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*Primary Research Paper*

# Suspended matter in the Scheldt estuary

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*Key words:* suspended matter, estuarine energy, Scheldt ETM, flocculation, $\delta^{13}C$, light penetration

## Abstract

The Scheldt estuary is characterised by a specific energy pattern resulting from the interaction of wave energy, tidal energy and river energy. It divides the estuary into three parts and governs suspended matter transport and distribution pattern. Observation of suspended matter transport shows the existence of three estuarine turbidity maxima (ETM), a marine-dominated ETM in the lower estuary at the river mouth, a river-dominated ETM in the upper estuary with suspended matter concentration reaching up to 300 mg/l, and the most important tide-dominated ETM in the middle estuary with suspended matter concentrations from several hundred milligrams per litre up to a few grams per litre. Resuspension is the dominant phenomenon in this last ETM due to the tidal related bottom scour, which is initiated when a critical erosion velocity of 0.56 m/s is exceeded. An assessment of residual current along the axis of the estuary shows distinctive pattern between the surface water flow and the near bottom water flow. Also the local morphology of the river, natural or man-made, has a prominent effect on the orientation and strength of the residual currents flowing along either side of the river or river bend. Evaluation of suspended matter concentration in relation to the current flow shows no systematic correlation either because of phenomena as scour lag and settling lag mainly in the middle estuary, or because of the current independency character of uniform-suspension mainly in the upper and lower estuary. Quantification of suspended matter load exhibits a net downstream transport from the upper estuary, a near-equilibrium sustainable status in the middle estuary and a net upstream transport of suspended matter from the lower estuary. The characteristic of suspended matter is induced by and is a function of e.g. tidal phase, spring-neap tide, longitudinal and vertical distribution mechanisms, seasons, short and long terms of anthropogenic influence and/or estuarine maintenance. Suspended matter is dominated by complex and cohesive organo-mineral aggregates. It consists of a variable amount of an inorganic fraction (average of 89%) and an organic fraction and occurs largely as flocs, the size of which is remarkably larger in the upper estuary and smallest within the ETM in the middle estuary. Independent time series measurements (1990–2000) of suspended matter property show an increasing sand fraction, a decreasing organic matter content, a rise in $\delta^{13}C$ as well as a decrease in water transparency. These independent measurements exhibit coherent consequences of estuarine maintenance operations. Maintenance dredging of the shipping channel and harbours and dumping operation in the Scheldt strengthen marine influence further landward, resulting in a sustained tidal range increment and upstream flow and transport of suspended matter.

## Introduction

In estuaries suspended matter determines habitats, is involved in the food web by supplying food, especially for benthic organisms, and consists of particles that attract organic and inorganic substances as well as contaminants. Even "unpolluted" suspended matter can give rise to environmental concerns. For instance, its high concentration can change light conditions for photosynthesis and can also constitute a physiological difficulty for higher trophic levels (Herman

& Heip, 1999). Undoubtedly, suspended matter is of primary importance for aquatic health and environmental management and constitutes a key parameter in the estuary.

The distribution and concentration of suspended matter in an estuary is in fact a contingent phenomenon depending on interrelated primary processes such as meteorological and hydrodynamic conditions, chemical and biological activities and actual material supplies and sources. Also bottom morphology and composition have an impact on the vertical and lateral suspended matter distribution. Tidal and seasonal variations in salinity and water temperature regulate biological and chemical processes that consequently affect suspended matter by flocculating or deflocculating it. Nevertheless, the importance of each process is not easy to define and little is quantified because of complex nature and coupling of one process with other processes.

The characteristic of suspended matter in an estuary is induced by and is a function of reciprocity between order (tidal phase, spring-neap tidal cycle) and chaos (turbulence, deposition–erosion, resuspension, river runoff, short and long terms of biological and anthropogenic activities). In addition, suspended matter aggregates so that its characteristics do not necessarily depend only on dispersed particle characteristics or chemical constituents. *In situ* particle size spectrum of flocculated suspension can be an intrinsic property of suspended matter, at least over short periods of time, affecting the behaviour of a suspension in an estuary. Besides the supply from natural sources, anthropogenic input such as dredging and dumping operations and various wastewater discharges may also influence the quality and the quantity of suspended matter (Schoellhamer, 2002).

The Scheldt estuary extends 160 km in length and includes an approximately 60 km long fresh water tidal zone stretching from near the mouth of Rupel (92 km) to Ghent (160 km) representing one of the Western Europe largest freshwater tidal areas (Fig. 1). It is a funnel-shaped coastal plain

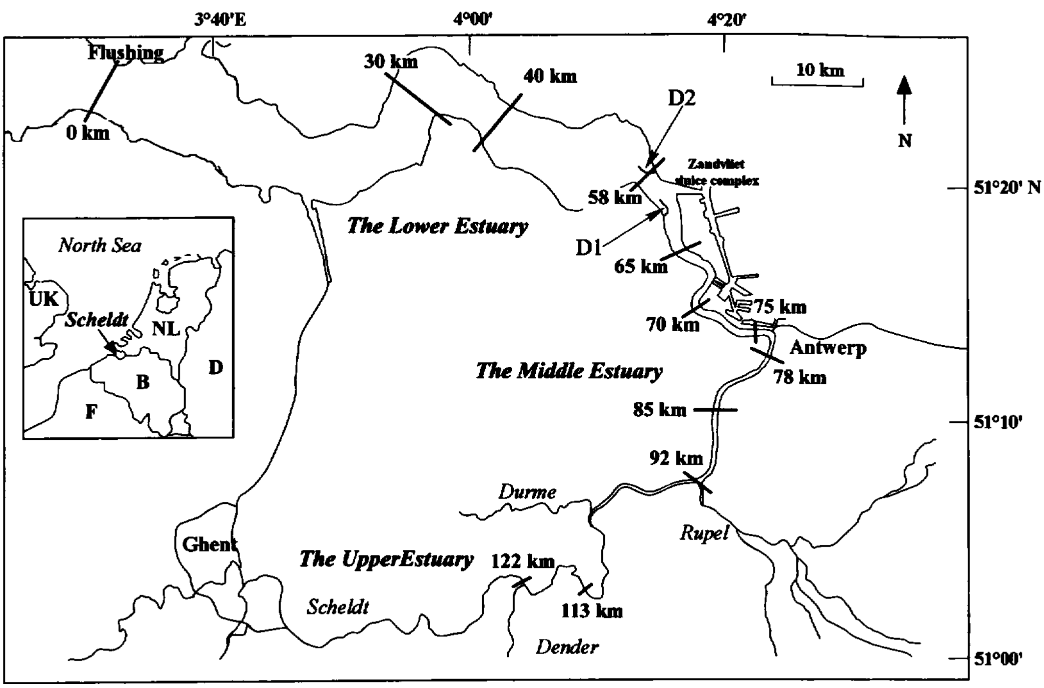


*Figure 1.* Areal map of the Scheldt estuary. Numbers on the map indicate distance in kilometre relative to the river mouth. Near 58 km, two underwater dams: D1 – Plaat van Doel and D2 – Ballastplaat. The salinity intrusion reaches around 92 km during the period of low river runoff and about 40 km during the period of high river runoff. The tide intrusion extends to Ghent (160 km) where it is stopped by a dam. The lower estuary: the river mouth (0 km) – the Belgian–Dutch border (58 km); the middle estuary: the Belgian–Dutch border (58 km) – the mouth of the Rupel (92 km); the upper estuary: the mouth of the Rupel (92 km) – Ghent (160 km).

estuary with a semidiurnal meso- to macro-tidal regime. Observations for the last two decades (1980–2001) show that the mean tidal range at the river mouth fluctuates between 4.85 and 2.81 m during spring and neap tides, respectively. As the tidal wave enters the estuary, the mean tidal range increases to above 5.25 m at 92 km and then decreases further landward to about 2 m near Ghent (160 km). The river discharge varies from 50 $m^3/s$ during dry summer to 300 $m^3/s$ during wet winter months with an annual average between 100 and 200 $m^3/s$ (Fig. 2; Taverniers, 2000). The freshwater discharge is small compared to the high tidal discharge with annual average of about 50 000 $m^3/s$ for both ebb and flood tides near the river mouth (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). It is a highly dynamic estuary subject to important anthropogenic activities, such as maintenance dredging of the shipping channel and harbours. The estuary has undergone major deepening modifications and dredging operations since the late 1960s (Fig. 3 illustration of the nineties). This deepening decreases the friction experienced by the incoming floodwater, which yields more marine water entering the estuary leading to an increase in tidal range. Figure 4 shows a sustained increase in tidal range of about 18 cm

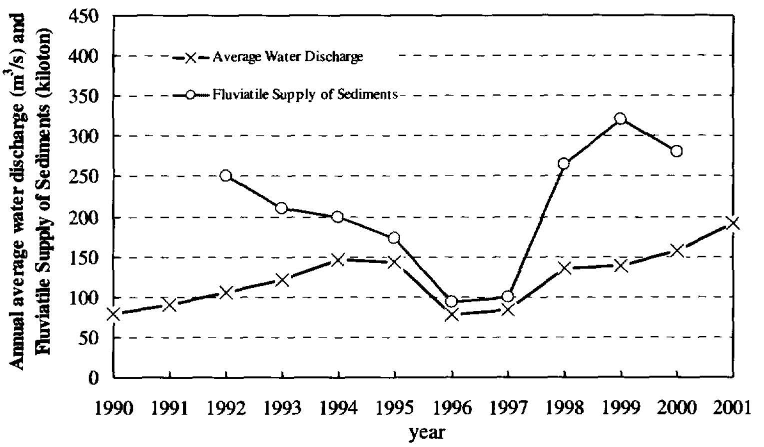


*Figure 2.* Annual average fresh water discharge and fluviatile supply of sediments. Data from Taverniers (2003) Administration Waterways and Maritime Affairs, Section Maritime Entrance, Antwerp, Belgium.

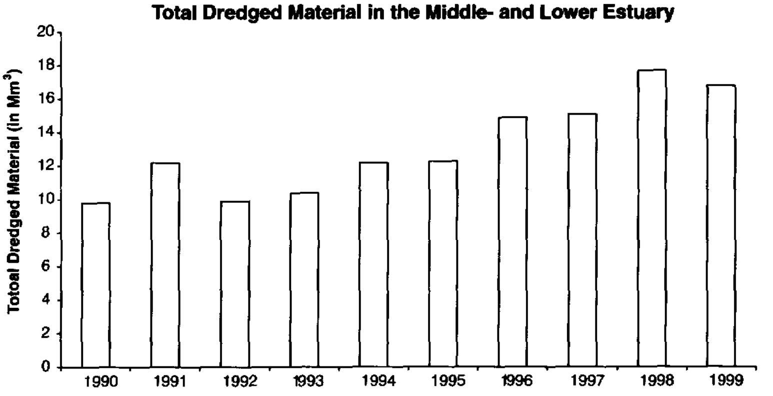


*Figure 3.* Dredging operations in 1990s in the Scheldt. Data from Taverniers (2003) Administration Waterways and Maritime Affairs, Section Maritime Entrance, Antwerp, Belgium.

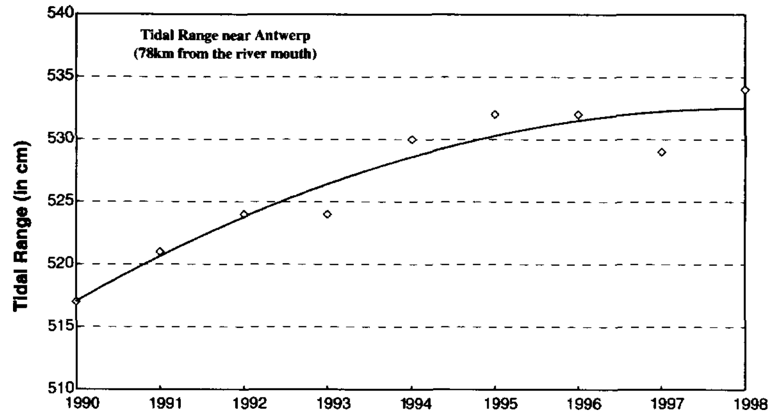


*Figure 4.* A sustained increment of tidal range near Antwerp (78 km) from 1990 to 1998. Data from Taverniers (2003) Administration Waterways and Maritime Affairs, Section Maritime Entrance, Antwerp, Belgium.

near Antwerp from 1990 to 1998 with an average of ca. 2 cm per year in this period. This is quite significant compared with the anticipated sea level rise reported in the North Sea region of 0.1 cm (Flemming, 1982; Baeteman & Declercq, 2002) per year due to global climate change.

To date most of the suspended matter related studies have focused on the middle and lower reaches of the Scheldt estuary, yet there is a lack of knowledge of the upper reach, also known as fluvial estuary or tidal freshwater zone. Another aspect that has not yet been well documented is how suspended matter responds to physical forcing, where the forcing may be natural or anthropogenic, and what is the nature of the impacts. The considerable complexity of suspended matter regime of the Scheldt estuary requires further effort to address. The objective of this paper is to examine the characteristics of suspended matter, including its distribution variations, organic and inorganic fractions, dispersed as well as *in situ* particle size spectra, and stable organic carbon isotope concentrations, under the prevailing physical dynamics for the complete range of estuarine extent, from the upper to middle and lower reaches, and the changes of suspended matter characteristics over the time considering the possible consequences of dredging/dumping operations. Direct observations from a recent 5-year (1998–2002) field study in the Scheldt together with unpublished Scheldt estuarine research data are summarised here. They elicit examples of what seem to be important features of estuarine events and what to expect as the sequence of suspended matter response in general.

## Sampling strategy and equipment

### *Suspension sampling*

Suspended matter samples from the main river channel were drawn by pumping water from 1 m below the water surface and from 1 m above the bottom through continuous flow centrifugation at a rate of 1 $m^3$/h. In some cases additional water samples were also taken at regular depth intervals along the water column. Replicate samples were collected in 250-ml, 500-ml, 1-l PVC bottles and 60-l PVC barrels to have adequate material for various chemical and physical analyses purposes. Samples for chemical analyses were frozen immediately using liquid nitrogen after collection, stored at −20 °C and either lyophilised or thawed at 1–4 °C before analyses. Samples for physical analyses were stored in dark at 4 °C until examination.

### *Water flow and suspended matter load*

Variations of current velocity, salinity and suspended matter load over one complete tidal cycle were measured at nine stations located at six transects in the upper, middle and lower reaches of the Scheldt estuary. These measurements were carried out at periods of expected high- (spring) and low-(autumn) river discharge in 1996, 1997 and 1998 as well as in 2002. Considering the morphology of the bottom, measuring stations were anchored at both sides of the main river channel. Vertical profiles of water current velocity, salinity and suspended matter load were measured every 20 cm on a continuous basis at every 30 min interval with a NBA type DNC3 direct reading current meter and a SeaCat calibrated STD and optical backscatterance turbidity probe. Water samples were simultaneously collected parallel to these profiles using PVC bottles (250 ml) as explained in the previous section to ensure the gravimetric suspended matter concentration and to calibrate the measurements from the turbidity probe.

In situ *particle (floc) sampling*

*In situ* particle size measurements along the estuary in 1996–1998 were carried out with the *in situ* suspension camera and image analysis system described in detail in Eisma et al. (1990). Measurements in 1999 and 2002 were completed by Environmental Scanning Electron Microscopy Wet Mode (ESEM-WM) on duplicate or triplicate suspension samples prepared using the wide-tip (diameter of 5.5 mm) pipette withdrawal method. All the samples, except the tidal cycle measurements when sampling took place on the hourly basis, were acquired around periods of maximum flood current, when the largest amount of suspended matter involving in the erosion–sedimentation cycles was expected to be in suspension.

*Water transparency measurement*

A 5-year (1994–1999) fortnightly transparency measurement was carried out around spring tide at low water level at three locations, 58 km, 40 km and 0 km (the river mouth) in the lower estuary, using Secchi disc. The Secchi depth was determined by the average of two Secchi disc readings: at the depth where the disc disappeared from sight and at the depth where it reappeared. The field measurements of water transparency were performed by a research team of Directorate-General for Public Works and Water Management, Institute for Inland Water Management and Waste Water Treatment (RIZA), the Netherlands.

**Analytical methods**

*Suspended matter concentration*

Total suspended matter concentration was determined according to a standard non-filterable solids method using Nuclepore 0.45-$\mu$m pore-size filters. After filtration, samples were dried at 105 °C till constant weight.

*Dispersed particle size spectra*

Water samples (60–80 samples per year), taken 3.5 m below the water surface around spring tide mainly in spring (Mar–May) and autumn (Oct–Nov) along the axis of Scheldt from 1991 to 1998, were analysed for their suspended sediment grain-size distribution. The dispersed particle size spectrum was obtained using a method detailed in Chen (2003). Approximately 20 g of the lyophilised suspended matter sample was first pre-treated by removing salts, organic matter and carbonates using $H_2O_2$ and HCl. Then the pre-treated sample was used for dispersed particle size analyses. The coarse fraction (75–2000 $\mu$m) was separated by wet sieving, 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 fine fraction (<75 $\mu$m) was obtained using the Sedigraph 5100.

*Organic matter content*

Suspended matter samples (60–80 samples per year), collected 3.5 m below the water surface close to spring tide mainly in spring (Mar–May) and autumn (Oct–Nov) along the estuarine axis from 1990 to 2001, were analysed for their total organic matter content. Total organic matter content was obtained by standard loss on ignition at 430 °C for 24 h (Gale & Hoare, 1991). About 2 g of the lyophilised suspended matter sample was 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 deduced from triplicate measurements on the aliquots of the same sample.

*Non-dispersed* in situ *particle (floc) size spectra*

Floc sample was investigated using ESEM-WM and viewed at 250, 500 and 1000× magnification. 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 and perimeter were determined manually using the image software SigmaScanPro5 (Chen, 2003)

*Stable organic carbon isotope concentration*

Suspended matter, from continental shelf (60 km offshore) to 160 km upstream from the river mouth, collected 3.5 m below the water surface in late June 1993 and in early May 1998 was analysed for its stable organic carbon isotope concentration. Lyophilised and homogenised suspended matter of approximately 3 mg were weighed in silver cups, heated at approximately 80 °C and treated with dilute HCl to remove possible carbonates and redried. Then, the silver cups were folded with tweezers and combusted in a Carbo Erba NA 1500 elemental analyser. The resulting combustion gas ($CO_2$) was led into a boro-silicate vacuum line and cryogenically trapped in glass tubes, which were subsequently connected to the mass spectrometer inlet. Stable carbon isotope ratios were then measured on a Delta E Finnigan Mat dual inlet isotope ratio mass spectrometer, and their values are expressed relative to the VPDB (Vienna Peedee Belemnite) standard. Reference materials for carbon were graphite (USGS-24: $\delta^{13}C = -16.1$ ‰), sucrose (IAEA-C-6: −10.4 ‰) and polyethylene foil (IAEA-CH-7: $\delta^{13}C = -31.8$ ‰). The precision for 12 consecutive measurements on the aliquots of the same sample for $\delta^{13}C$ was less than 0.03 ‰.

## The complexity of suspended matter

Suspended matter is primarily induced by hydrodynamic conditions and has its temporality. Albeit its ephemerality, suspended matter exhibits some relatively perceivable distribution variations. Field measurements illustrate its vertical, longitudinal, seasonal, short-term and long-term patterns.

*Vertical variations*

Comparison of the vertical profiles of suspended matter data from the Scheldt estuary (see e.g. Fig. 5) indicates that the suspended matter concentration has a multilayer structure: an upper uniform-suspension layer separated by a lutocline from an underlying graded-suspension layer. The "uniform suspension" or "wash load" is generated by a steady supply from the river, the sea or from local sources and has a suspended matter concentration that does not vary significantly with either depth or time. Field measurements show a mean concentration, in the top 25% of the water column, of 110 ± 50 mg/l and of 100 ± 70 mg/l respectively in the upper and the middle estuary and is below 50 mg/l in the lower estuary.

The "graded suspension" develops when supplies from the sources become strongly variable and has a suspended matter concentration that varies in space and time. The major sources for variable supplies are from intertidal erosion, from drainage of the polderland, from industrial and domestic input (D'Hondt & Jacques, 1982; Baeyens et al., 1998) and from bottom scour. In the Scheldt, the graded-suspension shows an increasing suspended matter concentration towards the bottom, where it may reach up to several grams per litre, and it occurs mainly in the middle estuary. The graded-suspension varies considerably with the tide and may itself be subdivided in several sublayers separated by secondary lutoclines. The major source for this graded-suspension formation is resuspension of bottom sediments and bottom scour that depends on the nature and the morphology of the bottom.

The vertical distribution of suspended matter during a tidal cycle is illustrated in Figure 5. Suspended matter concentrations, at about the first 3–4 h of the flood tide (Fig. 5a), demonstrate a two-layer development along the water column. A uniform-suspension layer, with a variation of less than 20 mg/l, extends about 60% of the upper water column and a graded-suspension, with a variation of more than 100 mg/l, is found in the lowermost 40% of the water column. The further development of this two-layer structure can be observed during the sequential ebb tide (Fig. 5b). It is obvious that the overall suspended matter concentration is much higher during the ebb tide,

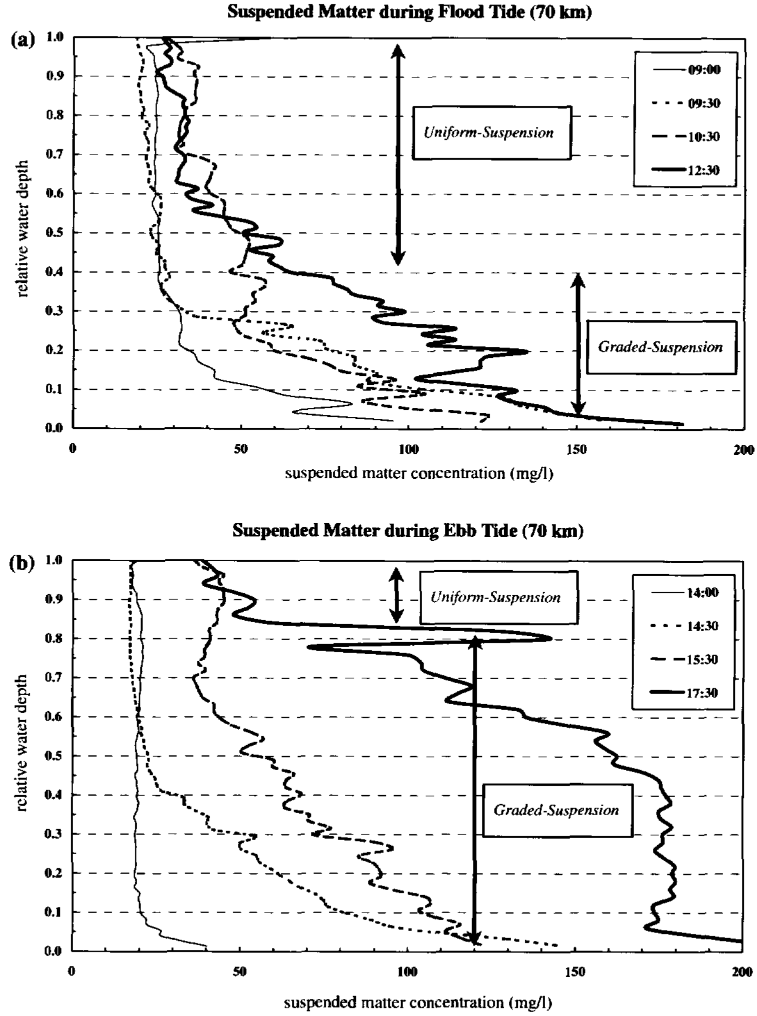


*Figure 5.* Vertical distribution of suspended matter during a tidal cycle. An example of measurements carried out at an anchored station near 70 km. Y-axis indicates relative water depth, where 1 is water-surface and 0 is bottom.

the uniform-suspension layer becomes very thin and the graded-suspension stretches out up to 85% of the water depth. The swift and striking change of suspended matter concentration from one tidal phase to the other illustrates resuspension and re-working of bottom sediments. In the example, resuspension of bottom sediments at ebb tide is the major supply source of the suspended matter into the water column.

*Longitudinal variations*

Suspended matter shows large spatial variations. In the lower estuary (0–58 km) it is characterised by low values fluctuating around 50 mg/l and seldom goes above 100 mg/l (Fig. 6). The suspended matter in the middle estuary (58–92 km) has an average concentration of 82 ± 65 mg/l in the uppermost 10% of the water column, and a range of 150 mg/l to 2.5 g/l in the lowermost 10% of the water column. The values close to the surface are largely in agreement with the mean concentrations of 100–200 mg/l reported by other Scheldt studies in the middle estuary (e.g. Wartel, 1973; Van Eck et al., 1991; Hellings, 2000; Van Damme et al., 2001), and the values close to the bottom are of the same order as documented earlier by Wartel (1973). Further upstream in the upper estuary

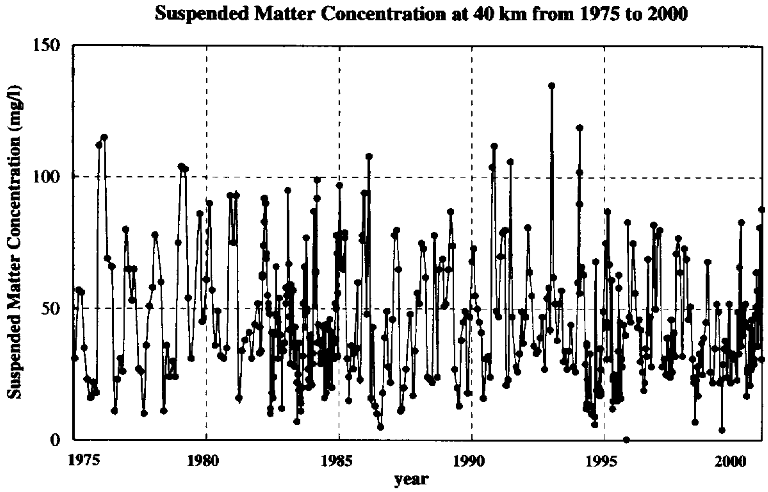


*Figure 6.* Suspended matter concentration in the lower estuary. Fortnight measurements took place near 40 km at low water level around spring tide. Data from the Directorate-General for Public Works and Water Management, Institute for Inland Water Management and Waste Water Treatment (RIZA), the Netherlands (2002).

(92–160 km), the suspended matter has an average concentration of 110 ± 65 mg/l in the uppermost 10% of the water depth, and a range of 100–1000 mg/l in the lowermost 10% of the water depth.

*Seasonal, short term and long term variations*

The suspended matter concentration shows short- as well as long-term variations. On a short term basis the concentration may show a distinct variation between ebb and flood tides as illustrated in the earlier section, and may vary during the neap-spring cycle with lower concentrations during neap than during spring (Fettweis et al., 1998), as well as may have seasonal variations that occur resulting from differences in erosion in the river basin. Since rainfall controls the fresh water discharge of the Scheldt river, soil erosion in the Scheldt catchment area has a strong effect on the sediment supply and hence on the suspended matter concentration in the estuary. On a long term basis the overview of concentration may vary over a time span of decades, and may be related to possible climatic changes more, in particular, in the rainfall regime.

Seasonal, short term and long term variations of suspended matter are illustrated with an example of field measurements of surface water at 58 km at low water level around every spring tide (Fig. 7). There is a seasonal variation pattern on the yearly basis with high values in winter-spring time and low values in summer and autumn. There are no significant short-term yearly differences in suspended matter concentration for either the period of 1977–1980 when it fluctuated around 100mg/l, or the period of 1997–2000 when it varied around 50 mg/l. However, on a long-term basis the variation is considerable. The concentration in the late 1990s is on the average of 50% less than that of the late 1970s. The reason for such a decline is not clear. Yet, it may be due to a decrease of land drainage because of an increased urbanisation, or due to an increase importance of water volume, resulting from the channel deepening since the late 1960s in the estuary, relative to the matching amount of suspended matter.

## Estuarine energies and turbidity maxima

In an estuary, the ephemerality and complexity of a state of suspended matter are induced by different energy cycles. Total estuarine energy is a complex phenomenon resulting from the combined effect of periodic and aperiodic energies. Periodic energy cycles range from fractions of one second (such as turbulence) to weeks (neap-spring-neap cycles) or even to years (such as a lunar cycle of about 18.6 years). An example of an

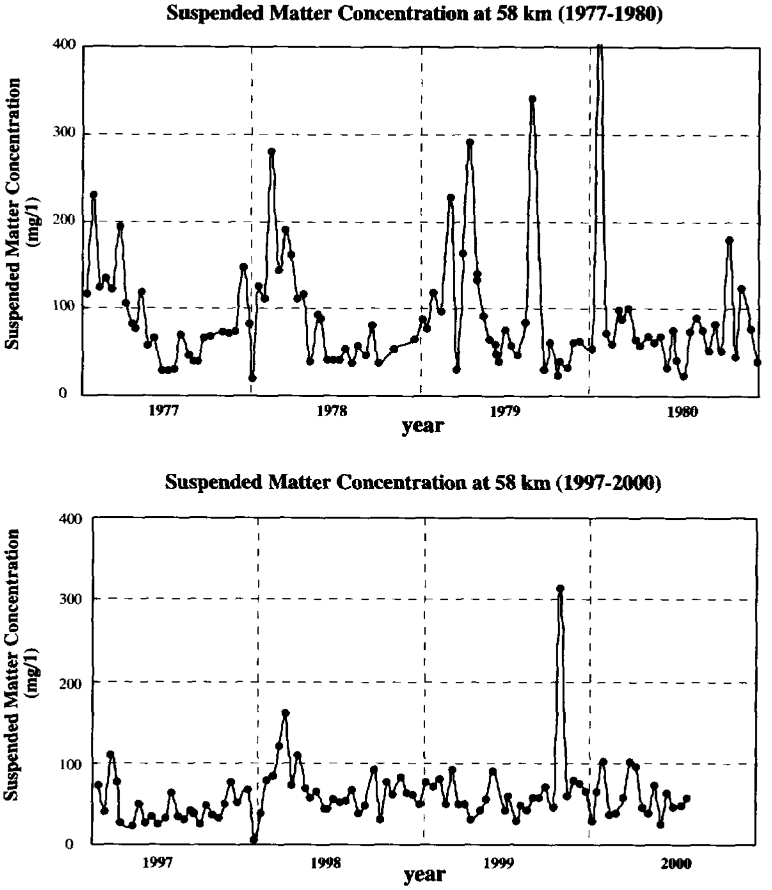


*Figure 7.* Suspended matter concentration over two decades (1977–1980 and 1997–2000). Fortnight measurements near 58 km at low water level around spring tide. Data from the Directorate-General for Public Works and Water Management, Institute for Inland Water Management and Waste Water Treatment (RIZA), the Netherlands (2002).

aperiodic energy input is river discharge governed by rainfall that may occasionally be very high and can occur at any moment of the year. Suspended matter in any point of an estuary is subjected to the total estuarine energy that defines when and where deposition, resuspension or erosion takes place. In a first approach, a simple conceptual model may be sufficient to adequately describe the total energy distribution (Dalrymple et al., 1992). The total energy distribution along the Scheldt estuary is calculated based on the average tidal and runoff conditions (Smets, 1996) at every 2 km interval. The result of the Scheldt energy distribution (Fig. 8) closely follows the model proposed by Dalrymple et al. (1992). A total energy maximum is situated between 58 and 100 km. A total energy minimum is in the vicinity of 120 km, where the tidal energy equals the fluvial energy (balance point).

As any other coastal plain estuary the Scheldt estuary is characterised by a specific total energy pattern – a combined power of marine processes (waves and tides) and fluviatile processes (Fig. 8). Wave energy (wave height) decreases very rapidly in the direction of upstream and is only important in the river mouth. Tidal energy (tidal range) first increases from the river mouth toward upstream reaching a maximum, as the tide is compressed into smaller cross-sectional areas (convergence). The effect of convergence is, however, with the narrowing of the river channel, counter balanced by loss of energy due to friction. Over a certain distance, frictional energy dissipation exceeds the effect of convergence causing the tidal energy (tidal

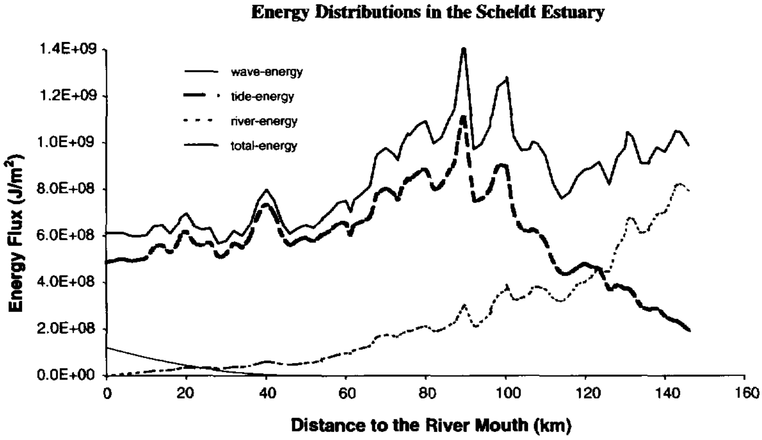


*Figure 8.* The Scheldt energy distributions. Wave energy ranges from $2.5 \times 10^7$ J/m$^2$ at the river mouth to zero near 50 km, and is multiplied by a factor 5 to be able to show up on the given Y-axis scale of this figure. Data from Wartel and Francken (1998).

range) to decrease to zero at the tidal limit. In the upper estuary a river-dominated energy maximum occurs as a result of the high fluvial energy input (Fig. 8). In principle, such an energy system divides the estuary into three parts (Dalrymple et al., 1992): (1) The lower estuary – tidal energy is important, where the total energy remains at first relatively constant and then increases slightly toward upstream. Marine processes dominate. (2) The middle estuary – tidal energy dominates and also the total energy maximum occurs. (3) The upper estuary – river energy dominates and is characterised by a seaward decreasing fluvial energy.

Suspended matter transport and distribution are powered by and follow this energy distribution pattern in the Scheldt. Observations exhibit the existence of three estuarine turbidity maxima (ETM). The most important ETM, which is determined by the total energy maximum, occurs in the middle estuary extending roughly from 58 to 100 km with near-bottom suspended matter concentrations from several hundred milligram per litre up to a few grams per litre. This is the well-acknowledged ETM and numerously documented in the Scheldt estuarine research. It has been understood as and attributed to a combined result of flocculation due to the mixing of fresh and saltwater in the low salinity reach and the meeting area of two bottom residual currents, of which a seaward oriented bottom residual current upstream of this area and the other landward oriented bottom residual current downstream of this area (Nihoul & Ronday, 1976; Wollast & Peters, 1983; Wollast, 1988). In this ETM, riverborne particulate material is retained resulting in a residence time which is much longer than in the other regions of the estuary (cf. Wollast, 1988; Herman & Heip, 1999). As a matter of fact, the coexistence of this ETM with the area of total energy maximum as described above indicates that this ETM is above all genuinely linked to the interaction of tidal range, which is at maximum in this area, with erosion and deposition processes (Allen et al., 1980; Guézennec et al., 1999; Dyer, 1994). The second ETM occurs at the mouth of the Scheldt in front of the Belgian–Dutch coast (Van Mierlo, 1899; Fettweis & Van den Eynde, 2003). This ETM is marine-dominated and characterised by high wave energy and tide energy with suspended matter reaching more than a few hundred milligram per litre. Besides the prevailing energies, convergence of residual currents (Bastin, 1974) and hydrodynamic trapping of SPM (Nihoul, 1975; Gullentops et al., 1976) have been proposed to explain high suspended matter concentration in front of the Scheldt mouth. The third ETM, dominated by high fluvial energy, occurs in the upper estuary. Monthly observations of suspended matter distribution over the water column between 58 and 160 km (Ghent) show that the area of river-dominated energy maximum is also the area of high suspended matter concentrations (reaching up to 300 mg/l), denoting this area as a third ETM in the Scheldt, a river-dominated ETM.

## Water flow, suspended matter concentration and transport

### *Residual currents*

A residual current is the algebraic difference between depth- and tide-averaged ebb and flood current velocities, or in other words, it is the net current resulting from integration of the total current over a complete tide cycle. In the Scheldt, in the uppermost 1 m water-layer, the near-surface residual currents are oriented seaward with a mean excess velocity ranging from 0.17 to 0.28 m/s upstream of 58 km and weakening further downstream to 0.09 m/s at 40 km from the mouth. In the lowermost 1 m water-layer, the near-bottom residual currents are differentiated into distinct sections along the axis of the Scheldt estuary. They are oriented seaward in the upper estuary and landward in the lower estuary. Nihoul and Ronday (1976) as well as Wollast (1988) reported that near bottom residual current reached equilibrium at approximately 75 km from the mouth. Current measurements between 1996 and 2002 confirmed this report. Results show that for a tidal range between 4.7 and 5.5 m (close to the spring tide) and a river discharge at 92 km of 60–100 $m^3/s$ (close to the annual average Scheldt discharge value) the near bottom residual currents are in equilibrium in the vicinity of 70 km.

The estuarine morphology, natural or man-made, has a prominent effect on the water flow. Though residual currents have distinct patterns in the main channel along the axis of the Scheldt estuary as outlined above, they may unevenly distributed across the river. For instance, in the vicinity of 58 km, two underwater dams (Fig. 1), Plaat van Doel and Ballastplaat located at upstream and downstream side of the measuring site respectively, strengthen the ebb currents passing the right side (outer bend) of the river. In addition, the gyratory water movement in the access channels (Fettweis & Sas, 1999) to the Zandvliet–sluice complex (Fig. 1) influences the flow pattern in the main channel. As a result, the vertical current flow pattern observed near 58 km shows a complex anticlockwise helical shape (Chen, 2003). Also the asymmetry of the local morphology of the river bed can influence the current and lead to an unequal residual-current strength at the right and left side of the main river channel. For example, near 58 km, the residual current at the right side of the river channel is ebb-oriented and is twice as strong as the flood-oriented residual current (ca. 0.25 m/s) at the left side of the river channel.

### *Suspended matter concentration*

To describe the suspended matter behaviour in the Scheldt estuary, it is necessary to picture the mass movement in relation to the current flow. Therefore, the depth-averaged suspended matter concentration, expressed as $kg/m^3$, is compared to the depth-averaged current velocity, in m/s.

Measurements within the ETM in the middle estuary show that the maximum depth-averaged suspended matter concentrations generally occur at the same time as the maximum depth-averaged current velocities. This suggests that, in the ETM, resuspension is an important phenomenon (West & Sangoydin, 1991). Thereby, it is important to determine the critical erosion velocity at which this resuspension is initiated. The critical erosion velocity referred here is the value of the depth-averaged current velocity in the lowermost 1 m water-layer shortly after slack water when a sudden increment of suspended matter concentration is recorded. A critical erosion velocity of 0.56 m/s is found based on more than 400 accurate measurements of depth profiles of both current velocity and suspended matter concentration recorded on the bulk of all seasons and all stations (between 20 and 100 km). This observed value of critical erosion velocity is in accordance with the value (0.7 m/s) documented in the earlier Scheldt research (Wartel, 1972; Baeyens et al., 1981) and is also close to the values found in other estuaries (Avoine, 1982; Wolanski et al., 1995).

The effect of resuspension on suspended matter concentration within the ETM in the middle estuary is illustrated with an example of a complete tidal cycle measurement near 70 km at the right side of the main channel (Fig. 9). Shortly after the onset of ebb tide, the critical erosion velocity is exceeded and the depth-averaged suspended matter concentration increases from 70 to

130 kg/m$^3$ in 30 min and more than triples to 465 kg/m$^3$ in the following 3 h without any further increase in current velocity. It signalises that bottom sediments have been stirred up during the increasing ebb current. When the ebb current decreases, the depth-averaged suspended matter concentration decreases slowly staying, however, far above the values of the increasing tide and thus exhibiting a settling lag. During the subsequent flood tide, the depth-averaged suspended matter concentration increases gradually with the depth-averaged current velocity to 200 kg/m$^3$, and it also decreases progressively when the flood current decreases. In this example no hysteresis is observed during the flood tide.

Measurements within the ETM in the middle estuary show that hysteresis takes place during ebb tide, like the example shown here (Fig. 9), or during flood tide, or during both ebb- and flood tide. The difference in hysteresis occurrence is mainly ascribed to local morphology of the river. Consequently, the differences in suspended matter concentration between ebb and flood tide result, in the first place, from the differences in the current velocity and turbulence patterns (Winterwerp et al., 2001), but also from the regional distribution of sediment deposit which causes differences in local supplies. So far, no systematic correlation has been observed in the ETM between the depth-averaged suspended matter concentration and the depth-averaged current velocity. Phenomena as scour lag and settling lag make that the concentrations of suspended matter deviate from a straightforward correlation with the current velocity. These phenomena, typical for the ETM, contribute to the generation of a graded-suspension.

Measurements in the upper and lower estuary point out mainly uniform-suspension. Suspended matter concentration is below 50 kg/m$^3$ and varies little over the tide. It can also be observed that the depth-averaged suspended matter concentration is independent of the current velocity (Fig. 10).

These results confirm that high-suspended matter concentration within the ETM in the middle estuary is mainly attributed to the resuspension of local bottom sediments induced by tidal current and due to total energy maximum in the region. Suspended matter remains longer in suspension within the ETM zone in the middle estuary than either upper or lower estuary.

*Suspended matter transport*

An effort is attempted to quantify the total amount of suspended matter, expressed as ton/m$^2$, in each tidal phase transported through a 1 m wide cross section for various transects along the estuary using integrated depth- and time-averaged suspended matter concentrations measured

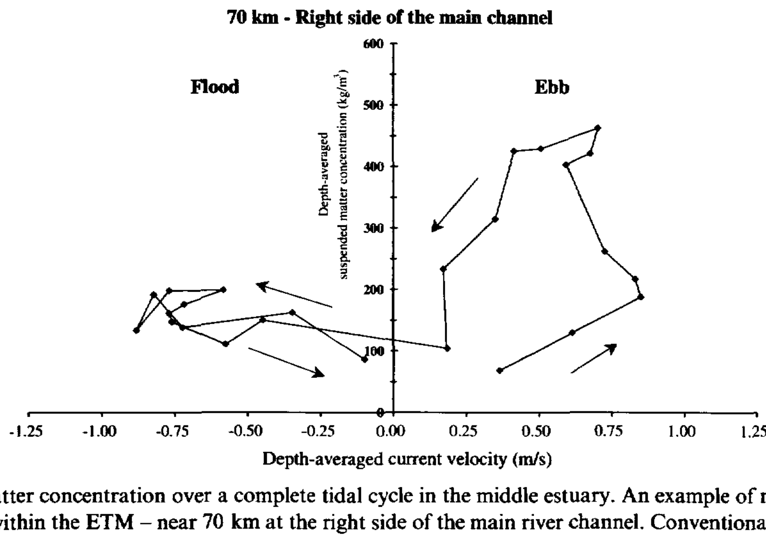


*Figure 9.* Suspended matter concentration over a complete tidal cycle in the middle estuary. An example of measurements carried out at an anchored station within the ETM – near 70 km at the right side of the main river channel. Conventionally, flood current velocity is indicated as negative. Each point on the figure stands for every 30 min measurement.

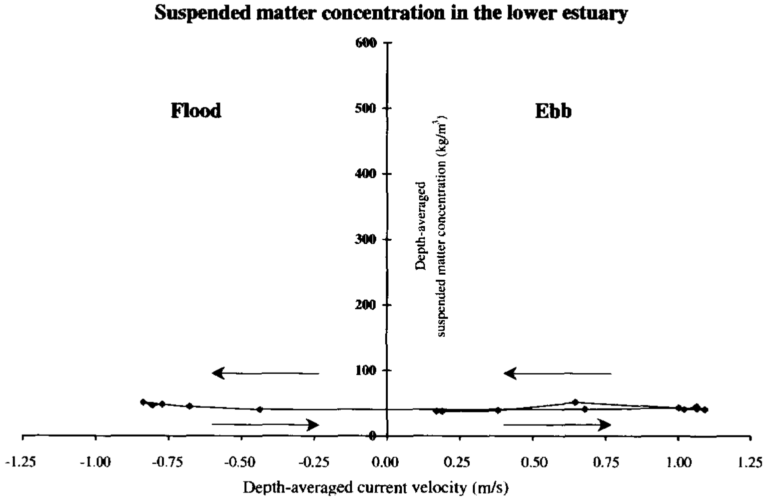


*Figure 10.* Suspended matter concentration over a complete tidal cycle in the lower estuary. An example of measurements carried out at an anchored station near 40 km. Conventionally, flood current velocity is indicated as negative. Each point on the figure stands for every 30 min measurement.

around spring tide. The suspended matter transported in the upper estuary fluctuates around 1.1 ton/$m^2$ during ebb and about 0.5 ton/$m^2$ during flood tide. In the lower estuary it fluctuates around 0.7 ton/$m^2$ per tide, showing minor variations with the tidal phase. In the middle estuary, approximately 3.3 ton/$m^2$ of the suspended matter is transported during ebb tide and around 2.4 ton/$m^2$ during flood tide. Most of the suspended matter load in the middle estuary is ascribed to the locally resuspended bottom sediments.

Based on the measured suspended matter load, an ebb to flood ratio of the suspended matter transport is calculated. It changes from 2 in the upper estuary – signifying a net downstream transport, to 1.1 or 1.2 in the middle estuary – denoting a quasi-equilibrium situation, and sometimes may drop below unity in the lower estuary pointing out a net upstream transport of suspended matter.

The morphology of the river, either natural or man-made, has an important effect on suspended matter transported at different tidal phases. A very pronounced ebb to flood ratio of suspended matter transport is seen near 58 km. It is of about 3.2 near the right side (outer bend) of the river and 0.8 near the left side (inner bend) of the river. Such striking difference is undoubtedly related to the observed water flow and current pattern in the area as discussed earlier.

## Suspended matter properties

In the Scheldt, suspended matter is dominated by complex and cohesive organo-mineral aggregates. To understand and determine surface water quality issues adequately, it is necessary to know the existing forms of suspended matter: individual primary particles and floccules of fine organic and/or inorganic particles. This is important because different forms have different surface-to-mass ratios, which are largely responsible for the transport of many hydrophobic chemicals in estuarine systems.

### *Organic and inorganic fractions of suspended matter*

Organic matter in an estuary is supplied from divergent sources: terrestrial, riverine, marine (Soetaert & Herman, 1995), autochthonous production and anthropogenic causes. A considerable amount of suspended matter samples (60–80 each year) collected between 1990 and 2001 along the axis of Scheldt (between 20 and 100 km) were analysed for their total organic matter content (% dry weight) and grain-size distributions. It is found that suspended matter contains a variable organic fraction with an average range of about 8.5–25% dry weight (Fig. 11). The organic matter content decreased noticeably from an average of about 18 ± 5% before 1996 to lower values since 1996

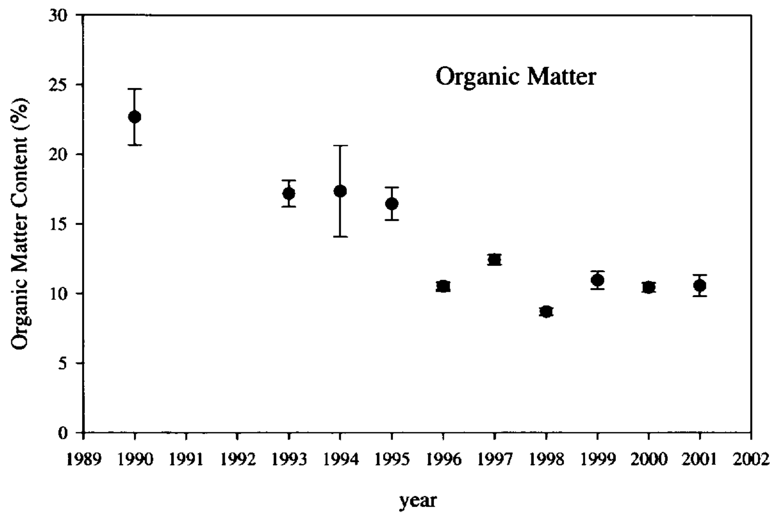


*Figure 11.* Organic fraction of suspended matter. Suspended matter samples (60–80 samples per year) collected along the axis of Scheldt between 20 and 100 km. Bars indicate standard error.

with an average of about 10 ± 2% (Fig. 11). The inorganic fraction of suspended matter contains mainly silty clays with a fairly low amount of sand (Fig. 12) but a high amount of clay (average of 50%). These properties characterise the Scheldt suspended matter as fine cohesive sediment. The sand fraction showed a marked increase from a mean value of 6.4% before 1996 to a mean value of 11.5% since 1996. A negative correlation is found for the variances of sand and organic matter with a correlation coefficient ($r^2$) of 0.48. Besides, Leermakers et al. (2001) reported that total mercury concentrations in the Scheldt were significantly higher before 1995 than after 1995. However, for the time being there is no clear explanation for the observed distinctive difference before 1996 and since 1996 shown by these independent measurements. Nevertheless, the observed differences can possibly be related to difference in input sources. The data of water discharge and fluviatile sediment load (Fig. 2) as well as dredging operation (Fig. 3) for the same time span may point out some probable contributing sources.

*Dispersed particle physical properties*

The physical property of suspended matter in the Scheldt has a brand of silty clay (Wartel et al., 1998). Grain-size analyses exhibit a geographical confinement with areas of relatively coarser particles, areas of finer ones, and a transitional category of silty clay that can be found throughout the whole estuary. Few existing data of upstream of 85 km shows a silty-clay composition. The vicinity of 85 km consists of fine sandy-clay. The area near Antwerp (78 km) is of typical coarse silt. Between 60 and 70 km clay is dominant. Downstream of 58 km suspended matter becomes relatively coarser: silty clay in the lower estuary and sandy clay in the mouth of the Scheldt.

*Non-dispersed (flocculated) particle physical properties*

Suspended matter in estuary occurs largely as non-dispersed particles, mostly flocs. Flocculation of suspended matter is mainly determined by particle concentration, turbulence intensity, salinity, organic matter and the differential settling of suspended particles at low current velocities (cf. Edgerton et al., 1981; Eisma, 1986; Fennessy et al., 1994; Van Leussen, 1994; Milligan, 1996). The average floc size against the distance between the Scheldt mouth and 122 km is plotted in Figure 13; each point on the figure represents an average of 400–1200 individual floc-measurements. The average floc-size increases from near 58 km toward upstream (Fig. 13). And flocs as large as 1200 $\mu$m are observed in the upper estuary. The longitudinal floc-size distributions present a similar

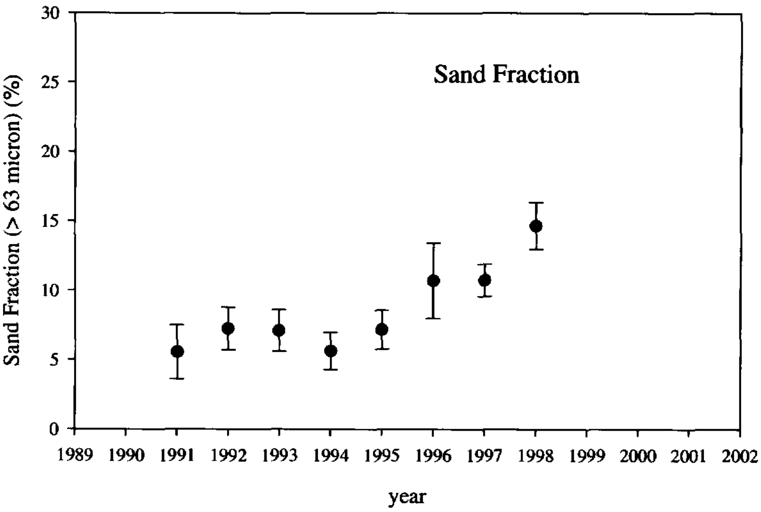


*Figure 12.* Sand fraction of suspended matter. Suspended matter samples (60–80 samples per year) collected along the axis of Scheldt between 20 and 100 km. Bars indicate standard error.

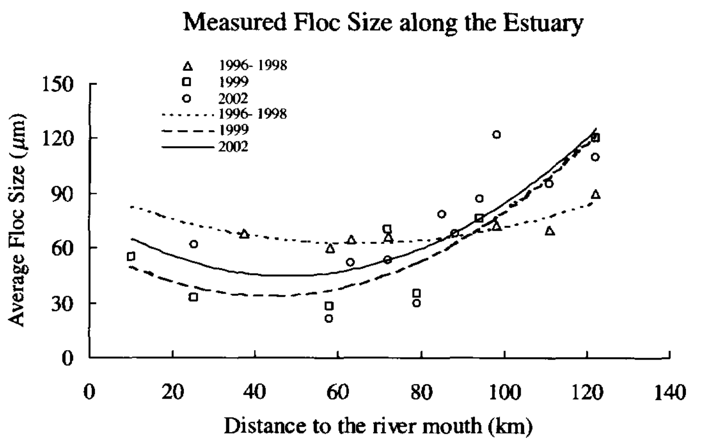


*Figure 13.* Average floc-size distribution in the Scheldt Estuary. Each point in the plot represents an average of over 400 measurements. Lines are second order polynomial trendline.

trend. Large flocs are repeatedly found at low salinity areas around 80 km and further upstream. Flocs become smaller toward downstream showing least size between 40 and 80 km, a zone where the highest estuarine energy occurs as outlined earlier. This suggests that the increment of suspended matter concentration to a certain extent leads to a proportional increment of the particle collision frequency resulting in floc break-up or floc abrasion (Einstein & Krone, 1962; Van Leussen, 1994). However, downstream of this finest-floc zone, flocs become larger toward the high salinity area from 40 km down to the river mouth, yet, they are not as large as those flocs observed in the upper estuary (Fig. 13). The trend of landward increasing floc size is in agreement with previous studies in the estuaries of Elbe (Eisma, 1995), Scheldt (Eisma, 1995) and Gironde (Gibbs et al., 1989; Eisma, 1995), where large flocs are regularly observed around the contact of fresh and saline water (Gibbs et al., 1989; Eisma, 1995) and in the tidal fresh water part of the estuary (Eisma, 1995). In this study, no evidence was found for an intensified flocculation in the salinity zone between 2 and 5 in the Scheldt as suggested by Wollast (1988). Other key factors like particle concentration, turbulence intensity and organic matter quality and content are most likely more predominant in governing floc formation.

The relationship between suspended matter concentration, current velocity and floc size evolution was investigated over a complete tidal cycle at a selected freshwater location: 113 km from the river mouth. This study was built on three conditions: (1) only fresh water is present; (2) organic matter is constant or shows a negligible variation and is tide independent; (3) turbulence intensity is closely related to current velocity (Fennessy et al., 1994). The tidal range was 4.2 m, which is close to spring tide; the tidal curve was asymmetric (Fig. 14) with an ebb current extending for ca. 7 h 30 min and a flood current lasting for about 5 h. The maximum ebb current was not as strong as the maximum flood current, but it lasted about three times longer. The suspended matter concentration was positively correlated with the ebb current velocity and reached the highest value during the ebb tide (Fig. 14). At the onset of the flood, the surface suspended matter concentration dropped from 151 to 69 mg/l and continued dropping down to 45 mg/l notwithstanding the increasing flood current (settling lag). Once the flood current reached above 0.58 m/s, the surface suspended matter concentration increased to 70 mg/l and continued increasing to 89 mg/l for a short time in spite of the decreasing flood current (scour lag), and finally dropped below 40 mg/l around slack water.

Evolution of floc-size within a tidal cycle is plotted in Figure 14, where each point on the floc-size curve stands for a result of 400 and up to 1000 individual floc-measurements for every hour following a complete tidal cycle. Large flocs formed when both the recorded current velocities and the suspended matter concentrations reached values close to the maximum (Fig. 14). The floc-size peak A1 occurred at the maximum ebb current velocity and an increasing suspended matter concentration close to maximum. It signifies that the availability of more suspended particles may increase the frequency of collision among particles, whereby flocculi easily attach to each other and form larger flocs. At this very initial point the floc forming was more dominant than its breaking up. A similar scenario was seen at the peak A2. However, during the flood tide the relatively stronger current and the lower suspended matter concentration did not or could not increase the floc size as much as those during the ebb tide. Shortly (within an hour) after peak A1, the floc size dropped sharply. It is assumed that a sustained strong current velocity and high suspended matter concentration resulted in breaking up of flocs formed during the preceding tidal phase. It follows that an increase in current velocity up to the value close to the critical erosion velocity (in this case 0.56 m/s for ebb and 0.58 m/s for flood current) generates an increment in turbulence, which promotes flocculation. However, it seems that an upper limit of current velocity exists above which flocs are disrupted as can be deduced from the sudden decrease in floc size.

The peak B appeared at slack water, no current and the suspended matter concentration still very high, yet flocs were only about half size of those at the peak A1. It is observed that, when current velocity drops below 0.5 m/s, the change in floc size (the 95th percentile) is opposite to the change of the suspended matter gradient, the difference between the suspended matter concentration near the bottom and near the surface. A small gradient coincides with an increase in floc size; a large gradient corresponds to a decrease in floc size. The latter case is likely due to the formed large flocs settling out of the water column during slack water (Fig. 14).

Measurements show that the evolution of floc formation within a tidal cycle is governed by different phases of tidal related processes. The tide-related current velocity and suspended matter concentration play dominant roles in flocculation, which is in agreement with what Eisma (1995) reported in a tidal station study in the Scheldt (72 km from the river mouth), where floc formation was found not to be controlled by salinity, but rather by the current velocity and the suspended matter concentration. Apparently, large flocs form at high current velocity and high suspended matter concentration, yet they may also be absent under these conditions as shown and discussed above.

Therefore, it seems unlikely that in an estuary, where conditions change randomly within a short time, a universal relation can be found between flow conditions and floc size. Factors controlling large floc formation are not necessarily determined

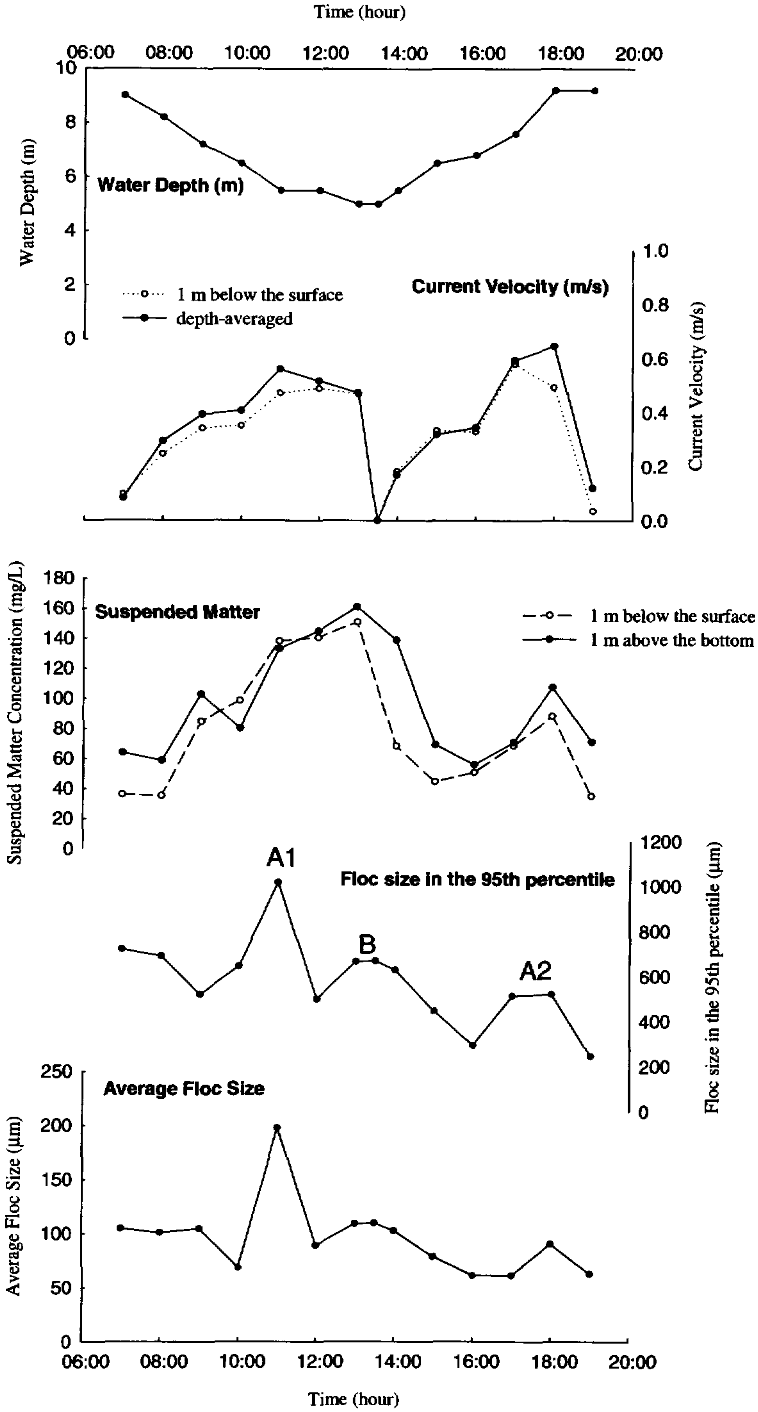


*Figure 14.* Tide related flocculation evolution. Floc size evolution, suspended matter concentration and current velocity over a complete tidal cycle at an anchored freshwater station: 113 km from the river mouth. Floc size was measured at 1 m below the water surface. Each point on the floc-size curve stands for a result of 400 and up to 1000 individual floc-measurements.

only by a high suspended matter concentration, but rather by a threshold of suspended matter concentration and its quality. Likewise, it is not necessarily the current velocity but a threshold of turbulent intensity that controls floc size. In the latter case, the maximum floc size is determined by the smallest turbulent whirls (Van Leussen, 1997). The floc formation processes may not depend only on a single relationship but on a more complex relationship that still needs to be revealed.

**Fluvial and marine components of suspended matter**

One important characteristic of suspended matter that needs to be examined is the equilibrium between its fluvial and marine components. Mixing of suspended matter from fluvial and marine origin in the estuarine region can induce complicated biological and/or physicochemical modifications of active substances including contaminants. The natural stable carbon isotope ($\delta^{13}C$) can serve as powerful tool for identifying sources on the organic fraction of suspended matter in riverine, estuarine and coastal systems (Raymond & Bauer, 2001). It has been used successfully as a convenient tracer for the origin of the suspended organic matter in estuarine environment (e.g. Nihoul et al., 1978; Jasper & Hayes, 1993; Middelburg & Nieuwenhuize, 1998; Hellings, 2000; De Brabandere et al., 2002). The longitudinal evolution of $\delta^{13}C$ along the axis of Scheldt is shown in Figure 15. Although the samples of 1993 (late June) were not collected during the same season as the samples of 1998 (early May), a comparison of two sets of data is still possible. The reasons are: (1) $\delta^{13}C$ values followed a quite predictable seasonal trend with generally the lowest values occurring in spring and summer (De Brabandere et al., 2002); (2) the spatial distribution of $\delta^{13}C$ in spring and summer is similar (Hellings et al., 1999; Hellings, 2000). Indeed, a similar $\delta^{13}C$ longitudinal distribution pattern was observed in 1993 and in 1998, with the most negative values (below −27 to about −30‰) upstream of 92 km and progressively less negative values (above −27 to near −21‰) downstream of 58 km (Fig. 15). Both 1993 and 1998 $\delta^{13}C$ values showed a wide spatial variation. In 1993 the $\delta^{13}C$ ranged from −20.93 to −29.58‰ with mean values of −28.4 ± 1.1‰ upstream of 58 km and of −20.9 ± 0.2‰ in the lower estuary. These values are in agreement with the ones reported by Middelburg & Nieuwenhuize (1998) for their observations in August 1994 (−28.9 ± 1.1‰ upstream of 58 km and −20.1 ± 1.7‰ in the lower estuary). In 1998 the $\delta^{13}C$ upstream of 58 km ranged from −27.04 to −29.84‰ with a mean value of −27.6 ± 1.1‰ consistent with the values reported by Hellings (2000) for measurements made in April 1998 (−27.6 to −29.0‰). In the lower estuary, the $\delta^{13}C$ ranged from −21.84 to

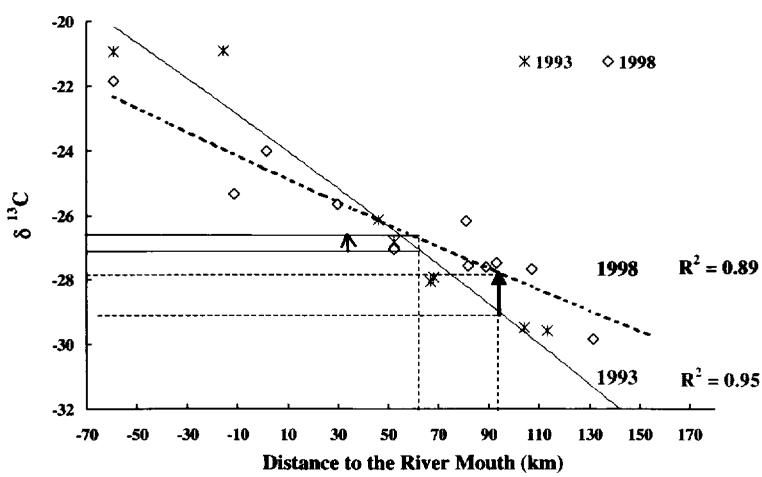


*Figure 15.* Longitudinal distribution of $\delta^{13}C$ ($C_{org}$ in suspended matter) along the Scheldt Estuary. $\delta^{13}C$ data of 1993 from Wartel et al. (1993). Arrows indicate the change of $\delta^{13}C$ values near 58 km and near 92 km.

−25.66‰ with a mean value of −23.7 ± 1.7‰. No other documented $\delta^{13}C$ values were available for the lower estuary in 1998. The $\delta^{13}C$ values measured for both 1993 and 1998 suspended matter samples are largely within the same range and closely comparable with the values reported in other estuaries as detailed in a review and synthesis of natural stable carbon isotope research by Raymond and Bauer (2001).

Although the geographical variations of $\delta^{13}C$ showed similar pattern in 1993 and 1998, the slope of the distribution is different (Fig. 15). To project these differences, the fraction of fluvial component of suspended organic matter for every $\delta^{13}C$ value is calculated and is plotted versus the distance from the river mouth (Fig. 16) along with the results of the sand fraction (>63 $\mu$m) and organic matter content of suspended matter. In 1993, the suspended matter exhibited ca. 90% of fluvial origin at 92 km and around 65% at 58 km and further decreased to the river mouth, while in 1998 these values were lower and presented ca. 70% at 92 km and around 55% at 58 km. The fluvial fraction of suspended matter measured near 58 km is largely in agreement with incidental information of the Scheldt from literature. Salomons & Eysink (1981) found 70% in 1977 and Verlaan et al. (1998) reported 40–60% between May and July in 1987.

The $\delta^{13}C$ value rise in 1998 compared to 1993 near 58 km and from that area further upstream indicates that either the marine influence increased further landward, or the fluvial-matter supply decreased, or else that the phytoplankton activity declined. $\delta^{13}C$ value can have fallen by blooming of phytoplankton demanding for $CO_2$ (Hellings et al., 1999, 2001; De Brabandere et al., 2002). Phytoplankton spring blooming consists mainly of riverine species, whereas in late spring and summer it consists of estuarine ones (Heip et al., 1995; Muylaert & Sabbe, 1996; Muylaert et al., 1999, 2000). Riverine and brackish phytoplankton generally have $\delta^{13}C$ values ranging from −44 to −24‰ (Coffin et al., 1994) while marine one has relatively high $\delta^{13}C$ value and typically close to −21‰ (Fry & Sherr, 1984). Thereby, if phytoplankton spring blooming did make a significant difference in $\delta^{13}C$ values, then the samples from early May in 1998 might supposedly have shown decreased $\delta^{13}C$ values upstream of 58 km, yet the opposite is observed. Therefore, the influence of phytoplankton activity on the $\delta^{13}C$ values for those two sampling periods is considered to be compatible, because in spring and summer $\delta^{13}C$ values are most negative set mainly by phytoplankton blooming activity (De Brabandere et al., 2002), and because no information is available for a possible variation between early May in 1998 and late June in 1993. Hence, the decrease of fluvial origin components in 1998 at the upper reach of the Scheldt must be due to other factors.

In 1998, both river discharge and fluvial matter supply were higher than those in 1993 (Fig. 2). A high river discharge can advect large amounts of terrestrial organic detritus having higher $\delta^{13}C$ signatures ($\delta^{13}C$ ca. −26‰; Middelburg & Nieuwenhuize, 1998; Hellings et al., 1999, 2000), and thus may contribute to the $\delta^{13}C$ value rise in the upper estuary in 1998. The isotopic composition of suspended matter contains information on the mixing of the various organic matter sources. Figure 16 shows an evident trend of increasing sand content from average of 6% in 1993 up to 17% in 1998 and decreasing organic matter content from average of 15% in 1993 down to 8% in 1998. That the suspended matter sampled in 1998 contains coarser grains and was poorer in organic matter may also explain the $\delta^{13}C$ signature rise in 1998. This assumption is based on the studies of Hedges et al. (1986), as well as Middelburg & Nieuwenhuize (1998), who reported their $\delta^{13}C$ research results of increased $\delta^{13}C$ values and reduced organic matter in their samples. It is important to note that 1998 was a year of intense dredging and deepening of the navigation channel (Fig. 3). Deepening of the channel naturally decreases the friction experienced by incoming marine water on the flood tide and allows more water to flow into the estuary causing an increase in the tidal range (Fig. 4). Consequently, there is no evidence for not taking into account the increased marine influence further landward and the upstream transport of marine-borne matter with high $\delta^{13}C$ values (ca. −20‰), which may be among one of the causes for the upstream $\delta^{13}C$ value rise in 1998. Increased dredging activity may also cause a possible mixing of recently suspended matter holding fresh organic matter either with dredged material or with eroded old matter, containing degraded organic matter, from the deepened channel. Sequentially, the reduced

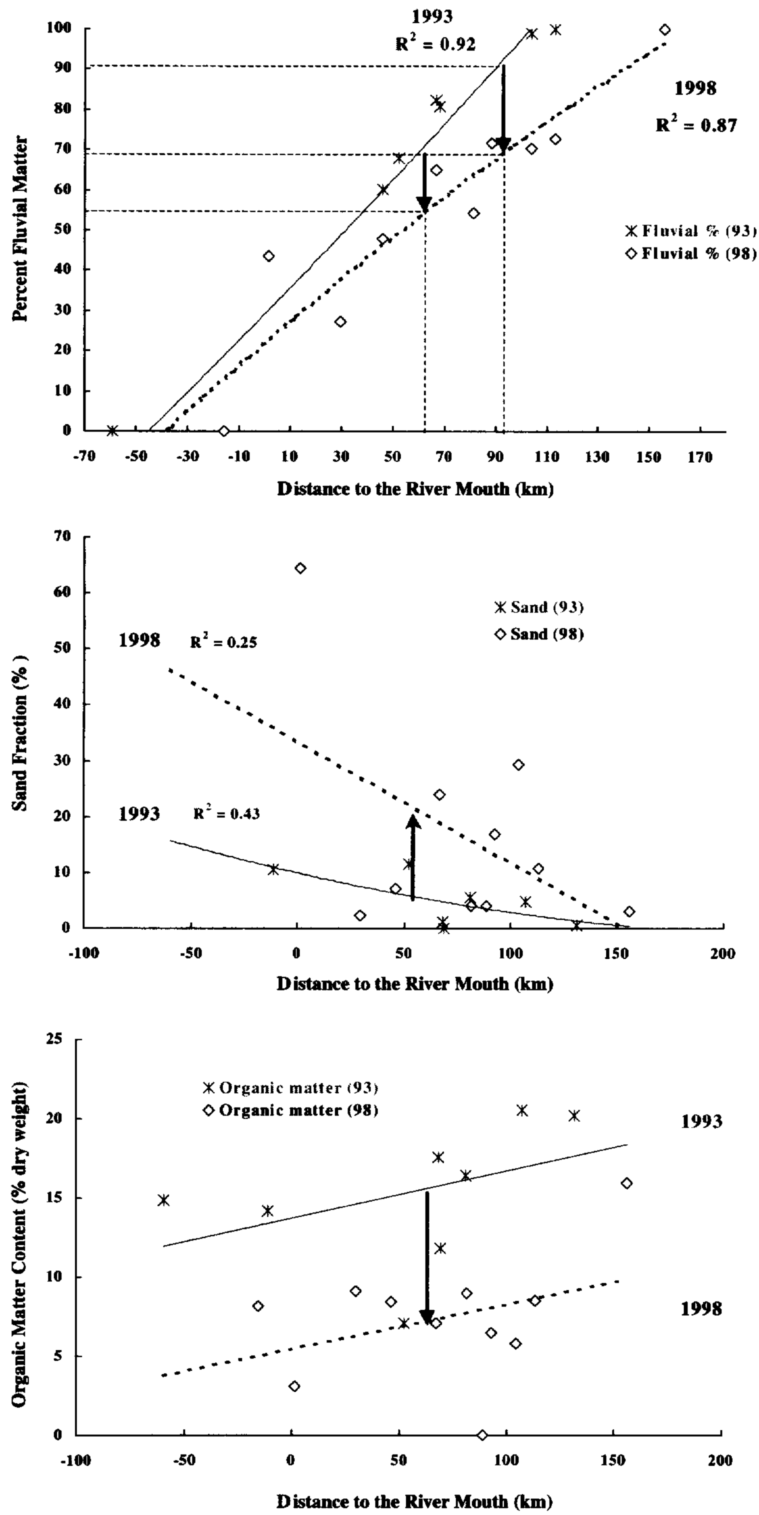


*Figure 16.* Fluvial fraction, sand (>63 μm) and organic matter contents of suspended matter.

organic matter in suspended matter may lead to the $\delta^{13}C$ value rise in 1998.

In summary, an obvious $\delta^{13}C$ value rise in the middle and upper estuary from 1993 to 1998 is attributed to a high river load on the one hand and enhanced marine influence further landward probably due to channel deepening in the lower estuary as well as low organic matter on the other.

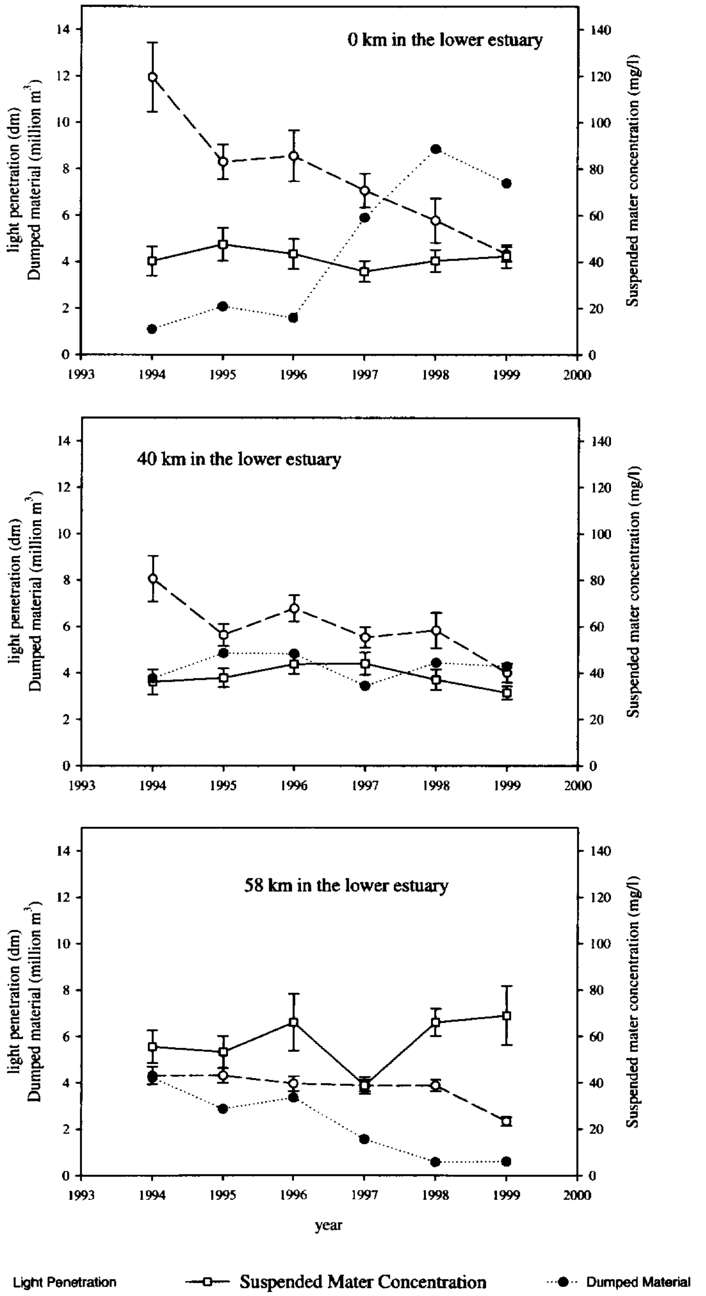


*Figure 17.* Light penetration in the lower estuary. Values are the yearly average of fortnight measurements between 1994 and 1999. Bars indicate standard error. Data from the Directorate-General for Public Works and Water Management, Institute for Inland Water Management and Waste Water Treatment (RIZA), the Netherlands (2002).

**Light penetration and suspended matter concentration**

Suspended matter by itself may be regarded as a "negative" substance because it reduces the light penetration and consequently affects primary production of an estuary. It is a generally acknowledged truth that, since nutrient limitation is almost non-existent, light is the exclusively limiting factor for phytoplankton growth virtually in the entire Scheldt estuary. In spite of low suspended matter concentration in the lower estuary, primary production is low and restrains nutrient turnover (e.g. Van Spaendonk et al., 1993; Soetaert et al., 1994; Kromkamp et al., 1995; Cloern, 1999; Kromkamp & Peene, 1999). Light penetration measurements between 1994 and 1999 in the lower estuary (Fig. 17), showed that water transparency decreased with distance from the river mouth from an average of 8 $\pm$ 3 dm at the river mouth (0 km), to 6 $\pm$ 1.5 dm at 40 km and further down to 3.5 $\pm$ 0.7 dm at 58 km. The 5-year trend of light penetration is declining and is most pronounced at 0 km. Considering that turbidity is one of the major influential factors for water transparency, this trend is remarkable when compared with the almost stable suspended matter concentration measured for the same time span at these three sites (Fig. 17). Measurements denote that transparency does not correlate with turbidity. The optical property of a suspension, however, is also related to suspended particle size. When taking into account the amount of dredged material dumped at the river mouth (Fig. 17), it shows that an increment in dumping material goes hand in hand with a decrement in transparency. Is transparency then associated with dumping? As particle size can influence the water optical property, one may argue that dredged old material is not or less flocculated than recent material due to the absence of living matter. The effect of non-flocculated matter on transparency is significant because of the light extinction by many non-flocculated fine individual particles including colloids (personal communication with Dr. Robert Finsy, Physical and Colloid Chemistry, Vrije Universiteit Brussel), however, their effect on suspended matter concentration is low because the total amount of particles is the same as for the flocculated matter. Nonetheless, this hypothesis cannot explain what is observed at the other two measuring sites, as the dumping material was either stable (at 40 km) or reduced (at 58 km) over this 5-year time. A tentative explanation, though it can be argued, is that a sustained landward flow and transport of suspended matter including resuspended dumping material due to a continuous increment of tidal range (Fig. 4) resulted in a decline of the transparency at the upstream measuring sites.

**Conclusions**

Direct field observations in the Scheldt estuary have elicited important estuarine features: energy distribution, water circulation pattern and critical current velocity as well as ETM zones, and sequentially have illustrated the suspended matter response in general. The variations in suspended matter distribution, its constituent fractions and the dispersed as well as *in situ* particle size spectra are primarily induced by hydrodynamic conditions and demonstrate their ephemerality and complex nature.

The Scheldt estuary is characterised by a specific total energy pattern – a combined power of marine (waves and tides) and fluviatile processes. This energy pattern divides the estuary into three parts: a lower part, where tidal energy is important and a net landward oriented transport of suspended matter occurs, a middle part, where tidal energy dominates and suspended matter converges, and an upper part, where fluvial energy prevails and a net seaward oriented transport of suspended matter takes place. A total energy maximum is situated between 58 and 100 km in the middle estuary. A total energy minimum is in the vicinity of 120 km, where tidal energy equals fluvial energy.

Suspended matter transport and distribution are powered by and follow the energy distribution pattern in the Scheldt. Observations exhibit the existence of three ETM. A marine-dominated ETM in the mouth of the estuary shows suspended matter concentration more than a few hundred milligram per litre. A river-dominated ETM in the upper estuary has suspended matter concentration reaching up to 300 mg/l. The most important tide-dominated ETM in the middle estuary coincides with the total energy maximum and contains suspended matter concentrations from several hundred milligram per litre up to a few grams per litre. This ETM genuinely results from the effect of high tidal range which is responsible for an important local erosion and deposition process. The data show that the suspended matter vertical distribution mainly exhibits a multilayer graded-suspension structure. The major source for such graded-suspension formation in this ETM is bottom scour initiated when a critical erosion velocity of 0.56 m/s is exceeded.

An assessment of residual current in the main river channel along the axis of the Scheldt estuary shows that the flow in the uppermost water layer (within 1 m below the surface) is oriented seaward, however, the lowermost water layer (within 1 m above the bottom) is differentiated into distinct sections. It is oriented seaward in the upper estuary, landward in the lower estuary and in equilibrium in the vicinity of 70 km in the middle estuary. Though residual currents have distinct patterns in the main channel, the local morphology of the river, natural or man-made, has a prominent effect on the orientation and strength of the residual currents flowing along either side of the river or river bend. Evaluation of suspended matter concentration in relation to the current flow shows no systematic correlation either because of phenomena as scour lag and settling lag mainly in the middle estuary, or because of the current independency character of the uniform suspension mainly in the upper and lower estuary. Quantification of suspended matter load exhibits a net downstream transport from the upper estuary, a near-equilibrium sustainable status in the middle estuary and a net upstream transport of suspended matter from the lower estuary.

It is found that suspended matter consists of a variable amount of organic fraction with an average range of about 8.5–25% dry weight and a complementary inorganic fraction characterised by silty clay. Suspended matter is flocculated. Large flocs are repeatedly found at low or no salinity areas around 80 km and further upstream. Flocs become smaller toward downstream showing least size within the ETM in the middle estuary. In this study, no evidence was found for an intensified flocculation in the salinity zone between 2 and 5. Evolution of floc formation within a tidal cycle is governed by different phases of tidal related current velocity and suspended matter concentration.

Independent time series measurements from 1990 to 2000 of suspended matter property show an increased sand fraction, a decreased organic matter content, a $\delta^{13}C$ value rise as well as a decrement of water transparency. These independent measurements exhibit their association with and coherent consequences of estuarine maintenance operations. Maintenance dredging of the shipping channel and harbours and dumping operation in the Scheldt strengthen marine influence landward resulting in a sustained tidal range increment and upstream flow on the one hand and probable mixing of recent suspended matter with dredged material or with resuspended old matter released from the new bottom after channel deepening on the other.

Given the measurement results of turbidity maxima, there is no doubt that they play an important role in modifying the load of suspended matter. It shall deserve some attention in the case of the river-dominated ETM, as an important feature of the ETM is how circulation phenomena in it trap particles and promote biogeochemical, microbial and ecological processes that sustain a dominant pathway in the estuarine food web. From an ecological point of view, is it sustainable when a large amount of suspended matter is removed from the estuary? If yes, then what is the effect of such a removal on the estuarine habitats? Flocculation of suspended matter in the Scheldt demands further attention for its mechanisms and its ecological relevance. To understand between the physics of estuary and various processes within it requires a resolutely interdisciplinary approach, and a complex, highly integrated program of field and laboratory measurements and experiments.

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