986 on the intertidal area of St. Annaland at 1–2 month intervals, using the sandy sediment surface of the intertidal flat as a tracer layer (see Misdorp et al., 1984).

Sample preparation and analyses

All sediment cores were processed within 24 hours. Sliced sections of 0.5 to 10 cm were dried at 80° C for 48–72 hours. A mean mass density of 2500 kg m^{-3}, determined initially from measured sediment weights and volumes, was routinely used to calculate the porosity and bulk density from the weight loss after drying.
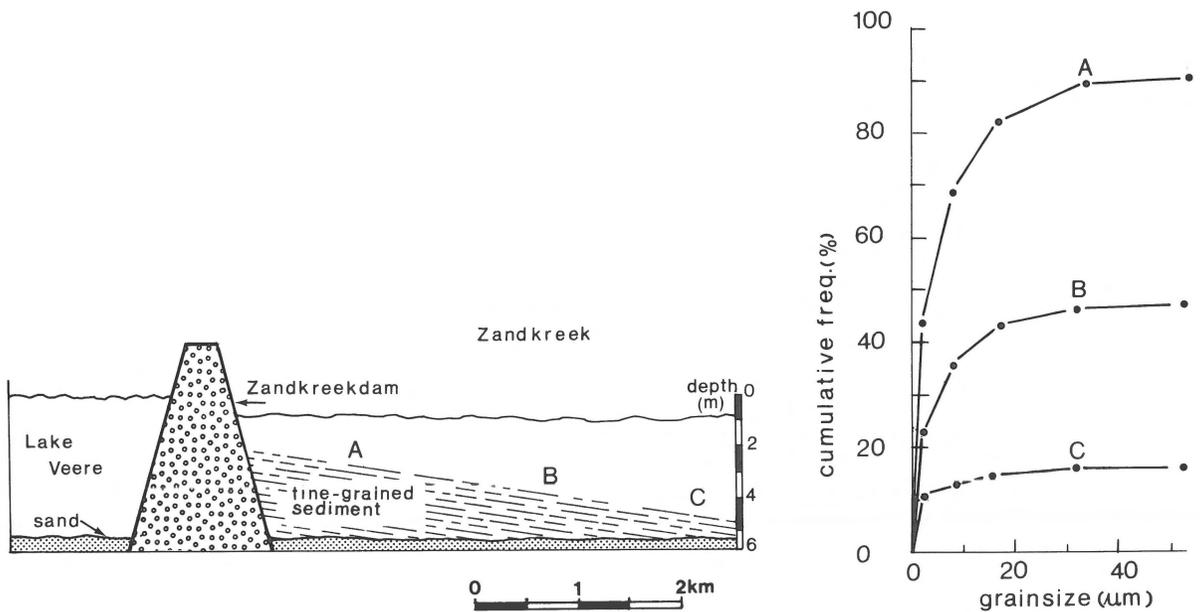
Fig. 2. Grain-size distribution of recent deposits in the Zandkreek (means of 5 samples). A. 0.2 km from the dam, B. 1.5 km from the dam and C. 3.0 km from the dam.

The grain size distribution of sand was determined by dry-sieving at 0.25 phi intervals using A.S.T.M. sieves. The silt and clay content was analyzed by sedigraph, after pretreatment with HCl and H_2O_2 to remove carbonates and organic material. Concentrations of clay + silt are expressed in terms of carbonate- and organic- carbon free sample weight. The term 'mud' refers to all matter of <50 μm in diameter (Terwindt, 1977).

Weight loss on ignition was routinely determined at 450° C and 950° C. Organic carbon was determined by wet oxidation with H_2SO_4 and $K_2Cr_2O_7$, and carbonate carbon by the volume of CO_2 liberated after acidification (Page, 1982). The elemental composition of 320 samples was determined using an X-ray fluorescence spectrometer, equipped with a Cr-tube. A half-gram sample of ignited (950° C) sediment was mixed thoroughly with 5 g Spectroflux type 1100 (Johnson Matthey Chemicals, England) and then melted at 1200° C to a disc. Another 75 samples were analyzed for Co, Cr, Cu, Fe, Mn, Sn and Zn by A.A.S, after digestion for one night in a mixture of HF, HNO_3 and $HClO_4$.

Results and discussion

Mud sinks

Abandoned channels. The accumulation pattern of mud in all abandoned channels was identical: the closer to the interior dams, the greater the accumulation (Fig. 1). Both the observed increase in mud thickness and the increase in percentage clay + silt towards the dam (Fig. 2) agree with accumulation mechanisms proposed by Van Straaten & Kuenen (1957) and by Postma (1967). The very recently abandoned tidal channels in the eastern basin (Mosselkreek, Marollegat, Windgat) in front of the Markizaatskade (completed in 1983) contained only thin, almost fluid mud layers.

Sedimentation rates varied from 1 to 15 cm yr^{-1} (Table 1). Very high rates of sedimentation (approximately 15 cm yr^{-1}) occurred in the Zandkreek. Parts of this channel were dredged once every 5 years to maintain a depth sufficient for navigation. A sedimentation rate of 15 cm yr^{-1} corresponds to a mean settling rate of 0.2 mm per tide. Mud laminae of this thickness, with a mean porosity of 0.80–0.85 (see below) can be formed in one

tide, assuming a mean suspended matter content of 28 mg l^{-1} (Stortelder et al., 1984) and a particle settling rate of 3 m per tide (Terwindt & Breuser, 1972).

Clay + silt concentrations increased from <2% in active tidal channels to >90% at the ends of abandoned channels (Fig. 2). Thus transport of sand to the ends was negligible. Intercalating sand layers of 1–10 cm, possibly reflecting stormy weather conditions, were found in cores from the Volkerak and the Zandkreek, but not in cores taken at the ends of the abandoned channels. Organic carbon concentrations varied from 0.5 to 4% and were linearly related to the clay content, with a slope of 0.08, and to the clay + silt content, with a slope of 0.04.

The estimated total clay + silt and organic carbon accumulations in abandoned channels were 90–200 Gg yr^{-1} and 3–7 Gg yr^{-1}, respectively, for the period 1983–1986. (Table 1). The various ranges are related to the spatial variability in clay + silt and organic carbon concentrations and in the thickness of the mud layers.

Tidal flats. The clay + silt concentrations in the surface layers (0–3 cm) of intertidal areas in the Eastern Scheldt increased from ≤1% in the western part (Roggenplaat) to approximately 1–5% in the eastern part (Oenema & Slagmaat, 1986). Significantly higher (5–10%) concentrations were observed near the fringes of the Eastern Scheldt.

There was a slight seasonal variation of 2–3% clay + silt in the surface layers of tidal flats (Fig. 3). According to Vos (1986), the higher concentrations
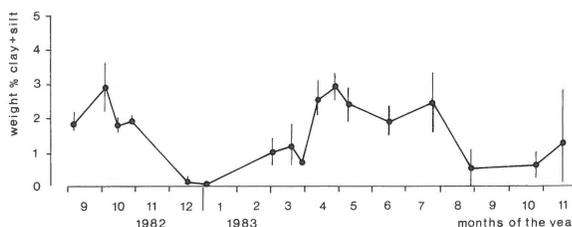

Fig. 3. Seasonal variation of the clay + silt content in the surface layer of the Galgeplaat intertidal flat in 1982–1983. Vertical bars indicate standard deviation.

in the summer were caused by the combined effect of silt + clay sedimentation and sediment stabilization by diatoms. However, there was no net accumulation of clay + silt on the tidal flats.

Mussel plots. About 1600 ha of tidal flats and tidal channels are used for the culture of the blue mussel *Mytilus edulis* (Drinkwaard, 1979). In these areas (mussel plots) large amounts of mud are temporarily accumulated by biodeposition of faeces and pseudo-faeces. In an aquarium filled with seawater of 11° C, settling velocities of mussel faeces were found to vary from 1.0 to 1.5 cm s^{-1} and pseudo-faeces from 0.5 to 1.0 cm s^{-1}. These velocities are of the same order of magnitude as the settling velocity of the fine sands (75–250 μm) of the Eastern Scheldt basin. Faecal pellets (length 2–5 mm, width 1–2 mm, and thickness <1 mm) are larger and more coherent than pseudo-faeces, but within one day the faecal pellets too coalesced on top of the sediment surface.

Biodeposition on mussel plots, calculated from

Table 1. Mean fine-grained sediment accumulation in abandoned channels in the Eastern Scheldt.

Channel	Cut off in	Surface area*	Sedimentation rate (cm yr^{-1})	Silt + clay (Gg yr^{-1})
Volkerak	1969	10.5	0.6– 3.1	30– 80
Krabbenkreek	1972	2.5	0.7– 5.7	10– 25
Zandkreek	1960	1.7	1.0–15.0	40– 45
Eastern basin	1983	5.0	1.0– 6.0	10– 50
Total				90–200

* approximate area of mud sedimentation (km^2).

the data of Smaal et al. (1986), was $1300\,Gg\,yr^{-1}$ in 1977–1983. Between 10 and 50% of the surface area of mussel plots was made up of mussel banks, with a mean of 25%. Using these data and a mean porosity of 0.60, the accretion rate of mussel banks by the biodeposition of faeces and pseudo-faeces was calculated to be $28\,cm\,yr^{-1}$. These estimates are rather crude, because the suspended matter concentrations vary throughout the tide and are higher just above the sediment surface (Steyaart, 1985).

Actual accretion rates were much lower, especially in the winter season. Mean accretion rates, measured in mussel plots at the intertidal flat of St. Annaland, were 2.5 cm in 1985 and 12 cm in 1986. These differences were ascribed to differences in mussel density and weather conditions. Accretion rates were high (12 cm) in the period April-October 1986, but in the subsequent period to January 1987 no further accretion was measured. The increasing height of the mussel banks caused an increased exposure to waves and tidal currents. Consequently, all current faeces and pseudo-faeces were eroded, especially in the winter season when the water is rougher. Similar patterns of mussel bank accretion on tidal flats were observed by Kamps (1962) and Misdorp et al. (1984). The investigation of 185 sediment cores from mussel banks, taken throughout the Eastern Scheldt in 1984–1986, also revealed that the thickness of the mud layers was usually 15 cm or less.

From a comparison of calculated accretion rates ($28\,cm\,yr^{-1}$) and measured actual accretion rates ($10-15\,cm\,yr^{-1}$) it follows that approximately 50% of the total bio-depositional flux of faeces disappeared. The actual accretion of $190-250\,Gg\,yr^{-1}$ of clay + silt and $7-10\,Gg\,yr^{-1}$ of organic carbon was removed by dredging at the end of the 1–2 year mussel growth period (Table 2). Consequently, no net accumulation of mud occurred in most of the mussel plots in the long term. In the mussel storage plots in the eastern basin of the Eastern Scheldt, relatively more faeces accumulated, because the calm hydrodynamic conditions precluded resuspension of faeces in this area (Misdorp et al., 1984).

Mussel bank sediments contained $35 \pm 15\%$ silt + clay and $1.5 \pm 0.7\%$ organic carbon. The relatively large sand fraction and the low organic carbon concentration compared to the composition of faeces (Smaal et al., 1986) suggest a significant sedimentation of resuspended bottom sediment during slack-water and during storms (e.g. Kamps, 1962). This would indicate that more than the estimated 50% of the total biodepositional flux was removed by wave agitation and tidal currents.

Salt marshes. Sediment accretion rates in salt marshes in the Eastern Scheldt varied from 0.5 to $1.5\,cm\,yr^{-1}$ (Oenema & DeLaune, 1988). These marsh sediments had a mean bulk density of $500\,kg\,m^{-3}$ and contained approximately 70% clay + silt and 5% organic carbon. For a total surface area of $16\,km^2$ (before 1983), the total accumulation of clay + silt and organic carbon was $30-80\,Gg\,yr^{-1}$ and $2-6\,Gg\,yr^{-1}$, respectively.

Mudsources

Fluviatile discharges. Mud discharges of rivers and polders were relatively small, but are well known ($30-60\,Gg\,yr^{-1}$; Stortelder et al., 1984). Most of the discharge occurred in the Volkerak, the northern branch of the Eastern Scheldt.

Dredging activities. The discharge of dredged material in the Eastern Scheldt, resulting from the construction and extension of harbours and canals varied considerably from year to year. During 1981–1986 approximately 200 Gg was dumped in the Eastern Scheldt annually, according to data from the Ministry of Public Works, Zeeland Division (RWS). Grain size distributions of this material are unknown, so the clay + silt concentration was estimated to vary between 10–50%. Periodic

Table 2. Mean fluxes of faeces and pseudo-faeces, and clay + silt in musselplots in the Eastern Scheldt.

	Fluxes in mussel banks (cm yr^{-1})	Fluxes of silt + clay (Gg yr^{-1})
Biodeposition	28	450
erosion	10–15	190–250
dredging	10–15	190–250

dredging of recently deposited mud in harbours (100 Gg yr^{-1}; data from RWS) was not included in these calculations, because these dredging rates were assumed to balance the sedimentation rates at these locations.

Channel erosion. The third source of mud was provided by the widening and deepening of tidal channels in the Eastern Scheldt (Van den Berg, 1986). Although the total volume eroded has been measured, the concentrations of clay + silt and organic carbon in it are not known. A rough estimate (400–800 Gg yr^{-1}) has been made by using the mean clay + silt concentration in sediment cores taken in the vicinity of identified erosion areas and the measured volume of erosion (Ten Brinke, 1987, pers. comm). These crude calculations give probably and upper limit, because clayey Calais and Dunkirk deposits (>35% clay) are supposed to contribute >75%, whereas the sandier deposits with clayey laminae would contribute <25%. It was observed, however, that clayey deposits exhibit a much greater resistance to erosion than the more sandy deposits (F. de Lange, 1987, pers. comm.). Consequently, a lower estimate of clay + silt erosion (100–200 Gg yr^{-1}) was obtained by excluding these clayey Calais and Dunkirk deposits from the calculations.

Exchange with the North Sea. The exchange of silt + clay and organic carbon with that in the North Sea was estimated from the difference between the known sinks and sources (Table 3). Thus far, the data indicate a net export of 330–680 Gg yr^{-1} of silt + clay to the North Sea. There would be significantly less export (30–80 Gg yr^{-1}) if the erosion of clayey Calais and Dunkirk deposits in channels were excluded from these budget calculations.

The estimated export of particulate organic carbon varied between a maximum of 30–80 Mg organic carbon per day and a minimum of 3–9 Mg organic carbon per day. These estimated fluxes are in reasonable agreement with data of Dronkers (1987) who measured a net export from the Eastern Scheldt of approximately 50 Mg organic carbon per day.
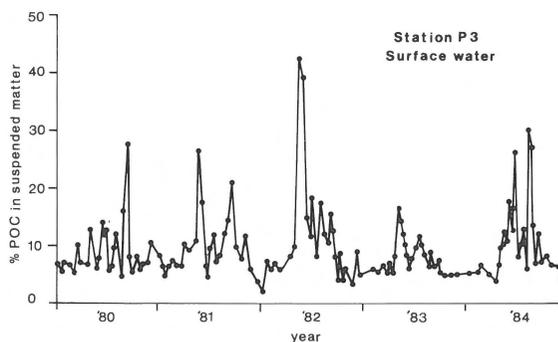

Fig. 4. Seasonal variation in the Particulate Organic Carbon (POC) content of the suspended matter in the Eastern Scheldt at station P3. Data from B. Wetsteyn.

Sediment composition and provenance
Porosity and organic carbon. Seasonal variations in factors affecting sedimentation, such as hydrodynamics, suspended matter concentrations and the organic carbon content of the suspended matter (Fig. 4), were reflected in variations in porosity and organic carbon concentrations of sediments in abandoned channels (Fig. 5). In spring and summer a large percentage of the suspended matter consisted of algae and recently formed algal detritus. In the winter season the organic carbon content of the suspended matter was lower (Fig. 4), because of a lower primary production and an increased concentration of inorganic matter. The latter resulted from increased resuspension of bottom sediment by wave agitation during the winter. Consequently, summer deposits had a higher porosity

Table 3. Estimated sinks and sources of clay + silt in the Eastern Scheldt (Gg yr^{-1}).

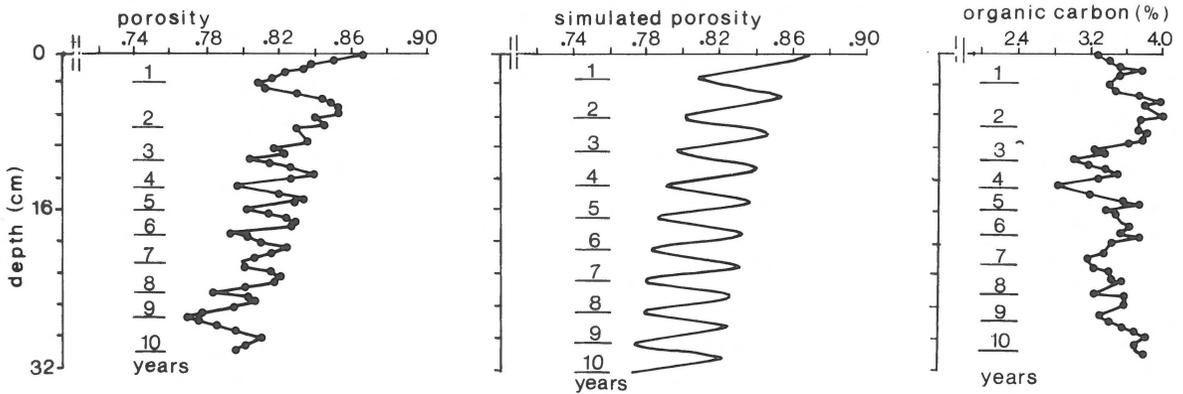|	Sinks	Sources
Abandoned channels	90–200	
Salt marshes	30– 80	
Discharges of rivers		30– 60
Discharges of dredged material		20–100
Erosion in tidal channels		400–800
Export to North Sea	330–680	
Total	450–960	450–960

Fig. 5. The porosity and organic carbon distribution with depth in recent deposits in the Zandkreek. Standard deviation of organic carbon determination is 0.018% (n = 8). For explanation of simulated porosity see text.

and higher organic carbon concentration than winter deposits (Fig. 5, see also Silverberg et al., 1985). The apparently undisturbed stratification suggests that there is no bioturbation in abandoned channels with high sedimentation rates. This is in accordance with the absence of macrofauna (except one crab) in all of the 40 investigated cores from the Zandkreek and Krabbenkreek.

The porosity in the superficial, almost fluid mud layers varied between 0.8 and 0.9. The porosity exponentially decreased with depth due to compaction. The porosity of the abandoned channel sediments fitted the following equation reasonably well, which includes the effects of compaction and seasonal variations in sedimentation conditions (Fig. 5b):

$$\Phi = A \sin(2\pi y_x) \left\{ \Phi_\infty + (\Phi_0 - \Phi_\infty) \exp \frac{(-bx)}{w_x} \right\}$$

where Φ_o = porosity at zero depth,
Φ_∞ = porosity at infinite depth,
w = mean sedimentation rate (cm yr^{-1}),
w_x = porosity corrected sedimentation
    rate: $\frac{(1 - \Phi_\infty)}{(1 - \Phi_x)} w$,
$y_x = \frac{(x + w_x/4)}{w_x}$,
x = depth (cm),
and A and b are constants.

The porosity decreased by 0.06 due to compaction (difference between Φ_o and Φ_∞). Differences in porosity between the summer and winter deposits (2A) were 0.05–0.06 cm^3 cm^{-3}. This would indicate that the bulk density of the winter deposits was 1.4–1.5 times the bulk density of the summer deposits.

The results presented in Fig. 5 indicate a sedimentation rate of 3.1 cm yr^{-1}. This agrees reasonably well with the mean sedimentation rate (3.3 cm yr^{-1}) calculated from the total thickness of the mud layer (85 cm) and the total number of years (26) of mud sedimentation at this site. Greater sedimentation rates in winter (expressed as g m^{-2}) can be inferred from the higher bulk density of the winter deposits.

The range of the cyclic variations, as a percentage of organic carbon in the sediment (0.4–1.0%), was significantly smaller than the mean difference (3–6%) between the summer and winter organic carbon concentrations in the suspended matter (Figs. 4 and 5). The latter seasonal variation apparently represents mainly easily metabolizable organic carbon that, after deposition, is rapidly oxidized by heterotrophic microorganisms in the surface layers of the sediment. The small but persistent cyclic variations in the sediment merely reflect seasonal variations in the content of inorganic admixtures (i.e. silt and very fine sand).

In none of the examined cores was any signif-
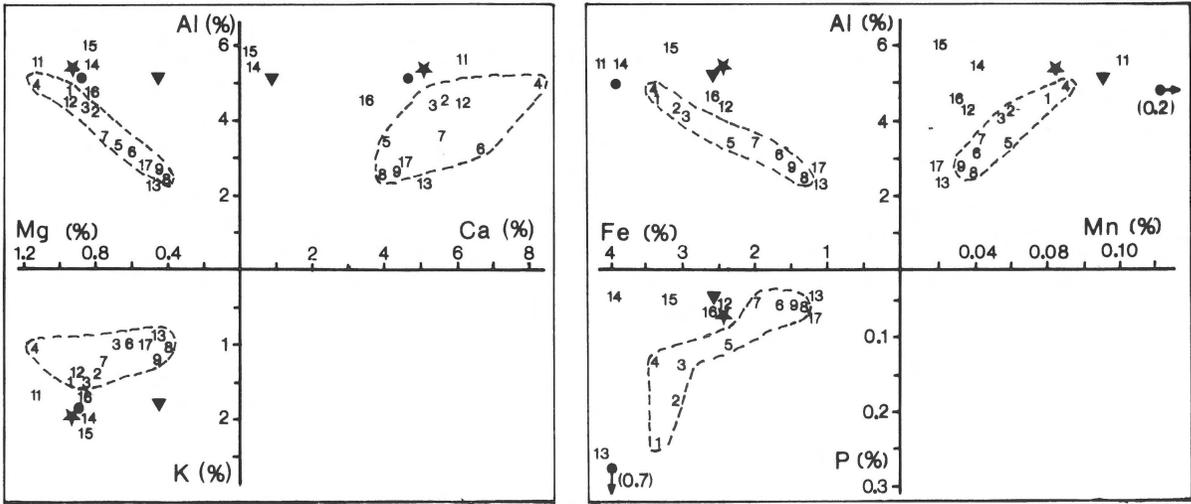
RECENT SEDIMENTS
1. Volkerak (2.5 km from sluices)
2. Volkerak (3.6 km from sluices)
3. Volkerak (5.7 km from sluices)
4. Zandkreek
5. Marollegat
6. Hammen
7. Roggenplaat
8. Brabants Vaarwater
9. St. Annaland

11. Volkerak (before 1970)
12. Zandkreek (Dunkirk)
13. Roggenplaat (Dunkirk)
14. Marollegat (Calais)
15. Mastgat (Calais: 3.2-4.3 m)
16. Mastgat (Calais: 4.4-5.5 m)
17. Mastgat (Calais: 5.6-6.8 m)
● Hollands Diep (Van Eck, 1982)
✶ Betuwe (CaCO₃-rich: Miedema, 1987)
▼ Betuwe (decalcified: ,,   )

Fig. 6. Mean elemental composition of recent (9 cores, 1–9) and subrecent (5 cores, 11–17) deposits in the Eastern Scheldt. Dotted line envelops recent deposits. Also shown are data of suspended matter from the river Rhine (Hollands Diep) and data of Holocene deposits from the Rhine in the Betuwe region.

icant decrease in the percentage of organic carbon with depth observed, except when the clay + silt concentration decreased. This also suggests that practically all easily metabolizable organic carbon, deposited in the sediment, oxidizes in the surface layers. The remaining organic carbon (3–4%), that is buried in the recent mud deposits, represents refractory organic carbon. The low $^{13}C/^{12}C$ ratios in organic carbon from suspended matter in the Eastern Scheldt (Anonymous, 1984) suggest that much of it comes from terrestrial sources such as peat. This fraction is practically indigestible.

The elemental composition. The elemental composition of sediment in the Eastern Scheldt is influenced by texture, sediment origin and diagenetic processes. Aluminum is a major constituent of the clay + silt fraction and is not involved in diagenetic redistribution processes. It was linearly related to

the clay + silt content (n = 59; R^2 = 0.94) and aluminum was used, therefore, to correct the element concentration for the effect of differences in texture. A graphical approach (Fig. 6) was employed to determine whether the sediments in the Eastern Scheldt have a homogeneous composition. The elemental composition of recent mud deposits showed little variation with depth and thus mean compositions were calculated for each core. A few cores had a small surface enrichment of manganese, iron and phosphorus, caused by diagenetic processes. This phenomenon was most apparent in salt marsh sediments, and these sediments were therefore excluded from this study.

There was a high correlation between the concentrations of aluminum (Al), magnesium (Mg), iron (Fe) and manganese (Mn) in the recent sediments (Fig. 6). Total phosphorus (P) increased with decreasing distance from the Volkerak sluices
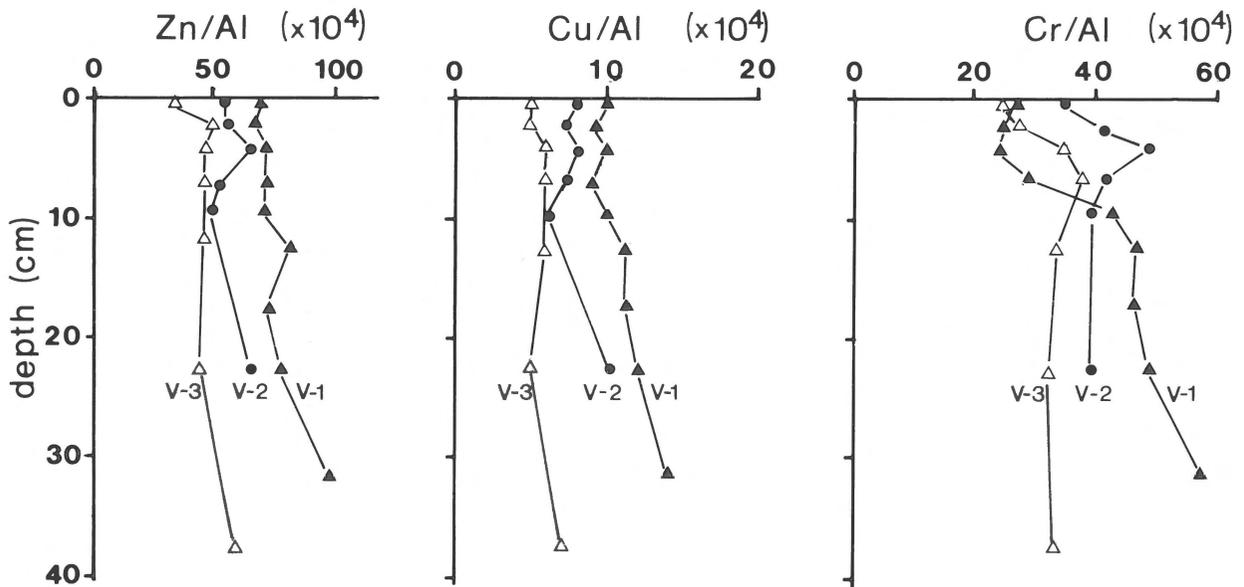
Fig. 7. Aluminum corrected Zinc, Copper and Chromium concentrations in recent deposits in the Volkerak. V-1 2.5 km from Volkerak sluices, V-2 3.6 km from sluices and V-3 5.7 km from sluices.

(Fig. 6), suggesting sedimentation of P-enriched fluviatile sediment from the Hollands Diep (Van Eck, 1982) in the vicinity of the sluices. The concomitant increase in heavy metal concentrations (Fig. 7) supports this conclusion.

The low manganese and heavy metal concentrations of recent sediments in the Eastern Scheldt (De Groot, 1963; Kerdijk, 1985), suggest that they are mainly of marine origin. Marine and fluviatile sediments in the Netherlands and their coastal waters differ in their chemical and mineralogical composition (De Groot, 1973; De Groot & Allersma, 1975; Salomons et al., 1975; Breeuwsma, 1985). Marine sediments are a variable mixture of fluviatile discharges of the Rhine, Meuse and Thames in the southern North Sea (Terwindt, 1977), and of material from the Atlantic Ocean, the English Channel and the Strait of Dover, transported northward into the North Sea (Eisma, 1981). The influence of the latter flow was reflected in the carbonate carbon compositions and concentrations of marine deposits in the North Sea (Verhoeven, 1963; Salomons, 1975).

The composition of subrecent deposits, especially the clayey Calais deposits, was different from

that of the recent sediments. Clayey Calais deposits immediately underneath the Holland-peat were decalcified in the upper 1.0–1.5 m (Fig. 6). Together with the decalcification a depletion of Mg occurred, because the carbonate contained approximately 5% Mg (Verhoeven, 1963). The Calais deposits in the Eastern Scheldt and the Rhine deposits in the Betuwe region in the central Netherlands (Miedema, 1987) contain comparable high K concentrations. This would suggest that the upper meter of the Calais deposits contains a significant admixture of fluviatile sediment. Note also the decrease in K/Mg ratio with depth in the core from the Mastgat. Fluviatile deposits have higher K/Mg ratios than marine sediments, because of the higher illite/smectite ratio in the former. (Breeuwsma, 1985).

The depletion of older, and especially of Calais deposits in P (300–800 μg g^{-1}) and Mn (300–700 μg g^{-1}) is likely to have been caused by early diagenetic processes (Aller, 1980; Krom & Berner, 1981). Eutrophication may have slightly enriched the recent sediments with phosphorus, especially in the Volkerak. Nevertheless, the fluviatile discharges of phosphorus, manganese and heavy metals in

the Eastern Scheldt were relatively small (Stortelder et al., 1984), and they probably accumulated only in the Volkerak sediments (Figs. 6, 7). This is supported by the fact that the amounts of clay + silt that were discharged and those that accumulated annually in the Volkerak were roughly equal.

Clayey Calais deposits cannot have contributed much to the recent sediments, because they are very different from the latter in P, Mn, K, Ca and Mg concentrations. Calais and Dunkirk deposits with sandy texture and clayey laminae, have a much smaller Mn and P depletion than the clayey deposits (Fig. 6). In part, this can be ascribed to analytical errors due to lower concentrations. However, such alternating sand-clay layers may have been deposited rapidly (Breuser & Terwindt, 1972; Van den Berg, 1986). This in turn slackens the rate of Mn of P depletion of the sediment.

Conclusions

Rapid accumulation of fine-grained sediment in the Eastern Scheldt occurred only in artificially created, abandoned channels, salt marshes and temporarily in mussel culture areas. The net depositional fluxes of clay + silt (120–280 Gg yr^{-1}) and of organic carbon (5–12 Gg yr^{-1}) in the study areas were smaller than the estimated influx of clay + silt and organic carbon. On the basis of the excess influx, an export of 900–1800 Mg day^{-1} of clay + silt and 30–80 Mg day^{-1} of organic carbon to the North Sea has been calculated.

Internal fluxes of clay + silt and organic carbon in the Eastern Scheldt were calculated to be as large as the fluviatile influx and the net efflux to the North Sea, or exceeded them by 1 or 2 orders of magnitude. A large seasonal cycling of clay + silt occurred in the surface layers of the intertidal flats (100–150 Gg yr^{-1}) and in mussel plots (190–450 Gg yr^{-1}). Erosion of tidal channels in the Eastern Scheldt turned out to be the largest source of clay + silt (400–800 Gg yr^{-1}). It is suggested that clayey Calais and Dunkirk deposits contribute a minor portion, given the differences in elemental composition between these subrecent deposits and the recent sediments. If so, the estimate of the clay + silt erosion from tidal channels should be

reduced to approximately 100–200 Gg yr^{-1}. Consequently, the estimate of the export of clay + silt and associated organic carbon to the North Sea should be reduced to 80–120 Mg day^{-1} and 3–9 Mg day^{-1}, respectively.

The net depositional organic carbon flux (5–10 Gg yr^{-1}) and the estimated net flux of organic carbon (1–29 Gg yr^{-1}) to the North Sea have a minor influence on the total organic carbon budget in the Eastern Scheldt. Rates of primary production and mineralization of organic carbon in the Eastern Scheldt were 1–2 orders of magnitude larger (Stortelder, 1985). Moreover, most of the benthic organic carbon was in a form indigestable to heterotrophes.

In the Eastern Scheldt, the abandoned channels with their rapid siltation (1–15 cm yr^{-1}) constituted rather unique environments. The sinusoidal distribution of porosity and organic carbon concentration in these sediments reflected seasonal changes in sedimentation conditions. It further suggested a steady accretion during the last decade or so and little or no physical disturbance of the stratification, for instance by bioturbation.

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