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Primary Research Paper

Seasonal variation of floc characteristics on tidal flats, the Scheldt estuary

Margaret S. Chen[1,*], Stanislas Wartel[1] & Stijn Temmerman[2]
[1]*Marine Ecosystem Management, Royal Belgian Institute of Natural Sciences, Rue Vautier 29, B-1000 Brussels, Belgium*
[2]*Netherlands Institute of Ecology (NIOO-KNAW), Centre for Estuarine and Marine Ecology, Korringaweg 7, 4401 NT Yerseke, The Netherlands*
*(*Author for correspondence: E-mail: Margaret.Chen@naturalsciences.be)*

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Abstract

The flocculation mechanism dominates the fate of suspended matter in the estuarine environment. By modifying the texture of suspended matter, flocculation is one of the principle factors determining the transport and deposition of suspended matter in estuaries. Surveys of the seasonal variation of dispersed particle and non-dispersed particle characteristics, organic matter content as well as suspended matter deposition in two contrasting intertidal environments, one freshwater and one brackish water, in the Scheldt estuary were undertaken at fortnightly intervals for a year. The study of non-dispersed particle, i.e. floc, is mainly focused on floc size, shape, and microstructure, properties presumed to be significant in the suspended matter transport processes in the estuary. In this study, floc size as well as floc sphericity correlate positively with the change of organic matter content and reveal that floc grows in a three-dimensional way with increasing organic matter. It is observed that relatively condensed, small and elongated flocs appear in winter and spring periods, while loose, large and spherical flocs occur during the summer. The study also reveals that suspended matter transported as dense flocs with size range of ca. 105–250 μm have a greater effect on its short-term deposition than loose flocs with size range of ca. 250–500 μm. As the measured suspended matter deposition is much higher in winter–spring than in summer, it is deduced here that highly compact and relatively dense flocs contribute to deposition during winter and spring periods resulting in a stable layer, while loosely formed flocs likely lead to an easier erodible layer during the summer. This study concludes that floc structure-related density is a more significant parameter than floc size in the suspended matter deposition processes.

Introduction

Transport of fine-grained sediment in estuarine intertidal areas is a highly dynamic process, and is primarily controlled by river discharge, tidal energy and wave action as well as suspended matter load in the estuarine water. Deposition of suspended matter on the tidal flats depends strongly on the properties of the suspended matter. The important components of tidal flat deposits are sand- to clay-sized mineral particles, colloidal particles and particulate organic matter. However, suspended matter occurs largely as fragile flocs in the ocean, coastal seas and estuaries (Nishizawa et al., 1954; Kranck, 1984; Eisma, 1986; Dyer et al., 2000; Milligan et al., 2001). Flocculation modifies the texture of suspended matter, and thus affects the transport and deposition of suspended matter in estuaries. The omnipresence of the flocculation phenomenon influences suspended matter transport (Chen, 2003) and is considered as an additional significant factor next to the above mentioned principal factors controlling the strength of the flocculated suspended matter and the resulting suspended matter deposition.

Because of their fragility, the natural flocs are usually investigated by Scanning Electron Microscopy (SEM), Transmission Electron

Microscopy (TEM) and *in situ* (video) camera. *In situ* (video) camera systems are commonly used to produce abundance and size profiles of particles without structural information (cf. Edgerton et al., 1981; Honjo et al., 1984; Eisma et al., 1990; Fennessy et al., 1994a, b; Milligan, 1996). SEM and TEM techniques have been shown to be adequate and valuable methods to be used to visualise the flocculation mechanisms, to obtain information of the floc microstructure, and to get insight into the spatial variation of the floc structure in estuarine systems (cf. Whalley, 1978; Eisma et al., 1982; Baerwald et al., 1991; Van Leussen, 1994; Droppo et al., 1996; Ransom et al., 1997; Bennett et al., 1999). As this research is aimed at investigating the dynamical properties of the floc and its deposition on two tidal flats, Environmental Scanning Electron Microscopy Wet Mode (ESEM-WM) is applied. The ESEM-WM technique insures the examination of a fresh wet natural sample and avoids arbitrary modification of the sample during procedures of critical point drying and coating or embedding, which are used in conventional SEM and TEM techniques. In this study, floc refers to a structure that is a complex entity formed into clusters or groups of several component parts adherent to each other into a conglomerated mass by a matrix, in which fine particles or groups of particles are bound by organic substances, and regardless of whether it is formed within or outside of tidal flat areas. The characteristics of floc examined by ESEM-WM and presumed to be significant in the sedimentary processes of the suspended matter on the tidal flats include floc size, shape (sphericity) and microstructure.

To gain knowledge of the significance of flocculation for the deposition of fine-grained sediments on tidal flats of the Scheldt estuary, the study of the texture of suspended matter and its short-term potential deposition rate are of special interest. This paper presents results from one-year fortnightly surveys performed on two tidal flats, a freshwater one and a brackish water one, in the Scheldt estuary (Fig. 1). The prime objective is to evaluate the seasonal variation of dispersed particle and non-dispersed particle, i.e. floc, characteristics, organic matter (OM) content as well as short-term potential deposition rate of suspended matter on these two contrasting tidal flats.

Methods

Study sites

A one-year (from September 2000 to September 2001) fortnightly sampling program was carried out on two tidal flats in the Scheldt estuary (Fig. 1). De Notelaar – a freshwater tidal flat (FTF), where tidal water has an average pH value of 7.5 ± 0.1, and Paulinaschor – a brackish water tidal flat (BTF), where tidal water has an average pH value of 7.9 ± 0.2 and an average salinity of 21 ± 3.4 ranging from 16 to 26. The FTF is situated 95 km from the river mouth near the upstream tip of the estuarine turbidity maximum, which extends roughly from 58 to 100 km, while the BTF is located 14 km from the river mouth in the marine dominated part of the estuary. Both tidal flats are mainly influenced by the tidal energy in the estuary (Chen, 2003). Besides, a seasonal sedimentation pattern was reported for two adjacent tidal marshes of de Notelaar and Paulinaschor (Temmerman et al., 2003), where higher sedimentation rates were observed during winter than during summer, there is no existing information or studies of the seasonal behaviour, in terms of erosion and sedimentation, of the tidal flats in the Scheldt estuary. This study is the first investigation of suspended matter short-term deposition rate in relation with seasonal variation of flocculation on the tidal flats in the Scheldt estuary.

Suspended matter collection

Suspended matter was collected using siphon samplers on the tidal flats. The siphon sampler, fixed on three wooden poles implanted on the tidal flat, is a 10-l white plastic round bottle (diameter of 20 cm and height of 37 cm) closed with a 12-cm wide stopper holding two tubes (Anonymous, 1961). A straight tube, immersed 3 cm into the siphon bottle, extends out of the stopper reaching above the high water level so that an open connection with the atmosphere is ensured. The other one is an inverted U-shaped tube serving as flow delivery. The inlet end of this inverted U-shaped tube is fixed outside the siphon bottle at 50 cm above the tidal flat surface, and the other end is fixed inside the siphon bottle, approximately 15 cm above the bottom. The siphon sampler

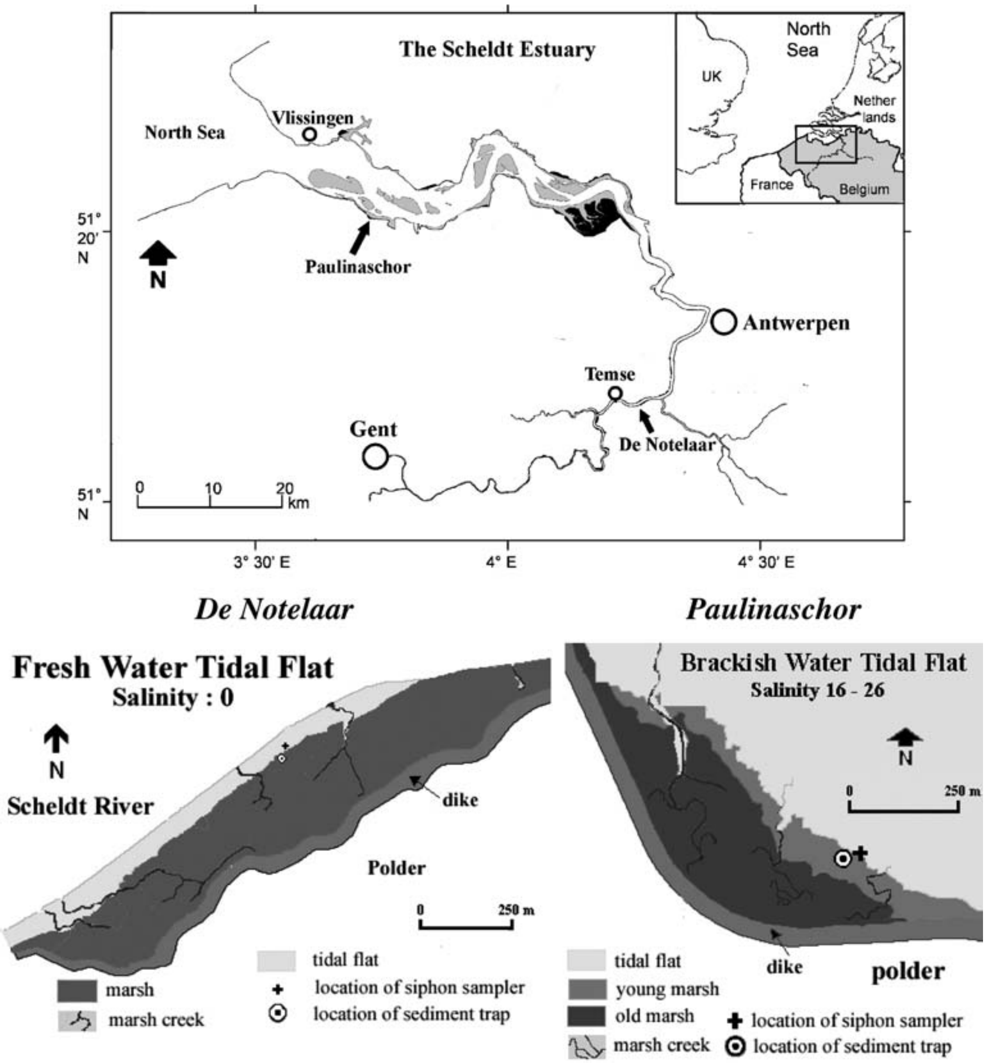

Figure 1. The scheldt Estuary. Localisation of De Notelaar (the fresh water tridal flat) and Paulinaschor(the brackish water tidal flat).

starts uptaking water when the tide rises approximately 1 m above the tidal flat surface. Outflow of the water from the siphon sampler takes place, ca. 5–6 h later, when tide falls below 50 cm above the tidal flat surface. Since the tube end is 15 cm above the bottom of the siphon sampler, it assures undisturbed settling of the suspended matter and avoids its dehydration. Every 14 days at neap tide of each spring-neap tidal cycle, the siphon samplers were collected and replaced by clean ones. The settled suspended matter in the siphon sampler was never consolidated but in a fluid state. The possible ongoing biological processes within the siphon sampler are considered as quasi-equivalent to the ones on the tidal flats because of two reasons. First, the temperature within the siphon sampler was ambient and equal to the tidal flat surface. Second, the settled suspended matter in the siphon sampler was always covered by a layer of *in situ* estuarine water; and the bottle was refilled ca. every 5–6 h at every tide, which is considered equivalent to the tidal inundation on the tidal flats. It is noted that the unknown shear rate, which may occur in the siphon sampler settings, may alter the flocs, however, if so, then the error effect is standard throughout the whole sampling period and does not influence the interpretation of the results of this study. It is also noted that shear rate on the flocs in nature on the tidal flats is not available as well. As stated earlier that this study is the first investigation of possible seasonal variation of flocculation on the tidal flats, without information of shear rate does not change the present study results, however, it shall be measured in the future research.

Suspended matter samples from the Scheldt main channel adjacent to the study sites were collected using PVC bottles (200 ml) every 14 days around neap tide of each spring-neap tidal cycle. Total suspended matter concentration was determined according to a standard non-filterable solids method using Nuclepore 0.45-μm pore size filters. After filtration, samples were dried at 105 °C till constant weight. The obtained suspended matter concentrations (SMC) are considered representative for the potential suspended matter supply to the tidal flats from the main channel.

Dispersed particle size spectra – physical properties of suspended matter

Physical properties of suspended matter were determined using a method detailed in Chen (2003). Approximately 20 g of the homogenised suspended matter sample were prepared by removing salts, organic matter and carbonates with H_2O_2 and HCl. The dispersed particle grain-size distribution of the coarse fraction (75–2000 μm) was separated by wet sieving on a 75-μm sieve, then dried at 105 °C, and finally dry sieved using an ASTM sieve series at a quarter phi (phi unit: $\phi = -\log_2 d_{mm}$, where d_{mm} is the dispersed particle diameter expressed as millimetre) interval. The grain size distribution of the fine fraction (<75 μm) was obtained using the Sedigraph 5100.

Organic matter determination

Total organic matter content was determined by loss on ignition at 430 °C for 24 h (Gale & Hoare, 1991). Samples were dried to a constant weight at 105 °C prior to combustion. The combustion of the recent and clay-rich sediments at 430 °C for 24 h can minimise destruction and weight loss of carbonates and dehydration of clays (Cattol, 1962), and the longer time span is more effective against stronger organic compounds such as cellulose. The precision is 1% for the total organic matter determination.

Non-dispersed particle – floc characteristics examination

Floc characteristics of suspended matter were examined from duplicate or triplicate samples taken carefully from the siphon samplers on site. Before the floc sampling, water was taken from the Scheldt main channel adjacent to the study sites and filtered through 0.2-μm pore size filter. Glutaraldehyde (2% final concentration) was added as a preservative. This particle free site water, further called as PFSW, is essential to prevent microorganisms' growth, and sustains *in situ* salinity and pH. No colloids were observed in the PFSW when viewed at 20,000× magnification under ESEM-WM. A pipette withdrawal method was applied to take the sample. A 1-ml automatic pipettor was fitted with a lab made wide tip (ø = 5.5 mm). The pipette tip was immersed slowly into the siphon-sampler, and the 1-mm top layer of the settled suspended matter was carefully and very slowly sampled to avoid shearing and immediately distributed into a 10-ml tower filtration system, which contained 3 ml (equivalent to height of 1.5 cm) of PFSW prior to the sample addition. By applying 3 ml of PFSW in the filtration, a gentle transfer of the flocs to the filter is assured; the eventual break up of flocs is minimised; and an even distribution of flocs onto the filter surface is obtained. The suspension was left undisturbed for 3 h for floc settling, and then filtered under very gentle manually controlled gravity filtration (hand-vacuum-pump, pump flow of 15 ml/per blow) through a 0.2-μm nuclepore filter. The filter was placed on top of a paper pad, which was saturated with PFSW, and stored in an enclosed box in the dark at 1–4 °C. Within 24 h the filter (with the retained flocs) was examined under ESEM-WM directly without any further preparation. Floc size, shape and microstructure were viewed at 250, 500 and 1000× magnification. Particles down to 4 μm could be measured precisely. Flocs smaller than 4 μm were not counted into the floc size distribution in this study. For each sample, a minimum of 20 images was taken and at least 400 and up to 1000 flocs were measured. Every individual floc length, width, perimeter and area were determined manually using the image software SigmaScanPro5. The procedure to acquire natural flocs described here has been tested experimentally in the laboratory on flocs generated in the floc-generator (a device used in flocculation simulation experiment), and has proved to be an optimal preparation that reflects the *in situ* state of the flocculation as closely as possible (Chen, 2003).

Short term suspended matter deposition rate evaluation

Short-term potential deposition rate of suspended matter was measured, from May 2000 to May 2001, using circular plastic sediment traps (diameter of 23.3 cm). The sediment trapping method is explained by Temmerman et al. (2003) and proven to be successful in field measurements. The traps were attached using steel claws and levelled exactly to the marsh surface adjacent to the tidal flats and near the main tidal creeks. A floatable cover was constructed above the sediment trap to protect the deposited sediment from splash by raindrops during low tides. Every 14 days around neap tide, the sediment traps were collected and replaced by clean ones. In the laboratory, the deposited suspended matter was washed from the traps and rinsed with deionized water, to remove salts, and sieved at 707 μm, to remove macroscopic plant and/or shell material. The remaining suspended matter was then oven-dried at 105 °C and weighed to determine the deposition rate of suspended matter (in g m^{-2}). The fortnight measurement of suspended matter deposition rate over a year was intended to gain knowledge of real deposition potential and did not investigate the erodibility of upper layer.

Results

Particle size spectra of dispersed suspended matter

On both tidal flats, suspended sediments were very fine-grained with a clay fraction (less than 4 μm) of more than 50% of the total grain-size distribution and a mean diameter below 3 μm (Table 1). Sediment properties, in terms of sand and clay fractions, are shown in Figure 2. The percentage sand on the FTF is relatively higher, around 10% and up to 17%, than those on the BTF where it is about 2–3% around the year and never exceeds 5%. The clay fraction on the FTF shows little variation and is mainly below 60%. However, on the BTF, the clay fraction shows a relatively wide variation and is mostly above 60%. In summer, on the FTF the sand content exhibits a noticeable decrease, while on the BTF the clay content shows a perceptible decrease. On the FTF, the silt-to-clay ratio increases from 0.4 in winter to 0.8 in summer, while on the BTF, this increase is from 0.2 in winter to 0.7 in summer. This denotes that the observed clear decrement of sand content on the FTF and of clay content on the BTF in summer is compensated largely by an increase in silt content on both tidal flats.

Organic matter

OM content of the suspended matter on both tidal flats shows very close values fluctuating around 9% (Fig. 2), however, in summertime high OM content exists on the BTF varying around 20% but not much change is observed on the FTF. This indicates a seasonal variation and an input of OM during summer on the BTF. Calculating annual average of OM content brings an average value of 9 ± 1% on the FTF and of 14 ± 5% on the BTF. It can also be observed that on the FTF, the change of OM shows a similar trend as the change of clay fraction; however, a different trend is observed on the BTF, where OM fluctuates in an opposite way to the change of clay fraction.

Floc characteristics

The seasonal distribution of the floc size, expressed as floc length, is shown in Figure 3. Over a one-year period from autumn (September) through winter and spring to summer (July), flocs on both tidal flats show a growth in length, demonstrated by an increasing proportion of flocs larger than 63 μm. On the FTF, floc size exhibits a clear

Table 1. Suspended matter properties. Values in the table are mean ± standard deviation. FTF, the fresh water tidal flat; BTF, the brackish water tidal flat.

	FTF	BTF
Sand	10 ± 4%	2.3 ± 2.3%
Silt	36 ± 4%	31 ± 6%
Clay	55 ± 5%	66 ± 8%
Coarsest grain-size	105 ± 10 μm	69 ± 15 μm
Grain-size mean	2.5 ± 1.4 μm	1.4 ± 0.5 μm
Largest floc	210 ± 71 μm	290 ± 170 μm
Floc mean	47 ± 17 μm	52 ± 30 μm

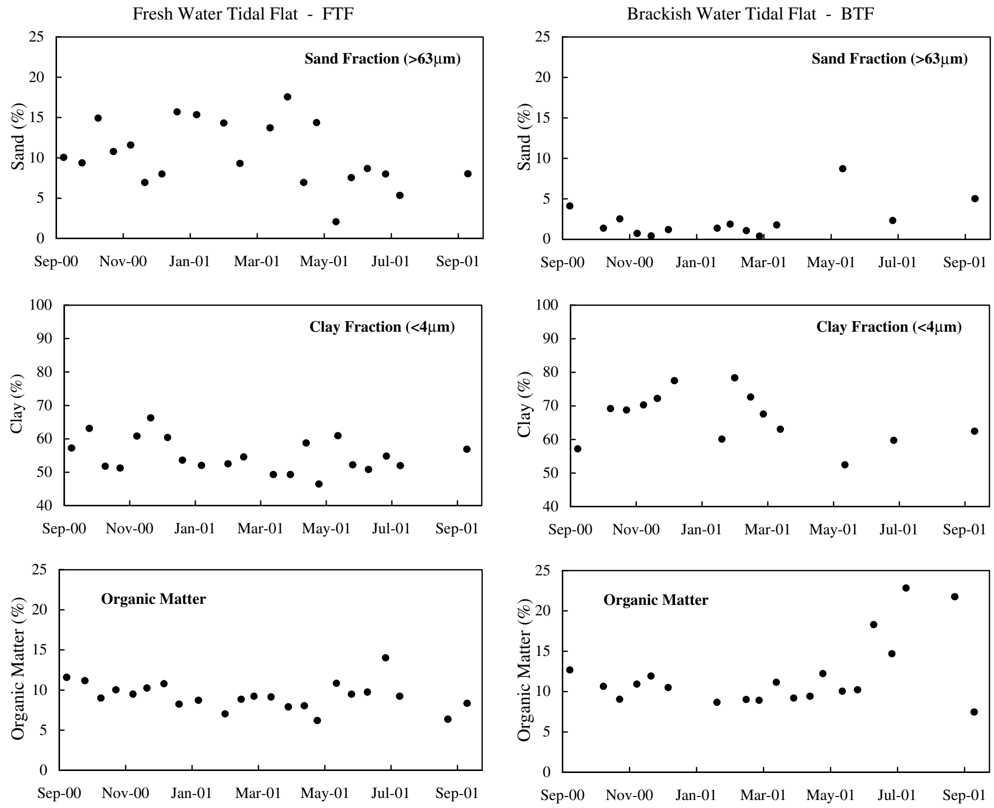

Figure 2. Suspended matter physical properties and organic matter content.

unimodal distribution in autumn and winter (September and December) with floc size ranging from ca. 20–177 μm. It develops a bimodal distribution in spring (March) with an increasing fraction of flocs larger than 63 μm, and demonstrates a trimodal distribution in June with a noticeably high proportion of flocs between 125 and 250 μm. Floc size on the BTF exhibits a clear unimodal distribution in winter and spring (December and March), and develops a trimodal distribution in June with a remarkably high proportion of flocs ranging from 125 to 500 μm.

Floc microstructure is revealed through ESEM-WM observations. During the winter and spring periods, flocs show up mostly as relatively small with few little voids and tightly compact structure. In summer, flocs appear mainly as considerably large with big obvious voids and loosely formed structure (Fig. 4).

Floc sphericity is defined by floc length-to-width ratio, where ratio 1 (i.e. 5 to 5) is spherical and ratio 1.25 (i.e. 5 to 4) is defined here as the least spherical. Thereby, spherical flocs, in this study, are referred to those flocs having a length-to-width ratio less than 1.25. The average length of the flocs varies from 30 to 90 μm in different seasons over the year on both tidal flats, however, it appears that there is no unique relationship between floc size and its sphericity (Fig. 5). Yet, on both tidal flats, the highest proportion of spherical flocs occurs in summer and also corresponds to the largest mean floc-size.

Short-term deposition rate of suspended matter

Over this one-year period, high river discharge appears from November to April (winter and spring) with a maximum of 270 $m^3\ s^{-1}$ in March and low river discharge from June to August (summer) with a minimum of 30 $m^3\ s^{-1}$ in August (data from Taverniers E., 2002. Administration Waterways and Maritime Affairs, Section Maritime Entrance, Antwerp, Belgium.) (Fig. 6). The amount of suspended matter load exhibits high and low values corresponding to the river discharge over this

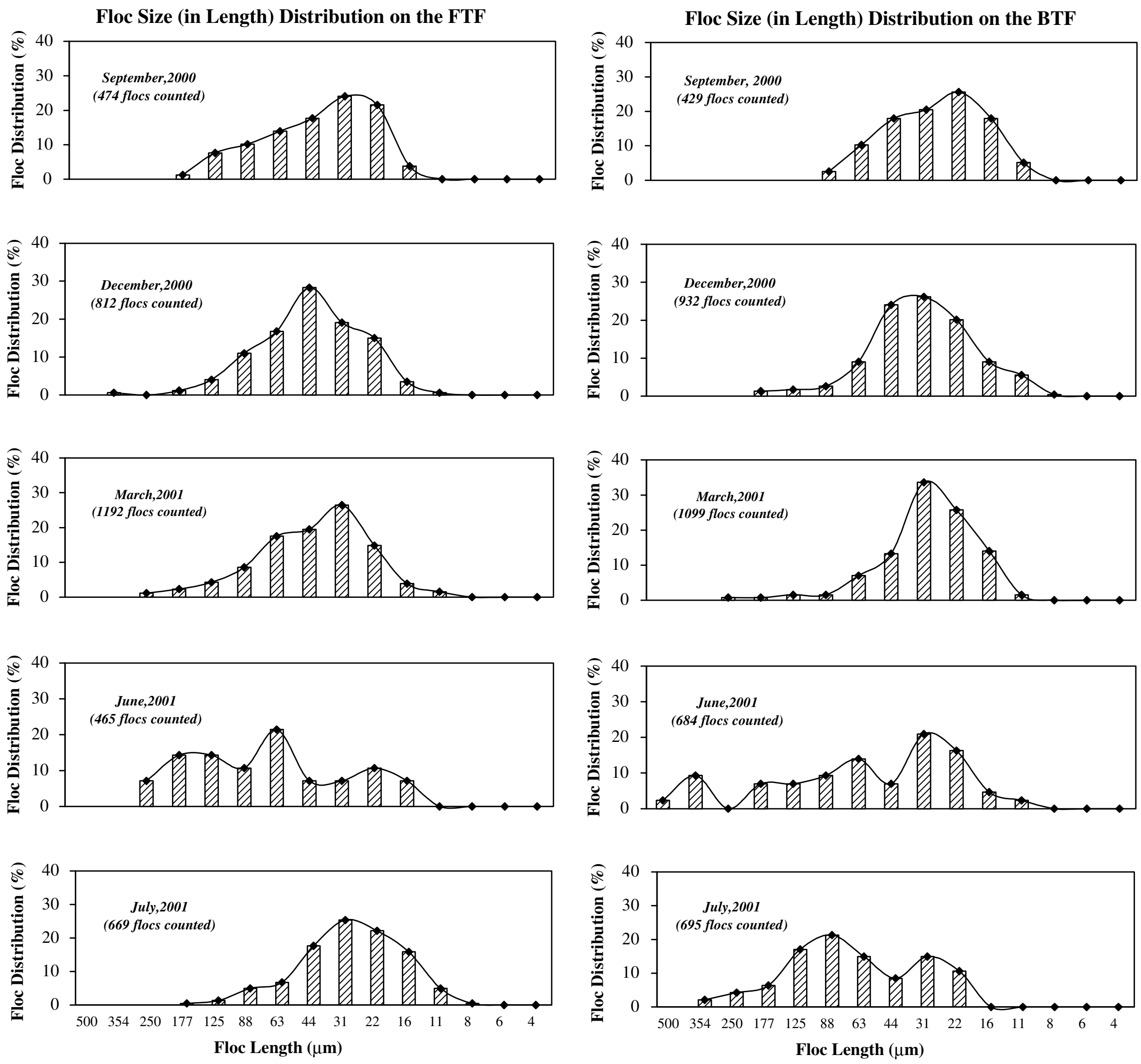

Figure 3. Floc size (in length) seasonal distributions. FTF, the freshwater tidal flat; BTF, the brackish water tidal flat.

one-year period (Fig. 6) with a maximum load of 103,000 ton month^{-1} in spring (March) and a minimum load of 8000 ton month^{-1} in summer (August and September) (data from Taverniers E., 2002. Administration Waterways and Maritime Affairs, Section Maritime Entrance, Antwerp, Belgium.). The fortnight measurements of SMC as well as the short-term potential deposition rate of suspended matter show a clear seasonal variation and portray a similar evolution pattern to that of river discharge and suspended matter load (Fig. 6). This points out that deposition of suspended matter on the tidal flats correlates positively to river discharge and supply of suspended matter as well. The potential supplies of suspended matter from the Scheldt main channel have annual average SMC values of 73 and 50 mg l^{-1} to the FTF and BTF, respectively. These values are largely in accordance with the long-term spatial variations of suspended matter in the surface water documented by Chen (2003), where SMC fluctuating around 82 mg l^{-1} in the middle estuary (58–92 km) and around 50 mg l^{-1} in the lower estuary (0–58 km). The SMC is higher in winter than in summer, which fits the seasonal suspended matter distribution pattern in the Scheldt (Chen, 2003) and is in agreement with

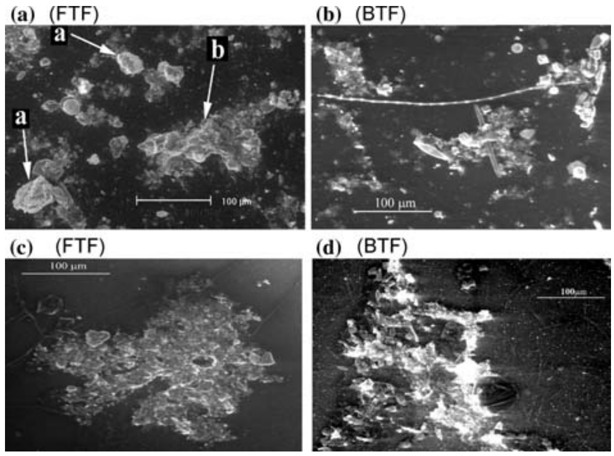

Figure 4. Illustration of ESEM-WM microphotographs of particles and flocs. All photos have the same measuring scale with bar length indication on each photos. Photo (a) and photo (b) examples of flocs in winter: small, dense and elongated flocs. Photo (c) and photo (d) examples of flocs in summer; large, loose and spherical flocs. Character "a" indicates mineral particles and character "b" indicates flocs, not all the mineral particles and flocs are indicated on the photos.

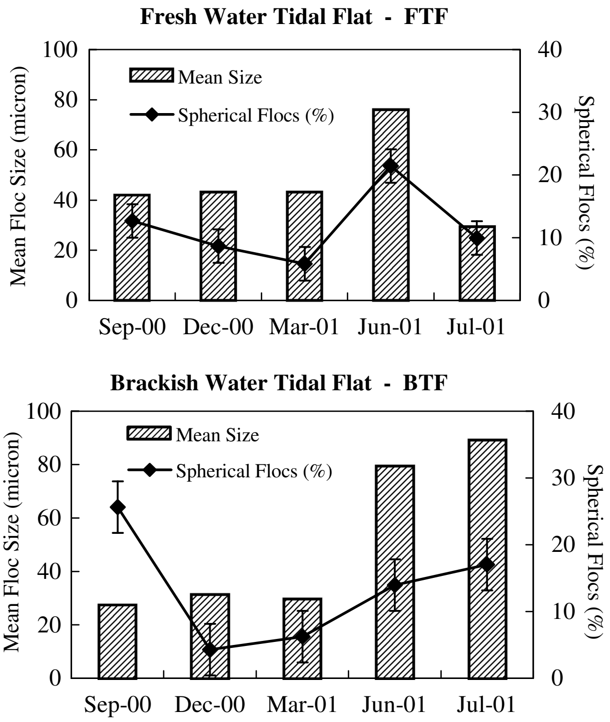

Figure 5. Seasonal distribution of average floc size and percentage of spherical flocs. Bars indicate standard error.

the SMC measurements reported on the adjacent tidal marshes by Temmerman et al. (2003). On both tidal flats, the measured deposition rates are relatively high in winter and low in summer. Deposition rate is higher on the BTF and shows a more pronounced separation between autumn–winter and spring–summer than deposition rate measured on the FTF, with average values of 1650 and 950 g m^{-2} per spring-neap cycle on the BTF and FTF, respectively.

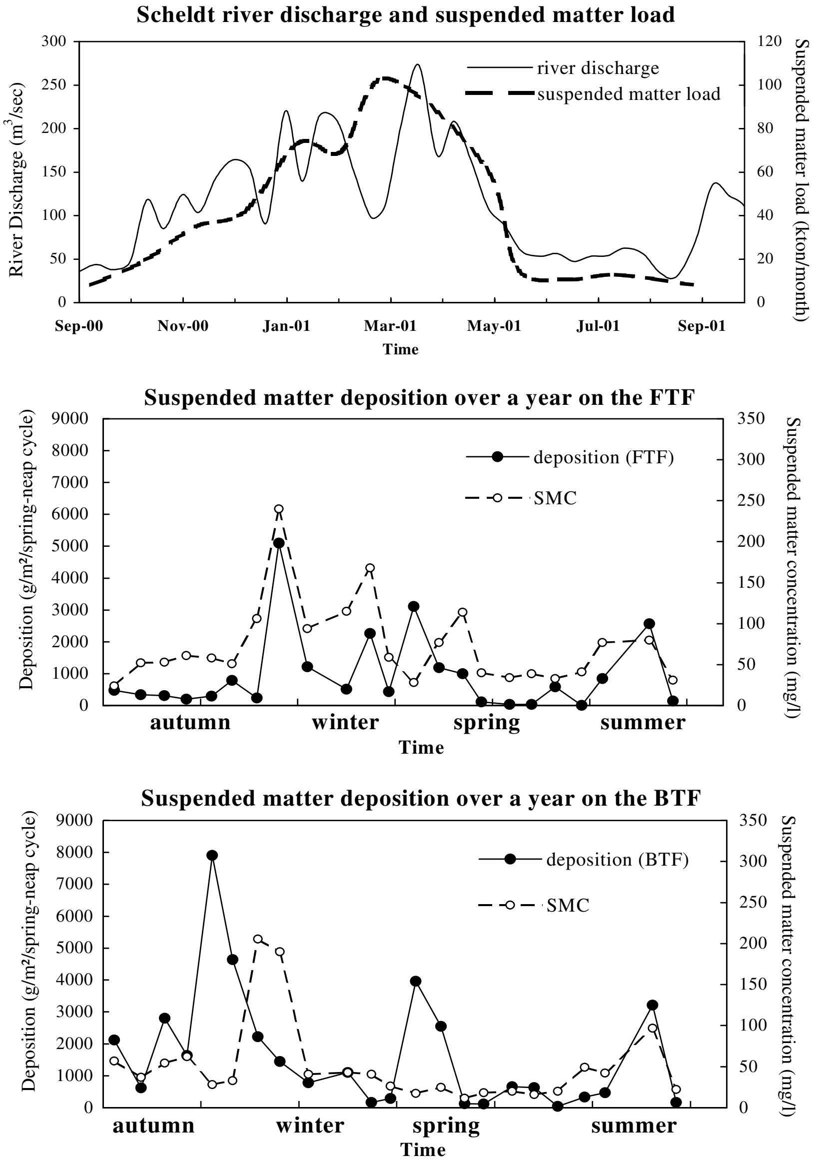

Figure 6. The scheldt river discharge and suspended matter load (Data from Traverniers E., 2002. Administration Waterways and Maritime Affairs, Section Maritime Entrance, Antwerp, Belgium). And over one-year fortnightly measurements of SMC and short-term deposition rate of suspended matter on the FTF (freshwater tidal flat) and the BTF(brackish water tidal flat).

Discussion

Seasonal variation of dispersed particle properties

On both tidal flats, the dispersed suspended particles were very fine (Table 1). The differences in physical properties of the suspended matter between two tidal flats were mainly reflected on two aspects. The first is that the particles were relatively coarser on the FTF with less clay fraction than those on the BTF (Fig. 2). This finding was consistent with the characteristics of suspended particles in the main channel in the Scheldt estuary, where fine sandy-clay at the vicinity of FTF and silty clay near the area of BTF (Chen, 2003). The second aspect is, obviously, fining of the particle grain-size on the

FTF and coarsening on the BTF in summer. The observed main seasonal change in grain-size composition in summer shows a decrement in sand content on the FTF and a decrement in clay content on the BTF. In theory, fine particles tend to aggregate due to their large surface area having a greater capacity for adsorption of inorganic and organic substances. Hence it is expected to find relatively larger flocs on the BTF than on the FTF, and it is also expected to observe a reduced floc-size in summer on the BTF due to decrement of clay fraction. However, the results of the floc size analyses show differently, and a remarkable increase of floc size occurs in summer (Fig. 5). Therefore, other factors must be at work.

In the Scheldt, suspended particles contain mostly silicon and probably consisted mainly of quartz or diatoms next to other silicate and alumino-silicate minerals. No systematic variations were observed either in particle chemical compositions (Van Alsenoy et al., 1989) or in mineral compositions (Van Eck et al., 1991) throughout the whole estuary, except for a seaward increment of both calcium-carbonate content (Wartel & Faas, 1986; Van Alsenoy et al., 1989) and smectite (Van Eck et al., 1991; Wartel & Van Eck, 2000). There has been no study yet on the effect of spatial carbonate variation on flocculation processes of suspended particles in the Scheldt. However, an important factor masking the intrinsic property of suspended particle is the fact that in almost all estuaries the particle possesses organic coatings (cf. Gibbs, 1977; Hunter & Liss, 1982; Van Leussen, 1994; Chen, 2003).

Floc size, floc shape and OM

The use of ESEM-WM technique has provided a valuable insight in suspended matter texture. This one-year survey not only shows that suspended matter is flocculated on both FTF, and BTF, but also reveals some noteworthy association between the amount of OM and the floc characteristics.

The mean values of the flocs and of the dispersed particles differ by an order of magnitude. The size of the largest flocs is up to 2–5 times bigger than the coarsest dispersed particles (Table 1). The results of this study show that the proportion of the number of the flocs larger than 63 μm, the evolution of the size of the largest floc population (floc-size in the 95th percentile) and floc sphericity all reveal a positive correlation with the change of OM content (Fig. 7). Here "floc size in the 95th percentile" is defined as floc size equal to or greater than 95% of all flocs, or in other words, 5% of flocs are larger than the-95th-percentile size. In winter and spring, flocs larger than 63 μm are more abundant on the FTF (about 20%) than on the BTF (about 4%). It is also important to note that at least 5% of the flocs are larger than 100 μm and reach up to 300 μm on the FTF (Figs 3 and 7). In summer, on the BTF, flocs larger than 63 μm increase strongly to about 50% of the total floc-size distribution, and over 5% of the flocs are larger than 350 μm reaching up to 500 μm (Figs 3 and 7).

Besides the seasonal variations in floc size, differences in floc shape are also observed. The changes in floc sphericity exhibit a clear positive correlation with the change of OM content, larger and more spherical flocs are generated during summer time when OM is also high. Furthermore, ESEM examinations reveal more elongated flocs in winter and spring (November–April), while spherical flocs are dominant during the summer period (June–August) (Fig. 4). It appears that, with increasing floc size, flocs are not necessarily more elongated, but rather expand in three dimensions. It has been known for a long time that floc formation and settling are controlled by a couple of processes and key factors, among which differential settling are of importance in this study setting (cf. Dyer & Manning, 1999). Settling flocs concatenate with small flocs that they encounter on their settling path through the suspension. This two-dimensional process generates large and elongated flocs. The omnidirectional growth of flocs as seen in this study, however, indicates a three-dimensional process whereby spherical flocs result from a random growth due to the adhesion of more dispersed particles and small flocs in the suspension including organic substances. With increasing floc-size flocs do not become longer (more elongated) but rather grow in three dimensions, which means that the floc growth is not a result of string like concatenation (chain forming), but rather a result of uptaking organic substances into the flocs. Figure 7 shows the effect of OM content on floc size and shape. Living (microorganisms) OM can produce non-living OM secretion or extracellular polymers which can surround either individual particles or flocculated particles

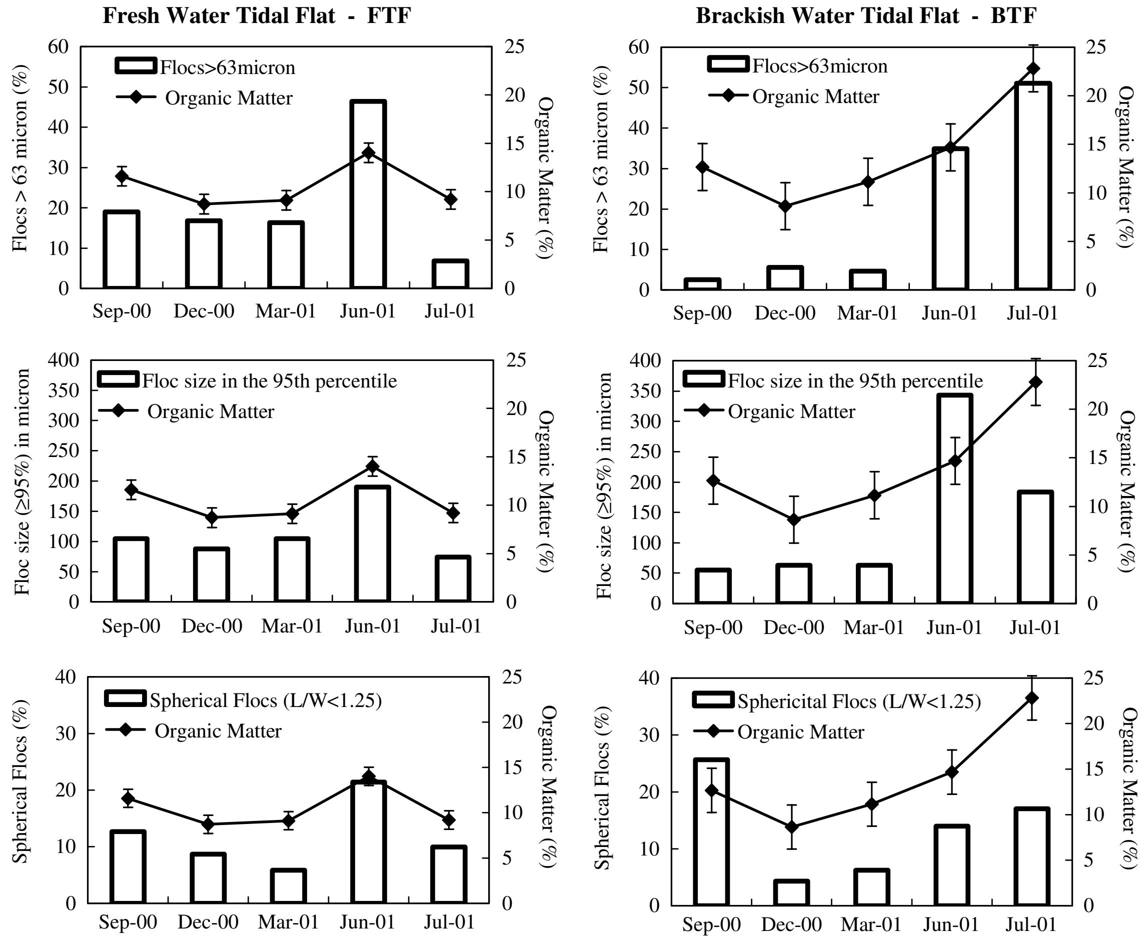

Figure 7. Seasonal distributions of flocs $> 63\ \mu$m, floc size in the 95th percentile, and spherical flocs in relations with organic matter content. Bars indicate standard error.

attaching them to each other, and acting as a strong binding agent or bridge between the particles. Generally, biological processes are responsible for the production of such polymers (cf. Eisma, 1986; Droppo et al., 1996; Bennett et al., 1999). It is frequently observed through ESEM-WM that diatoms and mycelia (as can also be seen in Fig. 4) as well as numerous bacteria exist in the samples from both tidal flats. It indicates that biological activity and/or OM is the key factor for the omnidirectional growth of flocs observed in this study.

Deposition and interaction of flocculated and dispersed particles

It is observed that flocs are generally smaller at winter and spring times. The floc size distributions on both tidal flats are skewed to the smaller sizes (Fig. 3). This may be attributed to low biological activity and/or low-degradable OM in winter. Besides, given the results of seasonal variation of floc and dispersed particle characteristics, two hypotheses are put forward concerning the possible interactions between floc and single grain on the FTF and the BTF, respectively.

One hypothetical mechanism is a corrasion effect of sand grains on flocs on the FTF. In this mechanism, transported sand particles serve as tools causing corrasion, which is merely sand blasting under natural conditions (Allen, 1985), at each contact with the flocs. The relatively high sand content in winter and spring (Fig. 2) may contribute to this mechanism by a corrasion effect of the sand grains on the fragile flocs and breaking up the larger flocs into smaller but condensed ones. Indeed, ESEM observations present more relatively small and tightly compact flocs co-existing with sand-sized mineral particles at winter–spring time (Fig. 4). In addition, river discharge (Fig. 6) is up to 10 times higher in winter and spring, consequently currents and turbulence may be stronger (Fennessy et al., 1994a). This can cause the large fragile flocs breaking up into smaller, condensed flocs on the FTF as observed by ESEM-WM (Fig. 4).

The second hypothetical mechanism is flocculation and its trapping effect on clay particles on the BTF. Flocs are networks in which clay particles are trapped. Suspension of fine sediments containing clay minerals tend to flocculate because of electrostatic charges and organic complexes on the particle surfaces, and because of the presence of polysaccharides (cf. Frankel & Mead, 1973; Paerl, 1977; Amos et al., 1988; Vos et al., 1988). During winter–spring period, clay content is relatively high on the BTF. Therefore, large flocs formation is expected. However, the floc size distribution is skewed to the smaller sizes (Fig. 3), flocs are relatively small and condensed (Fig. 4). This implies that there are processes or factors inhibiting large floc formation. Although, compared to the FTF, the effect of high river discharge in winter and spring is less significant on the BTF because of the high tidal discharge with annual average of about 30,000 $m^3 s^{-1}$ (for both ebb and flood, data from Hydrological Research division, Waterways and Marine Affairs Administration of the Environment and Infrastructure, Department of the Ministry of the Flemish Community, Belgium. 1996), the normal strong wind and related wave activity during winter can have a destructive effect on flocs and induce flocs breaking up on the BTF. This may explain the floc-sizes being skewed to smaller sizes. So, the high deposition rate shows that, in spite of predominant floc destructive processes, deposition of small and condensed flocs appears to be effective enough to form a stable layer on the BTF.

Besides the hypothetical interactions between flocculated and dispersed particles, a similar seasonal depositional pattern of suspended matter is observed on both tidal flats (Fig. 6). This seasonal depositional pattern shows high deposition rate from late autumn to spring and low deposition rate from summer to early autumn. This evolution displays close association with suspended matter load and supply to the tidal flats. The results demonstrate that the short-term suspended matter high deposition rate depends largely on high supply of suspended matter, which is potentially linked to high river discharge, and small and condensed flocs.

Floc microstructure and its effect on suspended matter deposition

Suspended matter short-term deposition and the possible interactions between flocculation and suspended particles discussed above bring up a research question: what is the effective impact of flocculation, whether floc size or floc structure, on suspended matter deposition?

Floc settling is widely known to depend on floc size (e.g. Fennessy et al., 1994a, b; Sternberg et al., 1999; Mikkelsen & Pejrup, 2001). Therefore, the observed large flocs formed in summer settled on the tidal flats are expected to contribute to a high short-term deposition rate. However, the measured deposition rate is low in summer. Hill (1998) compared settling of flocs from a number of environments, and found settling rates fairly constant even though component particle size and energy of the environment varied greatly. As floc size and its settling cannot give a satisfactory explanation to the field measurements, hence, the floc structure is proposed to explain the phenomenon.

Floc microstructure examination using ESEM-WM can visualise to some extent, the structure of flocs to which the floc strength is related. When deposition rate is high, floc microstructure is relatively tightly compact and flocs are small and elongated with little voids. It follows that small, condensed flocs and a low-degradable OM lead to the formation of a presumably stable deposition layer. On the contrary, when the deposition rate is low, floc microstructure is considerably loose and flocs are large and spherical with big voids, along with high more-degradable OM. This implies that, although in summer OM is high favouring large floc formation on the one hand, OM decomposition catalyses floc breaking up on the other. Deposition of these very loose degradable-OM-flocs, holding only few mineral particles, results in an easier erodible layer in summer.

The floc microstructure examination reveals the floc network and provides an estimation of floc strength, which in turn determines the floc characteristics such as size and shape as well as its settling. It is natural to assume that in this study the observed compact, and condensed small flocs with few little voids have a high density, while loosely formed large flocs with big voids hold a low density (Droppo et al., 1997). This assumption is in accordance with the study of Droppo et al. (2000) who show that the density of a floc is primarily controlled by its composition (organic and inorganic) and its porosity (pore size and structure), and consistently shows a negative relationship with floc size. Besides, floc effective density decreases with increasing floc size (Fennessy et al., 1994b; Dyer et al., 1996; Hill, 1998). Moreover, as floc size increases, its decreased density is related to the concomitant increase in porosity, and therefore water content. It is suggested here that floc structure influences the sedimentary processes, and floc strength is related to its structure. Fine-grained sediments transported as compact flocs affect the suspended matter deposition rate. In addition to high suspended matter load along with high river discharge in winter, suspended matter deposition rate is enhanced by the dense and small flocs together with the high sand supply on the FTF and by the dense and small flocs incorporating more available clay particles on the BTF.

Conclusions

Flocculation is one of the significant factors along with other principal factors, including river discharge, tidal energy and wave action as well as suspended matter load in the estuarine water, determining the transport and deposition of suspended matter on the tidal flats in estuaries. This study illustrates that seasonal variation in suspended matter, short-term deposition rate can be explained as a consequence of seasonal variation in river discharge and suspended matter concentration as well as seasonal variation in floc structure and density. The ESEM-WM study has provided important information of the textural properties of suspended matter. Floc microstructure and size exhibit clear seasonal variations and are correlated with the measured short-term suspended matter deposition rates on the tidal flats over this one-year survey. Floc size and sphericity positively correlates with the change of organic matter. High organic matter increases floc size in a three-dimensionally expanding way. The strength of flocs is related to their density and has an effect on the sedimentary processes. Highly condensed flocs contribute to suspended matter deposition resulting in a stable sediment layer in winter. Loosely formed flocs likely lead to an easier erodible sediment layer at summer time. It is deduced here that floc structure-related density is a more determining parameter than floc size in the sedimentary process of suspended matter.

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References

Allen, J. R. L., 1985. Principles of Physical Sedimentology. George Allen & Unwin, London: 139–152.

Amos, C. L., N. A. Van Wagoner & G. R. Daborn, 1988. The influence of subaerial exposure on the bulk properties of fine-grained intertidal sediment from Minas Bain, Bay of Fundy. Estuarine, Coastal and Shelf Science 27: 1–13.

Anonymous, 1961. The single stage sampler for suspended sediment. A study of methods used in measurement and analysis sediment loads in streams. St. Anthony Falls Hydraulic Laboratory, Minnesota. United States government printing office, reports 13: 5–103.

Baerwald, R. J., P. Burkett & R. H. Bennet, 1991. Techniques for the preparation of submarine sediments for electron microscopy. In Bennet, R. H., W. R. Bryant & M. H. Hul bert (eds.), Microstructure of Fine-grained Sediments from Mud to Shale. Springer-Verlag: 309–320.

Bennet, R. H., B. Ransom, M. Kastner, R. J. Baerwald, M. H. Hulbert, W. B. Sawyer, H. Olsen & M. W. Lambert, 1999. Early diagenesis of organic matter on mass physical properties and processes, California continental margin. Marine Geology 159: 7–34.

Cattol, D., 1962. The clay minerals. In Milner, H. B. et al. (eds), Sedimentary Petrography: Volume II – Principles and Applications (4th revised edn. Chapter 3). George Allen & Unwin Ltd., London.

Chen, M. S., 2003. Suspended matter and flocculation in the estuarine environment. Ph.D. Thesis. Vrije Universiteit Brussel, Belgium.

Droppo, I. G., D. T. Flannigan, G. G. Leppard, C. Jaskot & S. N. Liss, 1996. Floc stabilization for multiple microscopic techniques. Applied and Environmental Microbiology 62: 3508–3515.

Droppo, I. G., G. G. Leppard, D. T. Flannigan & S. N. Liss, 1997. The freshwater floc: a functional relationship of water and organic and inorganic floc constituents affecting suspended sediment properties. Water, Air and Soil Pollution 99: 43–54.

Droppo, I. G., D. E. Walling & E. D. Ongley, 2000. The influence of floc size, density and porosity on sediment and contaminant transport. In Stone, M. (ed.), Role of Erosion and Sediment Transport in Nutrient and Contaminant Transfer. IAHS Publication No. 263, Waterloo, Ontario: 141–147.

Dyer, K. R., M. C. Christie, N. Feates, M. J. Fennessy, M. Pejrup & W. Van der Lee, 2000. An investigation into processes influencing the morphodynamics of an intertidal mudflat, the Dollard Estuary, The Netherlands: I. Hydrodynamics and Suspended Sediment. Estuarine, Coastal and Shelf Science 50: 607–625.

Dyer, K. R., J. Cornelisse, M. P. Dearnaley, M. J. Fennessy, S. E. Jones, J. Kappenberg, I. N. McCave, M. Pejrup, W. Puls, W. Van Leussen & K. Wolfstein, 1996. A comparison of *in situ* techniques for estuarine floc settling velocity measurements. Journal of Sea Research 36: 15–29.

Dyer, K. R. & A. J. R. Manning, 1999. Observation of the size, settling velocity and effective density of flocs, and their fractal dimensions. Journal of Sea Research 41: 87–95.

Edgerton, H., P. Orntner & W. McElroy, 1981. In situ plankton camera. Oceans Sept. 1981: 558–560.

Eisma, D., 1986. Flocculation and de-flocculation of suspended matter in estuaries. Netherlands Journal of Sea Research 20: 183–199.

Eisma, D., G. C. Cadee, R. Laane & J. Kalf, 1982. Preliminary results of Aurelia- and Navicula cruises in the Rhine and Ems estuaries. January – February, 1982. Mitt. Geol. Paläont. Inst. Univ. Hamburg. SCOPE/UNEP Sonderb 52: 633–654.

Eisma, D., T. Schuhmacher, H. Boekel, J. Van Heerwaarden, H. Franken, M. Laan, A. Vaars, F. Eijgenraam & J. Kalf, 1990. A camera and image-analysis system for *in situ* observation of flocs in natural waters. Netherlands Journal of Sea Research 27: 43–56.

Fennessy, M. J., K. R. Dyer & D. A. Huntley, 1994a. Size and settling velocity distributions of flocs in the Tamar Estuary during a tidal cycle. Netherlands Journal of Aquatic Ecology 28: 275–282.

Fennessy, M. J., K. R. Dyer & D. A. Huntley, 1994b. INSSEV: an instrument to measure the size and settling velocity of flocs in-situ. Marine Geology 117: 107–117.

Frankel, L. & D. J. Mead, 1973. Mucilaginous matrix of some estuarine sands in Connecticut. Journal of Sedimentary Petrology 43: 1090–1095.

Gale, S. J. & P. G. Hoare, 1991. Quaternary sediments: petrographic methods for the study of unlithified rocks (Chapter 5.9). Belhaven Press.

Gibbs, R. J., 1977. Clay mineral aggregation in the marine environment. Journal of Sedimentary Petrology 47: 237–243.

Hill, P. S., 1998. Controls on floc size in the sea. Oceanography 11: 13–18.

Honjo, S., K. W. Doherty, Y. C. Agrawal & V. L. Asper, 1984. Direct optical assessment of large amorphous aggregates (marine snow) in the deep ocean. Deep-Sea Research 31: 67–76.

Hunter, K. A. & P. S. Liss, 1982. Organic matter and the surface charge of suspended particles in estuarine waters. Limnology and Oceanography 27: 322–335.

Kranck, K., 1984. The role of flocculation in the filtering of particulate matter in estuaries. In: Kennedy, V. (ed.), The Estuary as a Filter. Academic. Press, London: 159–175.

Mikkelsen, O. & M. Pejrup, 2001. The use of a LISST-100 laser particle sizer for in-situ estimates of floc size, density and settling velocity. Geo-Marine Letters 20: 187–195.

Milligan, T. G., 1996. In Situ particle (floc) size measurements with the Benthos 373 Plankton Silhouette Camera. Journal of Sea Research 36: 93–100.

Milligan, T. G., G. C. Kineke, A. C. Blake, C. R. Alexander & P. S. Hill, 2001. Flocculation and Sedimentation in the ACE Basin, South Carolina. Estuaries 24: 734–744.

Nishizawa, S., M. Fukuda & N. Inone, 1954. Photographic study of suspended matter and plankton in the sea. Bull. Fac. Fish. Hokkaido Univ., 5: 36–40.

Paerl, H., 1977. Bacterial sediment formation in lakes: trophic implications. International symposium: Interactions between sediments and fresh water, Dr W. Junk Publishers, The Hague. Centre for Agricultural Publishing and Documentation, Wageningen: 40–47.

Ransom, B., R. H. Bennett & R. Baerwald, 1997. In situ organic matter in recent marine sediments: a TEM investigation of organic matter preservation on continental margins and the monolayer hypothesis. Marine Geology 138: 1–9.

Sternberg, R. W., I. Berhane & A. S. Ogston, 1999. Measurement of size and settling velocity of suspended aggregates on the Northern California continental Shelf. Marine Geology 154: 43–53.

Temmerman, S., G. Govers, S. Wartel & P. Meire, 2003. Spatial and temporal factors controlling short-term sedimentation in a salt and freshwater tidal marsh, Scheldt estuary, Belgium - SW Netherlands. Earth Surface Processes and Landforms 28: 739–755.

Van Alsenoy, V., A. Van Put, P. Bernard & R. Van Grieken, 1989. Chemical characterisation of suspensions and sediments in the North Sea and Scheldt estuary. In: Pichot G (ed.), Progress in Belgian Oceanographic Research. Proceedings of the North Sea Symposium held in Ghent, 14 February 1989. Prime Minister's Services Science Policy Office. Ministry of Public Health and Environment.

Management Unit of the Mathematical Models of the North Sea and Scheldt Estuary, Brussel. Vol.1: 351–368.

Van Eck, G. T. M., N. De Pauw, M. Van Den Langenbergh & G. Verreet, 1991. Emissies, gehalten, gedrag en effecten van (micro)verontreinigingen in het stroomgebied van de Schelde en Schelde-estuarium. Water 60: 164–181.

Van Leussen, W., 1994. Estuarine macroflocs and their role in fine-grained sediment transport. Ph.D. Thesis. Universiteit van Utrecht, The Netherlands.

Vos, P. C., P. L. de Boer & R. Misdorp, 1988. Sediment stabilization by benthic diatoms in intertidal sandy shoals. In de Boer, P. L., A. van Gelder & S. D. Nio (eds.), Tide-influenced Sedimentary Environments and Fecies. D. Reidel Publishing Company: 511–526.

Wartel, S. & R. W. Faas, 1986. Calcium carbonate in Schelde-estuary bottom sediments. Bulletin Institut royal des Sciences naturelles de Belgique 53: 383–390.

Wartel, S. & G. T. M. van Eck, 2000. Slibhuishouding van het Schelde estuarium. Brussel (België) en Middelburg (Nederland), Koninklijk Belgisch Instituut voor Natuurwetenschappen en Rijksinstituut de Kust en Zee: 66.

Whalley, W.B. (ed.), 1978. Scanning Electron Microscopy in the study of the sediments. Geo Abstracts, Norwich, England: 414.