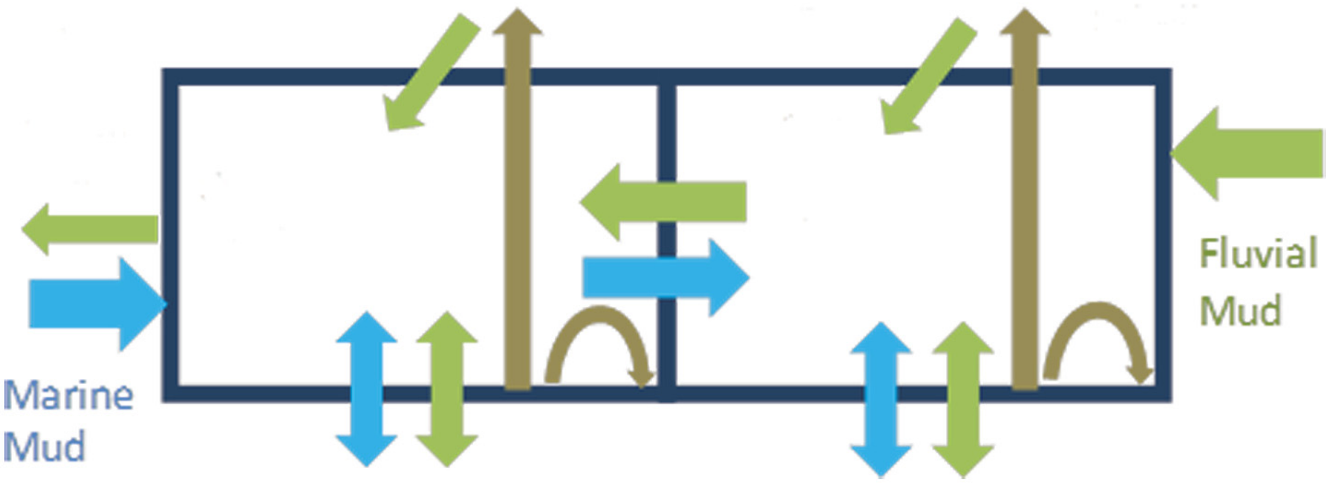


Flanders
State of
the Art

00_029_3
WL rapporten

Slibbalans Zeeschelde

Deelrapport 3 - Literatuurstudie

DEPARTMENT
MOBILITY &
PUBLIC
WORKS

www.flandershydraulicsresearch.be

Slibbalans Zeeschelde

Deelrapport 3 - Literatuurstudie

Dams, J.; Vanlede, J.; Plancke, Y.; Verwaest, T.; Mostaert, F.

February 2016

WL2016R00_029_3

This publication must be cited as follows:

Dams, J.; Vanlede, J.; Plancke, Y.; Verwaest, T.; Mostaert, F. (2016). Slibbalans Zeeschelde: Deelrapport 3 - Literatuurstudie. Version 4.0. WL Rapporten, 00_029. Flanders Hydraulics Research & Vrije Universiteit Brussel: Antwerp, Belgium.

Responsible publisher:

DEPARTEMENT **MOBILITY AND PUBLIC WORKS**

Flanders Hydraulics Research

Berchemlei 115, 2140 Antwerpen
T +32 (0)3 224 60 35
F +32 (0)3 224 60 36
waterbouwkundiglabo@vlaanderen.be
mow.vlaanderen.be
waterbouwkundiglaboratorium.be

In collaboration with:

Vrije Universiteit Brussel
Faculteit Ingenieurswetenschappen, Departement hydrologie en waterbouwkunde

B-1050 Brussels
Tel. + 32 2 629 30 21
Fax: + 32 2 629 30 22
E-mail: hydr@vub.ac.be
www.vub.ac.be/hydr

Documentidentification

Title:	Slibbalans Zeeschelde: Deelrapport 3 - Literatuurstudie		
Customer:	aMT	Ref.:	WL2016R00_029_3
Keywords (3-5):	Mud Balance, Western Scheldt, Sea Scheldt		
Text (p.):	92	Appendices (p.):	2
Confidentiality:	☐ Yes	Exceptions:	☐ Customer ☐ Internal ☐ Flemish government
	☒ No	☒ Available online	

Approval

Author	Reviser	Project Leader	Research & Consulting Manager	Head of Division
Dams, J. Vanlede, J.	Plancke, Y.	Vanlede, J.	Verwaest, T.	Mostaert, F.

Revisions

Nr.	Date	Definition	Author(s)
1.0	21/06/2013	Concept version	Dams, J.; Vanlede, J.
2.0	19/08/2014	Substantive revision	Plancke, Y.
3.0	18/03/2015	Revision customer	Bosmans, S; Roose, F.
4.0	26/02/2016	Final version	Vanlede, J.

Abstract

This literature review is a deliverable within the study “slibbalans Zeeschelde” (WL Project 00_029), and gives an overview of available knowledge on mud transport and stock in the Scheldt estuary. It is meant to be used as a reference and an inventarisation of available knowledge on the mud balance of the Scheldt estuary. Sometimes a claim by an author may have come at odds with more recent insights in system behaviour. The authors have tried to indicate that in the text. Because insights are constantly evolving, this document should be a living document.

First, available methodologies to estimate mud transport are presented. Anthropogenic activities in the Scheldt estuary that had a possible impact on the mud dynamics are listed. The main part of this literature review consists of a summary of the most important conclusions of literature describing the mud stock in the Scheldt estuary since 1964 and an overview of historic estimations of mud transport and sedimentation over time in different parts of the estuary.

For the sake of consistency, mud quantities are converted to Ton Dry Matter whenever possible (TDM in English, Ton Droge Stof or TDS in Dutch), which correspond to the mass of the grains of sediment in the water-sediment mixture.

CONTENTS

LIST OF TABELS

LIST OF FIGURES

1 INTRODUCTION

This literature review on mud in the Scheldt estuary is part of the project 'Slibhuishouding Zeeschelde'. This project, commissioned by the Maritieme Access division of the Flemish government, has two major goals. The first goal is to extend existing knowledge on the mud system in the Scheldt estuary with a focus on the Belgian part of the Scheldt. Especially sources and sinks of mud in the Scheldt basin and their historic evolution will be studied. Secondly the project 'Slibhuishouding Zeeschelde' wants to contribute to answering following managing questions: (a) what is the effect of a tidal dock on the mud balance, (b) what is the evolution of physical parameters influencing the mud balance and (c) how did the different components of the mud balance in the Scheldt estuary evolve during the last decades.

Research on mud in the Scheldt estuary started around the seventies. Because of the influence of mud on the transport of contaminants from the Flemish area upstream to the Dutch area downstream, mud transport became an important issue since the mid-eighties. Also the accumulation of mud in the harbours and access channels to the locks, requiring a substantial dredging effort to ensure maritime access to the port of Antwerp, demands a proper understanding of the mud balance. Both the Flemish and Dutch authorities ordered and performed several research projects on the mud system of the Scheldt in the past.

This literature review summarizes the most important results of available papers and reports concerning the mud balance of the Scheldt estuary. It can be mentioned that in past the mud dynamics have been studied mainly for the middle part of the estuary, i.e. the Western Scheldt and the Lower Sea Scheldt. The most down-estuarine part (Vlakte van de Raan) as well as the most up-estuarine part (Upper Sea Scheldt) were not taking into account in most of the available studies. The focus of this literature review is on net mud quantities, represented in ton of dry matter/year, calculated or estimated in previous research projects for the different mud balance components in the Scheldt estuary. Figure 1 gives an overview of these mud balance components. Green arrows represent the upstream and lateral input of fluvial mud in the estuary, its accumulation on the river bottom, intertidal areas and marshes and net downstream transport. Blue arrows represent the upstream transportation of marine mud and its accumulation in the Western and Sea Scheldt. Also artificial transport or removal of mud (brown arrows) are included in this literature review. Where possible a subdivision is made between the eastern and western part of the Western Scheldt.

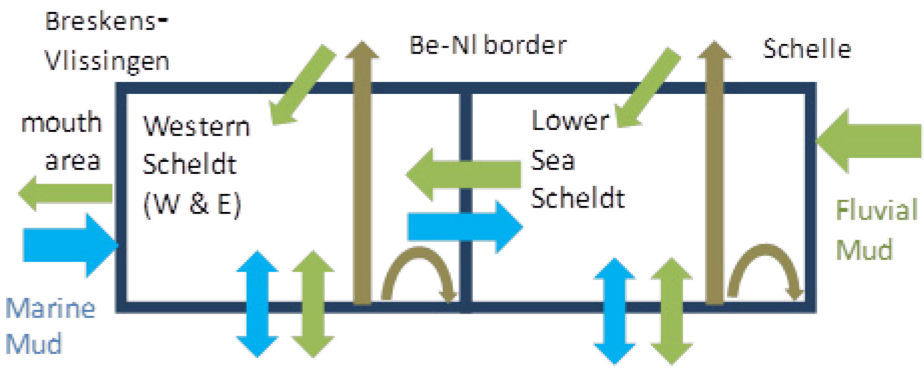


Figure 1 – Overview of the mud balance terms adressed in detail in this literature review

The following chapters are based on published material by several authors. When different views exist in the literature, this report tries to frame the differences without explicitly choosing for this or that figure as "truth". Part of the aim of this report is to show the scatter that exists in the published knowledge on the mud balance of the Scheldt estuary. This scatter in the results is expected in the field of sediment transport, due to the uncertainties associated with measuring and modelling sediment transport. Sometimes a claim by an author may have come at odds with more recent insights in system behaviour. The authors have tried to indicate that in the text. Because insights are constantly evolving, this document should be a living document.

2 MUD IN THE RIVER SCHELDT

The transport of mud through rivers and estuaries is a natural phenomenon and is essential for the ecology of the intertidal areas. Anthropogenic influences such as wastewater discharge and intensive agricultural activities have caused the quantity and quality of fluvial mud transported to the estuary to change over time. Moreover, natural and man-induced morphological changes of the river bed, as well as human interactions (e.g. poldering, construction of harbours) had an important impact on the mud dynamics in the Scheldt estuary.

The mud dynamics in tidal areas such as the Scheldt estuary is influenced by the tide, the upstream discharge of the river and the morphology (Baeyens *et al.*, 1998). The combination of these factors makes the mud concentration variable over time and space. Consequently also the sedimentation, erosion and transport of mud is highly variable in time and space.

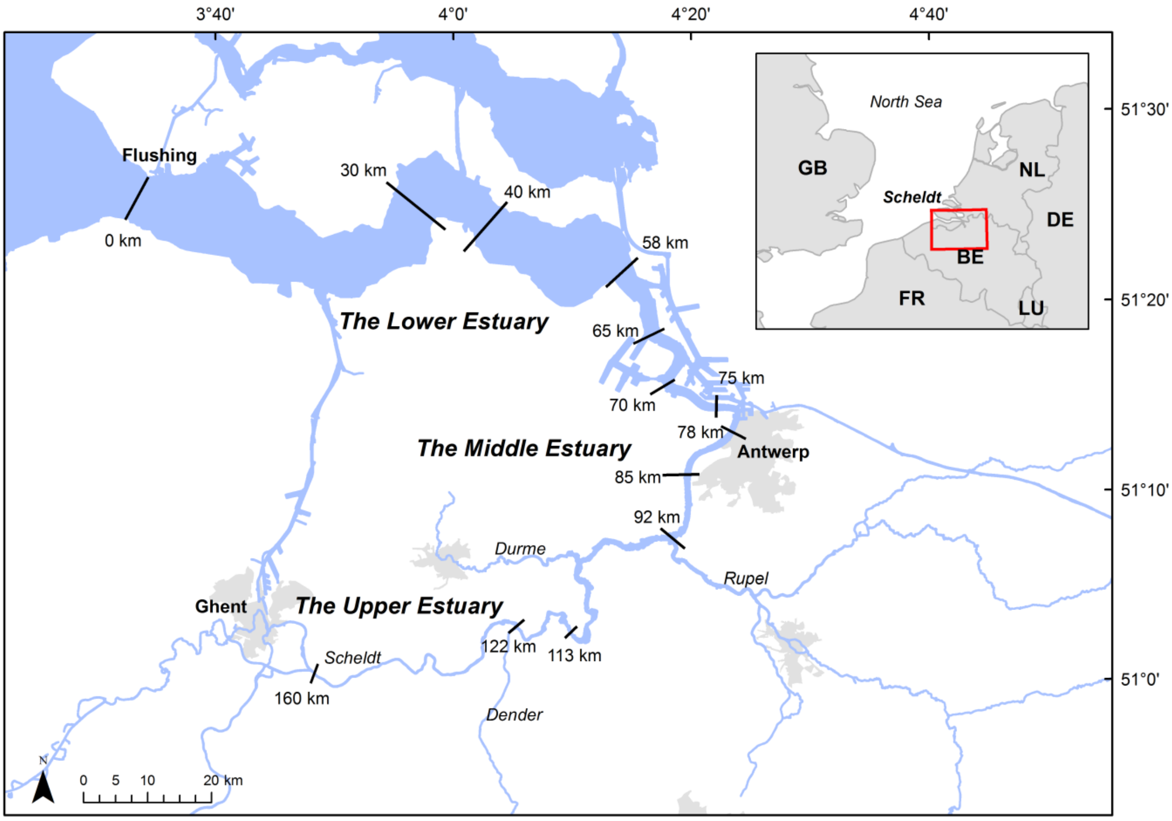


Figure 2 – the Scheldt estuary

Figure 2 shows the Scheldt estuary. The estuary can be divided into the mouth area (Vlakte van de Raan), the lower estuary, from the river mouth to the Belgian-Dutch border (58 km); the middle estuary, from the Belgian-Dutch border to the mouth of the Rupel (92 km); the upper estuary, from the mouth of the Rupel (92 km) to Ghent (160 km). The lower estuary is often referred to as Western Scheldt. The middle and upper estuary are called respectively Lower Sea Scheldt and Upper Sea Scheldt. The middle and upper estuary together form the Sea Scheldt. The total catchment area is about 22.000 km². The Scheldt is a lowland river with a total fall of around 100 m. The mean discharge of the Scheldt and its main tributary Rupel[1] in Schelle (about 90km from the mouth) is about 104 m³/s (Baeyens *et al.*, 1998). During winter and spring the freshwater discharge is significantly higher (on average 180 m³/s) than during summer and autumn (average 60 m³/s). Figure 3 shows the monthly discharge calculated at Schelle for the period 1949 – 2012, as reported in Vanlierde et al. (2013).

[1] The fresh water discharge of the Rupel-catchment is more important than this of the Upper Sea Scheldt (60-40%).

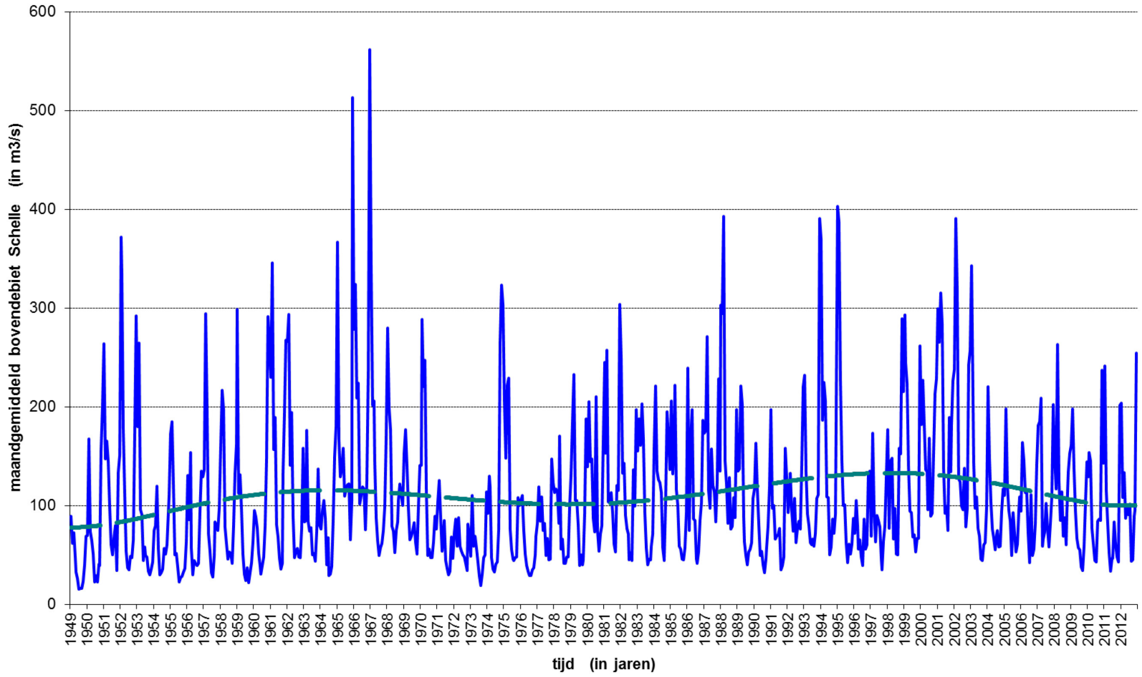


Figure 3 - Monthly discharge of Schelde at Schelle 1949 – 2012 (Vanlierde et al., 2013)

This freshwater discharge is however small compared to the high tidal discharge with annual average of about 50.000 m³/s for both ebb and flood tides near the river mouth. Because of the large tidal discharge and vertical mixing of salt and fresh water in the Scheldt, it takes on average about 3 months before the freshwater reaches the North Sea (Wollast & Peters, 1979). Because mud continuously deposits and re-suspends due to turbulent currents, their residence time is even much longer that the residence time of the water. Van Maldegem (1993) estimates the residence time of mud not deposited permanently on the marshes to be around 10 years.

The Scheldt estuary is characterized by a semidiurnal, meso- to macrotidal regime. From the mouth to approximately 58 km upstream, the Scheldt is a multi-channel system. The mean tidal range at the mouth in the southern North Sea ranges between 4.5 and 3.0 m during spring and neap tides respectively. Within the estuary, the mean tidal ranges increase to 5.9 m and 4.5 m at Schelle and decrease again further inland to 2.2 m and 1.8 m near Ghent.

The tidal zone of the Scheldt extends 160 km in length and includes an approximately 60 km long fresh water zone extending from near the mouth of Rupel (92 km) to Ghent (160 km) (Chen *et al.*, 2005). During winter and spring when the river discharge is higher the fresh water zone extends even to the city of Antwerp at 78 km from the mouth. The difference in winter and summer river discharge has also an important effect on the temporal dynamics of the mud transport.

Figure 4 represents the gross transportation of mud during one tidal circle as presented by van Maldegem (1993). Due to the tidal currents large loads of muds (50.000 ton of mud per tide or about 35 million ton per year) are exchanged with the active bottom layers of the Scheldt estuary and are transported upstream during flood and again downstream during ebb. In this literature review we are also interested in the net transportation of mud. This is the relatively small difference between the mud transported during ebb and flood. In general the net transportation is expressed in ton per year.

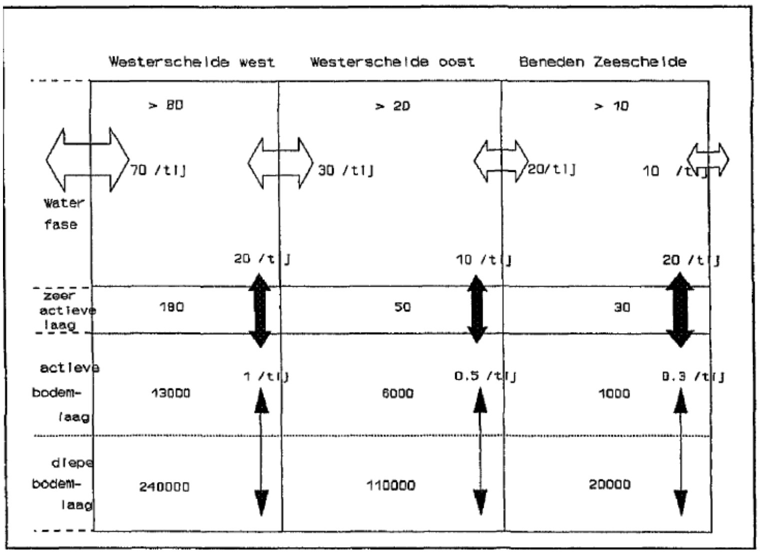


Figure 4 - Gross horizontal and vertical transport of mud during one tidal cycle [10^3 ton] (Source: van Maldegem, 1993)

In the Scheldt estuary a maximum turbidity zone, with high suspended sediment concentrations (SSC), is hypothesised in the region between the Belgian-Dutch border (58 km from the mouth) and Antwerp (78 km from the mouth). Wollast & Peters (1979) explained this maximum turbidity zone using the conceptual visualisation depicted inFigure 5. The residual transport close to the bottom is supposed to go through a zero-crossing around Antwerp.

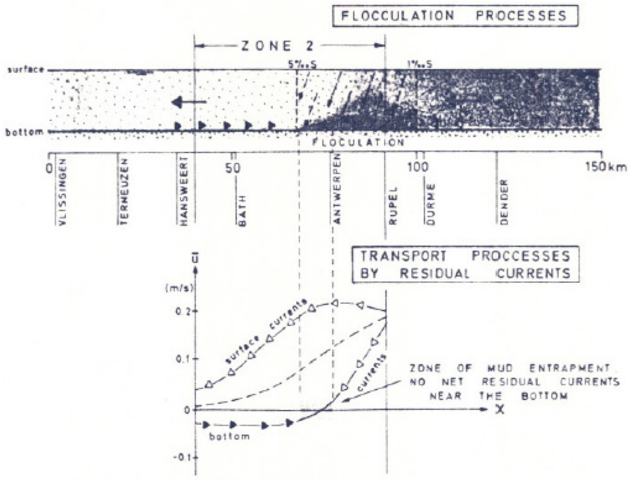


Figure 5 – Mechanisms of mud deposition (Source: Wollast & Peters, 1979)

Research by Chen *et al.* (2005) and Wartel & Francken (1998) shows that when the tidal, river and wave energy in the estuary are summed, three energy peaks appear as shown in Figure 6. Based on these energy peaks three Estuary Turbidity Maxima (ETM) could be expected. Besides the main ETM in the middle estuary extending roughly from 58 to 100 km from the mouth, Chen (2005) describes one smaller ETM at the mouth of the estuary and another one in the upper estuary.

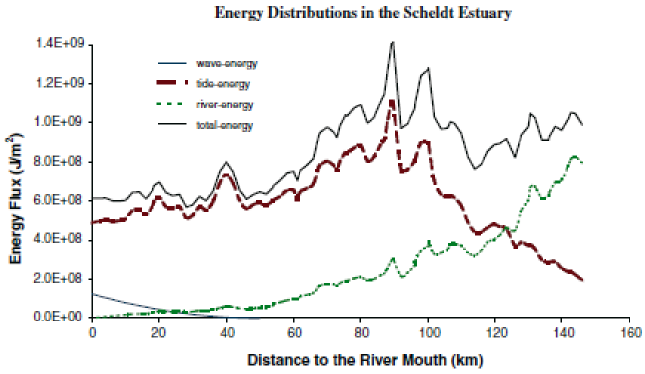


Figure 6 - The Scheldt energy distribution (Source: Wartel & Francken, 1998; Chen et al., 2005)

Riparian zones of the Scheldt estuary are characterized by tidal mud flats (in Dutch called “slikken”) and tidal marshes (Dutch: “schorren”). The tidal mud flats are flooded every high tide and are therefore non-vegetated. Tidal marshes are only flooded during springtide, once every two weeks, making them suitable for vegetation. Due to this vegetation, tidal marshes are preferential sedimentation locations in the estuary, causing a natural purification of the Scheldt water. Temmerman *et al.* (2006) estimates the area of salt, brackish and freshwater marshes in the Scheldt estuary at respectively 230, 2630, 420 ha. The brackish tidal marshes are dominantly situated in the area “Verdronken land van Saeftinghe”, situated on the left bank of the Scheldt downstream the Belgian-Dutch border.

Based on the morphology and grain-size distribution of the river bed, the Scheldt estuary can be divided into three zones with very distinct characteristics (Verlaan, 2000). The first zone is the fresh to slightly brackish water area upstream of Antwerp. The high tidal current velocities is this zone prevent permanent deposition of suspended matter in this area. Sediments consist therefore of medium to coarse sands, with between Antwerp and Rupelmonde locally gravel. In the brackish water zone between Antwerp en the Dutch-Belgian border the tidal current velocities are lower than upstream, resulting in more fine-grained sediments (fraction <6 µm: 10-30%). The mud concentration in the river bed is high in this zone, especially in the access channels to the locks where large amounts of mud are deposited. The sediments in the Western Scheldt consist of medium to coarse sands with only occasionally mud deposits. The mean grain-size gradually decreases from the tidal channels to the salt marshes (Verlaan, 2000).

3 METHODS TO ESTIMATE MUD TRANSPORT

3.1 Method based on discharge and suspended sediment concentration

The fluvial mud input from upstream the tidal area can be derived directly from discharge and sediment measurements. Claessens (1993a; 1994) and Taverniers (1995; 1996; 1997; 1998a; 1999; 2000; 2001) used a method based on continuously measured river discharge and water samples of which the mud concentration is determined every week. Two methods were applied by Claessens and Taverniers to combine the continuously measured discharge with the weekly mud concentration samples. The first method uses a correlation between all mud measurements in that year and their corresponding river discharge to calculate the mud content based on the average monthly discharge. In the second method the fluvial mud flux is calculated by multiplying the measured mud contents with the discharge. Both methods are compared, and applied for the period 1972 – 2009 in Van Hoestenberghe *et al.* (2013).

In the estuary estimating the net transport of mud is less straightforward. Under the tidal influence a large amount of mud is transported upstream during flood and again downstream during ebb. The transport during ebb and flood events is in the order of 100-1000 times larger than the net transport (van Maldegem, 1993). Nevertheless, several authors (e.g. Bakker, 1975; Salomons *et al.,* 1981; Swart, 1983) have estimated mud transport in the estuary using the net discharge and the average mud concentration at a certain location in the Scheldt estuary.

3.2 Method based on quantification of sources

As previously mentioned the horizontal transport of mud in the zone upstream the tidal area can be calculated directly by multiplying the river discharge with the mud concentration as done for example by Claessens (1993, 1994) and Taverniers (1995-2001). Due to the assumptions that have to be made to estimate the mud concentration in between the measurements, this method is subject to a relatively high uncertainty.

The fluvial input into the Scheldt estuary has also been estimated indirectly by quantifying the mud originating from the different natural and anthropogenic sources (Wollast & Marijns, 1981; IMDC, 1993; Cauwenberghs, 1998). The latter approach has the advantage that it allows to estimate the contribution of the different mud sources. Nevertheless, due to the complexity of the behaviour and the transport of mud in the river this method only allows a rough estimation of the input of fluvial mud in the estuary system.

3.3 Mass balance approach

In the estuary the net mud transport is often estimated using a mass balance approach. This mass balance method uses the quantifiable terms that play an important role for the transportation of mud to estimate natural net mud transport along an estuary. These quantifiable factors are for the Scheldt estuary: fluvial mud supply of the River Scheldt, sedimentation and erosion in the morphological units, suspended matter concentrations measured at several places in the estuary, fluvial-marine ratio of the mud on the bottom of the river and anthropogenic dredging and relocation volumes (van Maldegem, 1993; Wartel *et al.*, 2007).

A disadvantage of the balance method is that physical, chemical and biological processes that play a role in the mud transport are not taken into account. The balance is therefore only valid under the assumption that these physical, chemical and biological processes did not change. This implies that the method assumes that long term morphological changes of the estuary only have a minor influence on the mud balance (van Maldegem, 1993).

Regarding the sedimentation and erosion in the morphological units (tidal channels, tidal flats and salt marshes) the balance method makes the assumption that the mud is included in the sand matrix. According to van Maldegem (1993) this a valid assumption in the Scheldt basin due to the relatively low mud content in the Scheldt estuary.

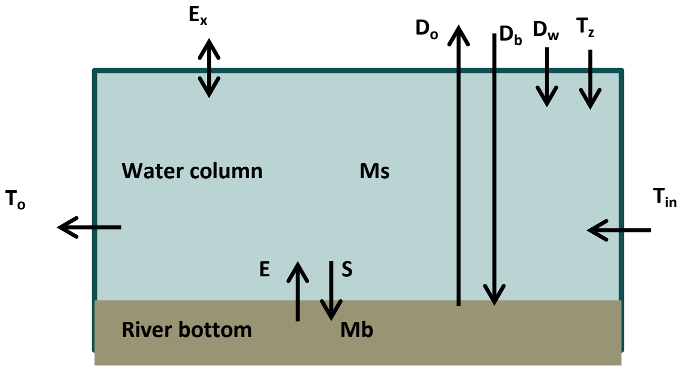


Figure 7 - Overview of the components affecting the mud balance in a section of the river (after van Maldegem, 1993)

Figure 7 illustrates the components of the mud balance as suggested by van Maldegem (1993). The mass balance equations for the water column and river bottom for each section are:

$$\frac{dM_s}{dt} = T_{in} + T_z - T_o + E - S + D_w - E_x$$

$$\frac{dM_b}{dt} = -E + S - D_o + D_b$$

In which $\frac{dM_s}{dt}$ is the change of the mass of mud in the water column over time (t), T_{in}, T_z, T_o are respectively the import, lateral inflow and export of mud from the considered river section, E and S are erosion and sedimentation of the river bottom, D_w is the dredging material spilled in the water column, E_x is the term including all other sources and sinks of mud in the section. $\frac{dM_b}{dt}$ is the change of the mass of mud in the river bottom, D_o and D_b represent the artificial exchange with the river bottom due to respectively dredging and relocation.

Under the assumption that the mass of mud in suspension (M_s) is relatively constant over time ($\frac{dM_s}{dt} \approx 0$), and $D_w \ll D_b$ the mass balance can be written as:

$$T_o = T_{in} + T_z - \frac{dM_b}{dt} - D_o + D_b - E_x$$

For two consecutive river sections: n and n-1, $\mathrm{T_{in\,(n)}} = \mathrm{T_{o(n-1)}}$ leading to the following general equation for section n:

$$T_{o(n)} = T_{in(1)} + \sum_{i=1}^{n} (T_{z(i)} - \frac{dM_b}{dt}_{(i)} - D_{o(i)} + D_{b(i)} - E_{x(i)})$$

In the above mentioned equation the only boundary condition is the input of fluvial mud at the boundary of the estuary ($T_{in(1)}$). Due to the difficulty to estimate the mass of marine mud entering the Scheldt from the North-Sea the mud balance is calculated from the most upstream area (generally from Schelle) towards the North-Sea (Vlissingen). Inevitably, the accuracy of the mass balance terms decreases from Schelle to Vlissingen.

The change in mass of mud stored in the river bottom is caused by the exchange of mud with a fluvial or marine origin. Because the import of marine mud at the sea side is unknown the ratio between marine and fluvial mud in the river bottom plays an important role in calculating the mud balance.

Several mud balance studies (e.g. Salden, 1998; Baeyens *et al.*, 1998) do not actually measure the exchange of mud with the bottom but assume it to be the balance of the suspended load data (Wartel *et al.*, 2007). Salden (1998) assumes 1/3 of the fluvial mud is too fine to deposit and is transported towards the Western Scheldt.

Baeyens *et al.* (1997) calculates the transport of particulate matter by multiplying the net discharge with the average turbidity. The difference between the input and output is assumed to be deposited. Other studies (e.g. Wartel *et al.,* 2007) try to quantify actual changes in the mud stored in the bottom of the estuary base on different lithological studies performed in 1964, 1986 and 1999.

3.4 Advection-diffusion method

van Maldegem (1993) also suggests a method based on the advection-diffusion principles to calculate mud transport in the eastern part of the Western Scheldt. The ratio of 50-100% fluvial mud against 0-50% marine mud in the water column and river bottom near the Belgian-Dutch border indicates a dispersive import of marine mud opposite the net discharge of the river.

The advection-diffusion equation that describes the dispersion can be written as:

$$T = Q\,c - D\,A\,\frac{dc}{dx}$$

Where T is the transport of mud, Q is the tidal averaged river discharge, c is the mud concentration, D is the dispersion coefficient, A is the cross-sectional surface and $\frac{dc}{dx}$ is the mud gradient. The equation could be used for both fluvial and marine mud. van Maldegem (1993) already indicated that this method has limited accuracy and he only uses it to check his results. The sediment flux due to the correlation of Q and c timeseries (tidal pumping for instance) and the sediment flux due to tidal asymmetries are not taken into account for instance.

From the advection-diffusion equation all terms can be measured except for the dispersion coefficient (D). To solve the problem of the unknown D, van Maldeghem (1993) calculates the mud transport starting from Hansweert in the Netherlands (around 40 km from the mouth) where the tidal averaged dispersion transport is assumed to be zero. When we assume the dispersion coefficients of fluvial and marine mud on the Belgian-Dutch border to be equal, the equations show that the ratio between the concentration changes of the fluvial and marine mud between the border and Hansweert is equal to the ratio between the dispersive transport of fluvial and marine mud over the Belgian-Dutch border.

3.5 Mud transport models

One of the earliest numerical models for the Scheldt estuary was devised by Baeyens et al. (1981) in order to simulate the physical behaviour, including instantaneous water levels and mean velocities over depth, salinity and turbidity in the water column and the sedimentary budget at the bottom. It was a two-dimensional (2D) depth-averaged model with a structured grid based on a multi-operational finite difference scheme.

IMDC (1993) describes a 1D mud transportmodel of the Scheldt from Vlissingen to Schelle, implemented in ESDISPER.

Mwanuzi (1997) Developed a finite difference 2D suspended sediment transport model from the mouth of the estuary to Schelle with a seperate fluviatile and marine fraction.

Lefèvre (2000) developed a mud balance for the Scheldt estuary using a software package called SLIB3D (SIMONA). The mud transport is calculated using an existing hydrodynamics simulation in TRIWAQ (SIMONA). The SLIB3D model allows the estimation of both marine and fluvial masses of mud along the estuary, but cannot take into account erosion of mud from the bottom, which is considered to be an important process. Lefèvre (2000) applies the model to simulate the impact of the river deepening and dredging activities in the Scheldt estuary on the mud transport.

The first 3D numerical sediment transport model of the Scheldt estuary seems introduced by Cancino & Neves (1994). It was a fully-3D finite difference baroclinic model system for hydrodynamics and fine suspended sediment transport with the effects of flocculation, deposition and erosion taken into account. Their approach provided a useful basis for a good understanding of the physical processes involved in sediment transport.

Verbeek et al (1998) explored the difference in sediment transport patterns between a 2Dh and a 3D hydrodynamic model, showing that a 3D model is more accurate in describing secondary flow patterns, which can attribute to as much as 40% of the siltation of sills.

IMDC (2004) describe a 3D mud transport model from Schelle to Waarde, built using Delft3D SED Online. The model was used to estimate the siltation in Deurganckdok and to determine the environmental impact of different alternatives for the maintenance dredging works in the Lower Sea Scheldt

Van Maren et al (2011) describe a detailed on-line mud transport model developed in Delft3D, that uses an equilibrium flocculation model to estimate the settling velocity. This model was used for the simulation of the effect of a Current Deflecting Wall at Deurganckdok.

In the framework of the Long term vision (LTV) of the Scheldt Van Kessel *et al.* (2011) also developed a 3D mud model for the Scheldt. The LTV mud model is not a morphodynamic model. However, concentration and spatial mud content can be simulated with reasonable accuracy.

Gourgue et al. (2013) recently developed a sediment module, with a focus on fine-grained, cohesive sediments, for the 2D finite-element model SLIM (Second-generation Louvain-la-Neuve Ice-ocean Model). The model allows the simulation of suspended sediment concentration (SSC) and the concentration of sediments freshly deposited on the river bottom.

Bi and Toorman (2014) developed a 2D mixed sediment transport model using a new approach for bottom friction modelling based on the Generalised Mixing Length (GML) theory with two-way hydrodynamic-sediment transport coupling, mixed sand-mud sediment transport (bedload transport as well as suspended load in the water column) and a dynamic non-uniform bed composition.

3.6 Calculating mud transport from long term morphological changes

Recently, Dam & Cleveringa (2013) used an alternative approach to estimate mud transport in the Western Scheldt. For the Western Scheldt there is an extensive dataset on historical bathymetric data since 1960. Dam & Cleveringa (2013) used these bathymetric data to look at volumetric change between different time intervals. Based on soil composition maps developed by McClaren they calculated the volumetric mud fraction of the observed change. In a first study three time intervals were considered: 1980-1992 (12 years), 1992-2000 (8 years) and 2000-2010 (10 years). These time intervals were selected based on the inclusion of the intertidal areas in the datasets.

Because this methodology only provides information on the volumetric changes of mud and sand over time in different sections (macrocells) of the Western Scheldt, a boundary condition is required to estimate the mud transport. Due to the difficulty of estimating the sediment exchange between the Scheldt and the North Sea, Dam & Cleveringa (2013) chose to use the transport with the Sea Scheldt as a boundary condition. Based on values presented by Haecon (2006) and Rijkswaterstaat (Zandbalans) the sediment transport to the Sea Scheldt and "Land van Saeftinghe" between 1994 and 2010 is estimated at 1.230.000 m^3/y. The mud fraction of this sediment volume is rather arbitrary chosen at 50%. Resulting in a net mud transport to "Verdronken land van Saeftinghe" and the Sea Scheldt of 615.000 m^3/y. This mud transport boundary condition has a major impact on the results of the mud transport. Based on the values in this literature review, in §10.17 a suggestion is made to improve this boundary condition.

3.7 Calculating mud transport from ADCP measurements.

Using a technique outlined in Merckelbach (2006), the backscatter intensity of an ADCP can be related to suspended sediment concentration (SSC). This way a single ADCP transect gives a combination of flow velocities and concentration, which can be used to calculate a sediment flux, as is shown for example in Levy et al (2014). This technique does not pick up however on the sediment concentrations close to the bottom due to the blanking distance, which limits the accuracy of determining net fluxes over a complete tidal cycle for instance.

4 ANTHROPOGENIC INFLUENCED ELEMENTS AFFECTING MUD STOCK AND TRANSPORT

4.1 River channel deepening and maintenance

Historical channel deepening is important, because of the possible impact channel deepening can have on tidal intrudion, both on the short and the medium-long term. An effect in tidal asymmetry will have an impact on sediment transport and long term balances, by influencing the residual transport (in magnitude and possibly in direction). The direct influence of channel deepening on the hydrodynamics (next to autonomous development) is still an active topic of debate.

Van Braeckel et al (2012) list changes in hydrodynamics (level of high and low water) observed during the different phases of channel deepening, and tries to link the two.

Historical overviews of river channel deepening and widening can be found in Van Braeckel et al. (2012).

Figure 8 and Figure 9 from Van Braeckel et al. (2012) show an historical overview of volumes of dredging, disposal and sand reclamation in the Western Scheldt and the Lower Sea Scheldt.

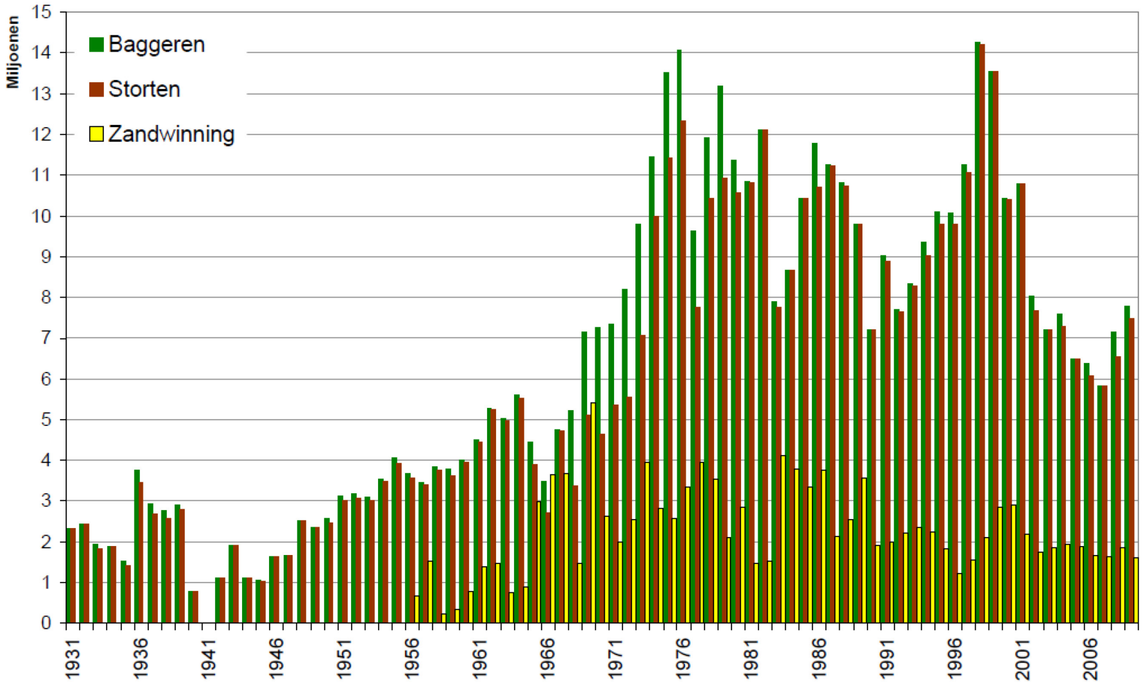


Figure 8 – Dredging, disposal and sand reclamation in the Western Scheldt (Van Braeckel, 2012)

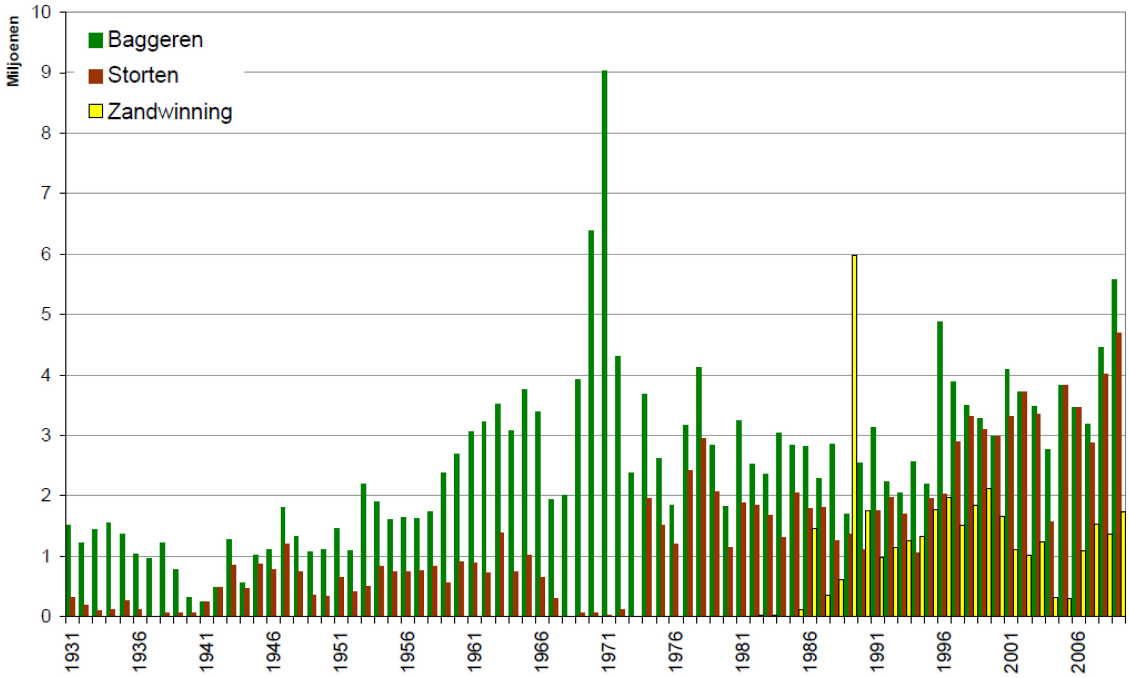


Figure 9 – Dredging, disposal and sand reclamation in the Lower Sea Scheldt (Van Braeckel, 2012)

4.1.1 First deepening to 34' (1970-1976)

In this operation, 14Mm³ was dredged in the Sea Scheldt (1970-1973), and 57.5 Mm³ in the Western Scheldt (1970-1975). The material from the Sea Scheldt was stored on land, whereas the material from the Western Scheldt was partly stored on land, and partly disposed back in to the eastern part of the estuary.

In the 70's also large quantities of sediment were extracted out of the system for infrastructural works (eg the harbour extension of Antwerp)

Figure 8 and Figure 9 also show an increase in yearly maintenance volumes: from 4 to 10 Mm³/year in the Western Scheldt, and from 2 to 3 Mm³/year in the Lower Sea Scheldt.

4.1.2 Second deepening to 38' (1997-1998)

During this phase, 17,5 Mm³ was dredged in the Western Scheldt (1997-1998). Dredged material was disposed back into the system.

After the second deepening, maintenance dredging in the Western Scheldt remained on the level it was before. Maintenance dredging in the Lower Sea Scheldt increased from 3 to 4 Mm³/year.

4.1.3 Third deepening to 43' (2008-2011)

During this phase, 7,7 Mm³ was dredged in the Western Scheldt (2010-2011), and 6,35 in the Lower Sea Scheldt (2007-2010). For the Lower sea Scheldt, this material was partly disposed back into the system, and partly stored on land.

For the Western Scheldt, the material was relocated to the edge of 4 selected shoals.

Two clear peaks appear in the dredging volume of the Lower Sea-Scheldt: during 1970-1971 and during 2004-2008 (Figure 10). The first peak coincides with the construction of the Zandvlietsluis and its access channel. The recent increase in dredging volume (2004-2008) is most likely caused by the construction works of the Deurganckdok and the deepening of drempel van Frederik.

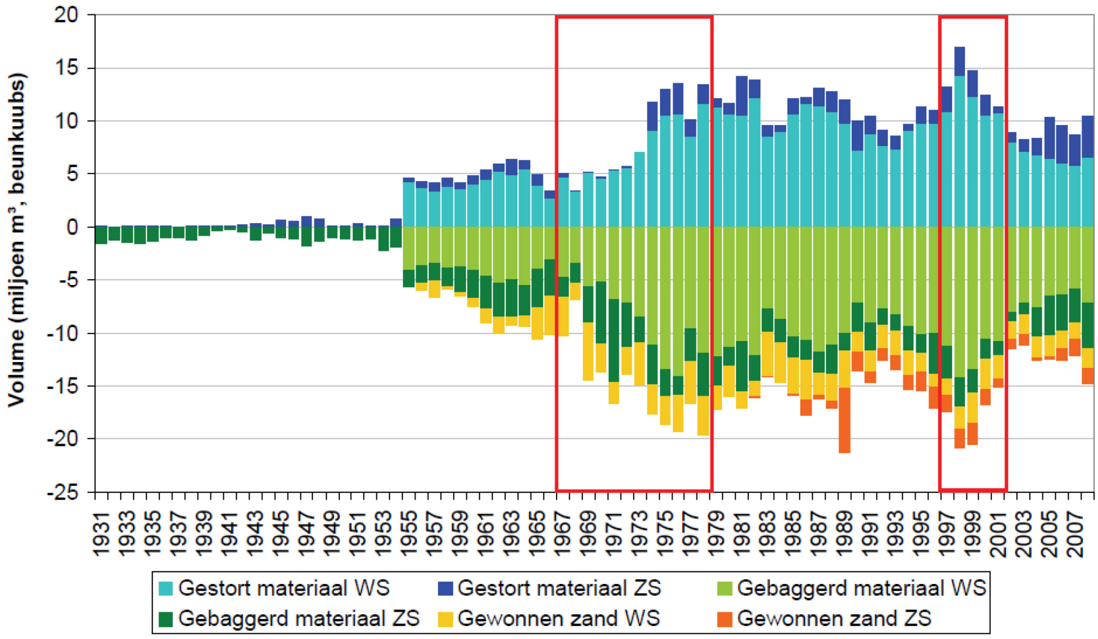


Figure 10 – Yearly volume of dredged material and sand extraction (-) and relocated material (+) in the Scheldt estuary

The material that was dredged for the deepening of the channel in the Western Scheldt is mainly sand, the mud content in the soil of the Western Scheldt is estimated around 2-12% (IMDC, 1993). In the Sea-Scheldt the river bottom contains more mud compared to the Western Scheldt. In the Lower Sea-Scheldt most dredging is performed downstream of Antwerp.

Santermans (2013) also gives a detailed overview of the evolution of vertical levels of the Sea Scheldt and te Western Scheldt in his appendix F.

4.2 Dredging

4.2.1 Western Scheldt

Santermans (2013) also summarized the mass of mud dredged from the Western Scheldt since 1983. Again the reduced volumes of mud (Santermans, 2013) are converted to tons using the conversion factor of 1.606 Ton/m³ V' (derivation see appendix A). Results are shown in Table 1. Both dredging and disposal mas in the western and eastern part of the Western Scheldt are given. Due to the relatively low mud content in the bottom of the Western Scheldt, the masses of mud are relatively low compared to the mass of sand dredged in the Western Scheldt. Most dredging is done in the western part of the Western Scheldt. Dredging material is generally disposed in the western part even if dredging occurred in the eastern part of the Western Scheldt. Except for a small amount in 1983 (about 3600 ton) no mud is transported in ships across the Dutch-Belgian border.

Since 1983 most mud in the western part of the Western Scheldt has been dredged from the sill of Borssele. In last two observed years mud has also been dredged from the Pas van Terneuzen. In the easter site of the Western Scheldt some mud has been dredged from the Overloop van Valkenisse (1998) and the sills of Valkenisse and Hansweert (2002). Most of the mud is disposed on the “Schaar van de Spijkerplaat”, “Everingen”, “Gat van Ossenisse” and “Ellewoutsdijk” in the western part and on the “Schaar van Waarde” in the eastern part (Santermans, 2013).

Table 1 – Mass of mud dredged from the Western Scheldt since 1983 [Ton/y] (Source: Santermans, 2013)

Year	Dredging			Disposal		
	Western part	Eastern part	Total	Disposal Western Part	Disposal Eastern Part	Total
1983	189.563	0	189.563	189.563	3.708	193.270
1986	30.767	0	30.767	30.767	0	30.767
1987	69.815	0	69.815	69.815	0	69.815
1988	137.917	0	137.917	137.917	0	137.917
1989	7.967	0	7.967	7.967	0	7.967
1991	1.638	0	1.638	1.638	0	1.638
1994	132.892	0	132.892	132.892	0	132.892
1998	12.936	55.494	68.430	68.430	0	68.430
2000	52.339	0	52.339	52.339	0	52.339
2001	14.152	0	14.152	14.152	0	14.152
2002	167.805	394.575	562.380	448.858	113.522	562.380
2005	41.600	0	41.600	41.600	0	41.600
2006	420.190	0	420.190	420.190	0	420.190
2008	88.730	0	88.730	88.730	0	88.730
2009	172.999	0	172.999	172.999	0	172.999

4.2.2 Harbours Western Scheldt

The harbours in the Western Scheldt are tidal harbours, meaning they are in direct connection with the Scheldt. The mud percentage in these harbours is between 70-90% (De Looff, 1978). van Maldegem (1993) estimates the contribution of the mud in the tidal harbours to the mud stock at above 5 million ton, which is for 90% of marine origin. van Maldegem (1993) assumes the average sedimentation rate of the harbours in the Western Scheldt between 1965 and 1987 at 0.38 m/y. Yearly about 1.932.000 ton of mud from the harbours in the Western Scheldt is disposed back into the estuary (van Maldegem, 1993).

Based on dredging information of Rijkswaterstaat the mass of mud dredged between 2002 and 2010 is calculated starting from the hopper volume (Table 2). The mud percentage (volume fraction) is assumed 70 or 90% (De Looff, 1978). The dry density of mud is estimated using the formula as given by Francken *et al.* (2000):

$$Mud\ mass = \frac{V_{mud} * (\rho_{mud} - 1)\ *\ \rho_{sed}}{\rho_{sed} - 1}$$

$$Mud\ mass = V_{mud} * 0.48$$

With V_{mud} the mud volume in m³, ρ_{mud} the density of mud, here assumed 1.3 ton/m³ and ρ_{sed} the density of the sediment particles (2.6 ton/m³).

Table 2 – Recent dredging activity in the Harbours of the Western Scheldt. Data is obtained from Rijkswaterstaat, Dienst Zeeland, via Frederik Roose (aMT). The mud percentage is chosen between 70 and 90% according to De Looff (1978).

year	beun volume [m³]	mud volume [m³] 70% slib	mud volume [m³] 90% slib	mud mass [ton] ($M_{mud} = 0,48 * V_{mud}$) 70% slib	mud mass [ton] ($M_{mud} = 0,48 * V_{mud}$) 90% slib
2002	7.007.789	4.905.452	6.307.010	2.354.617	3.027.365
2003	3.573.345	2.501.342	3.216.011	1.200.644	1.543.685
2004	5.057.094	3.539.966	4.551.385	1.699.184	2.184.665
2005	2.181.445	1.527.011	1.963.300	732.965	942.384
2006	2.273.674	1.591.572	2.046.307	763.954	982.227
2007	4.478.386	3.134.870	4.030.547	1.504.738	1.934.663
2008	5.273.332	3.691.332	4.745.999	1.771.840	2.278.079
2009	4.192.289	2.934.602	3.773.060	1.408.609	1.811.069
2010	2.786.257	1.950.380	2.507.631	936.182	1.203.663
avg				1.374.748	1.767.533

4.2.3 Sea Scheldt

During the recent decades the dredging strategy of mud in the harbours and access channels has changed. With respect to the mud balance especially the mud that is permanently removed from the estuary is of interest in this literature review.

Table 3– Quantity of mud [ton/y] dredged, relocated and removed from the Lower sea Scheldt (excluding the dredging in the harbour of Antwerp) reported by Ten Brinke (1992). The mud originates from dredging of sand (5% mud), the main channel (40% mud) and the access channels of the locks (100% mud).

	Dredged mud				Dumping of mud				Removed mud
year	5%	40%	100%	sum	5%	40%	100%	sum	net
1981	178.000	384.000		562.000	98.000	85.000		183.000	379.000
1982	141.000	286.000		427.000	107.000	130.000		237.000	190.000
1983	116.000	143.000	910.000	1.169.000	59.000	98.000	390.000	547.000	622.000
1984	137.000	254.000	1.024.000	1.415.000	26.000	176.000	894.000	1.096.000	319.000
1985	94.000	520.000	991.000	1.605.000	62.000	325.000	991.000	1.378.000	227.000
1986	133.000	299.000	601.000	1.033.000	31.000	299.000	601.000	931.000	102.000
1987	97.000	546.000		643.000	85.000	546.000		631.000	12.000
1988	163.000	429.000		592.000	80.000	429.000		509.000	83.000
1989	107.000	72.000		179.000	86.000	72.000		158.000	21.000
sum				7.625.000				5.670.000	1.955.000
avg				847.222				630.000	217.222

The dredging and relocation quantities used by Ten Brinke (1992) are presented in Table 3. The difference between the dredged and relocated mass of mud, presented in the last column, is the mud that is permanently removed from the system. According to this data about 217.000 ton/y was removed between 1981 and 1989. This is without the mud removed from the harbours which Ten Brinke (1992) took at 230.000 ton/y.

In the WVO (Wet Verontreiniging Oppervlaktewateren) permit of 1991-1995 for maintenance dredging works, the Dutch authorities required for the first time the removal of dredging material from the Lower Sea Scheldt. According the Afdeling Maritieme Schelde (AMS) of the Flemish government 2.000.000 ton DM was permanently removed from the access channel of the Kallolock during the period 1992-1994. Additionally, almost one million ton DM of dredging material from the docks behind the Zandvlietsluis was deposited on land.

In the IMDC (1993) report the dredging volumes between 1980 and 1989, obtained from the Antwerpse Zeehavendienst are used. The calculation of the mass of the dredged volume is done by converting the dreded material rich of mud and rich of sand to an equivalent volume with a density of respectively 2 and 1.8 ton/m³. The sand/mud ratio is related to the density, >1.6 ton/m³: 10% mud; 1.4-1.6 ton/m³: 50% mud; <1.4 ton/m³: 90% mud. From the dredging mass of 1.500.000 ton/y during 1980-1989 in the main channel, the amount of mud that is permanently removed is 280.000 ton/y.

Table 4 – Dredging mass in Lower Sea Scheldt and harbours. Dreding in the harbours of the left bank refers to the dredging of the Access channel of Kallo. Dredging in the right bank harbours, refers to dredging in the actual docks of the harbour, behind the locks.

Source	Year		Dredged mud mass [ton/y]			Dumping [ton/y]	Sediment removal [ton.y]	
		Dredging site	Lower Sea Scheldt, main channel	Harbours (left bank)	Harbours (right bank)	Sea Scheldt	depths	land
IMDC (1993)	1980-1989	Harbours		300.000		70.000	40.000	190.000
	1980-1989	Lower Sea Scheldt	1.500.000			1.220.000		280.000
Spronk (1994)	1981-1986	Lower Sea Scheldt	?				300.000	
	1987-1993	Lower Sea Scheldt	?				242.857	
	1989-1993	Harbours right bank			?		201.316	216.791
	1981	Harbours right bank			?	242.000		
	1982	Harbours right bank			?	60.000		
	1983	Harbours right bank			?	148.000		
	1984	Harbours right bank			?	246.000		
	1985	Harbours right bank			?	56.000		
	1986	Harbours right bank			?	42.000		
	1987	Harbours right bank			?	19.000		
	1988	Harbours right bank			?	14.000		
	1989	Harbours right bank			?	2.000		
	1990	Harbours right bank			?	6.000		
	1987-1990	Liefkenshoektunnel	2.000.000				2.000.000	
Claessens (1993;	1992	Access channel Kallo		?			240.000	
1994) and Taver-	1992	Harbours right bank			?			240.000
niers (1995-2001)	1993	Access channel Kallo		?			550.000	
	1993	Harbours right bank			?			320.000
	1994	Access channel Kallo		560.000			560.000	
	1994	Harbours right bank			1.860.000	1.592.500		267.500
	1995	Access channel Kallo		0			0	
	1995	Harbours right bank			835.000	738.000		97.000
	1996	Access channel Kallo		432.000			432.000	
	1996	Harbours right bank			220.000			220.000
	1997	Access channel Kallo		466.357			466.357	
	1997	Harbours right bank			260.000			260.000
	1998	Access channel Kallo		288.615			288.615	
	1998	Harbours right bank			300.000 - 425.387			300.000 - 425.387
	1999	Access channel Kallo		295.000			295.000	
	1999	Harbours right bank			?			0
	2000	Access channel Kallo		0			0	
	2000	Harbours right bank			540.000			2.600
	1992-1999	Lower Sea Scheldt and Harbours		?			380.000	
Wartel et al. (2000)	1992-1999	Access channel Kallo		?			169.571	
Vlaamse Gem.	1981-1990	Lower Sea Scheldt	?				250.000	
(1991)	1981-1990	Antwerp harbours					230.000	

Spronk (1994) reported an annual removal of 300.000 ton of mud from the Lower Sea Scheldt during 1981-1986 and 242.857 ton/y during 1987-1993. During 1989 and 1993 201.316 ton of mud has been disposed in depths and 216.791 ton has been pumped on land (Spronk, 1994). Also for the construction of the Liefkenshoektunnel (1987-1990) large amounts of mud have been removed from the Scheldt.

From 1992 to 2000 the mud removed from the system is reported in the annual reports of the Flemish government on the mass balance of the Sea Scheldt (Claessens, 1992 en 1993; Taverniers, 1994-2000). These reports are required to fulfil the requirements of the WVO permits. Between 1992 and 2000 Cleassens and Taverniers report a removal of mud from the harbours at the right bank and the access channel of the Kallolock of respectively 203.000 ton/y and 314.000 ton/y. The mud dredged from the access channel of the Kallolock is disposed in underwater cells in the Waaslandhaven, while mud dredged from the harbours of the right bank is either pumped back into the Sea Scheldt (up till 1995) or deposited on land.

Wartel *et al.* (2007) reports a removal of 1.187.000 tons of mud between 1992-1999 or 170.000 ton/y in the access channel for the Kallolock in his mud balance. This is significantly lower than the values reported in the reports of Cleassens and Taverniers in the same period. The reason for this discrepancy is unclear.

Santermans (2013) gives a clear overview of yearly dredging and disposal volumes from 1981 - 2011. For the purpose of this project the volumes presented in the report of Santermans (2013) are converted to mass. The unit used in the report of Santermans (2013) is reduced volume (V'), meaning that the original wet volume of mud is converted to the volume the mud would have if the density was 2 ton/m³. To convert the reduced volume of mud (V') to mass we use the formula:

$$M_d = 1.606 \cdot V'$$

with M_d: the dry matter mass of the dredged volume. The derivation of this formula and the underlying assumptions are given in appendix A.

Table 5 – Total dredging mass of mud from Lower Sea Scheldt since 1981 [ton/y]. Presented values are derived from reduced volumes of mud (m³ V') using a multiplication factor of 1.606 ton/m³V'. The dredging in harbours is not included in this table (Source: Santermans, 2013)

	Dredged **ton/y**	**Deposited back in the estuary** **ton/y**	**Removed** **ton/y**
1981	222.143	206.244	15.899
1982	267.529	265.390	2.139
1983	614.697	608.418	6.278
1984	1.390.089	1.268.917	121.173
1985	1.784.026	1.784.026	0
1986	1.325.483	1.325.483	0
1987	1.326.480	1.326.480	0
1988	1.379.517	1.378.827	691
1989	178.421	178.421	0
1990	127.361	0	127.361
1991	1.043.121	376.032	667.089
1992	1.059.805	892.515	167.291
1993	942.455	398.887	543.568
1994	1.242.097	688.343	553.754
1995	684.823	684.823	0
1996	1.645.018	1.217.557	427.461
1997	1.289.784	824.316	465.467
1998	1.195.108	909.883	285.226
1999	1.615.372	1.317.497	297.876
2000	1.860.768	1.860.768	0
2001	4.248.710	4.248.710	0
2002	4.601.434	4.601.434	0
2003	3.723.807	3.652.553	71.254
2004	2.053.809	2.053.809	0
2005	2.868.215	2.868.215	0
2006	2.242.183	2.242.183	0
2007	2.879.607	2.879.607	0
2008	3.062.342	3.062.342	0
2009	3.587.897	3.587.897	0
2010	4.602.115	4.602.115	0
2011	7.670.509	7.670.509	0

Table 4 shows the mass of mud dredged, deposited back in the estuary and removed from the Lower Sea Scheldt since 1981. The dredging in harbours is not included in this table. Detailed information per dredging location is given in Table 5. The difference between the dredged amount and the amount that is deposited back in the estuary is the mass of mud that is permanently removed from the system. The mass of mud removed from the system given in Table 4 closely correspond the mass of mud removed from the access channel of the Kallolock given by Cleassens and Taverniers (Table 3). However, the quantities for mud dredging, disposal and removal between 1981-1989 are considerably lower than the values reported by Ten Brinke (1992) (Table 3) and Spronk (1994) (Table 4). The reason for this discrepancy is unclear, but because the data in (Santermans, 2013) were derived directly from the reported dredging amounts, they are considered to be more accurate

Table 6 – Dredged mud mass from different zones in the Lower Sea Scheldt since 1981 [ton/y]. Presented values are derived from reduced volumes of mud (m³ V') using a multiplication factor of 1.606 ton/m³V'. (Source: Santermans, 2013)

Year	Container-kaaien	Deurganck-dok	Dr. Van Frederik	Dr. Van Lillo	Dr. Van Zandvliet	Access channel B-VC	Access channel Kallo	Access channel Z-B	Others	Total
1981	0	0	0	2.234	0	0	0	215.165	4.744	222.144
1982	0	0	0	2.139	0	0	0	265.390	0	267.529
1983	0	0	0	16.908	3.708	0	384.125	209.956	0	614.697
1984	0	0	0	337.565	0	0	1.012.238	40.287	0	1.390.089
1985	0	0	34.878	742.830	0	0	987.509	18.809	0	1.784.025
1986	0	0	0	694.568	38.575	0	592.341	0	0	1.325.483
1987	0	0	0	594.605	383.405	0	348.470	0	0	1.326.481
1988	0	0	0	764.803	269.755	0	691	0	344.269	1.379.517
1989	0	0	0	81.036	97.385	0	0	0	0	178.420
1990	0	0	0	127.361	0	0	0	0	0	127.361
1991	29.000	0	0	463.928	0	77.043	309.704	163.446	0	1.043.121
1992	13.657	0	0	742.916	22.046	0	210.070	26.266	44.851	1.059.806
1993	0	0	0	309.638	0	22.359	543.568	66.890	0	942.455
1994	0	0	0	319.594	216.176	11.110	475.806	219.410	0	1.242.096
1995	28.391	0	0	224.707	53.999	0	377.726	0	684.822	0
1996	3.935	0	0	45.864	0	47.138	427.225	1.120.856	0	1.645.018
1997	57.029	0	0	100.168	12.466	149.469	465.467	505.185	0	1.289.783
1998	26.281	0	2.051	190.635	0	30.784	288.256	657.101	0	1.195.108
1999	19.847	0	268.616	214.443	172.136	130.378	297.876	498.387	13.690	1.615.373
2000	12.846	0	267.828	500.552	424.122	83.767	0	571.652	0	1.860.768
2001	0	0	819.150	914.098	2.008.274	0	0	358.784	148.404	4.248.710
2002	29.167	0	1.000.376	987.356	2.343.926	30.964	20.231	111.688	77.727	4.601.434
2003	27.545	0	1.323.778	507.975	1.130.118	72.867	351.154	271.200	39.170	3.723.807
2004	198.309	0	391.899	242.061	782.588	58.945	0	284.407	95.600	2.053.809
2005	84.082	73.955	1.096.697	201.744	520.188	49.985	125.663	405.297	310.604	2.868.215
2006	236.777	944.037	12.993	104.432	70.277	0	218.353	467.807	187.507	2.242.183
2007	37.765	725.859	547.632	0	54.636	129.227	498.430	721.786	164.273	2.879.608
2008	6.744	1.281.379	111.193	72.631	12.755	142.179	665.053	753.853	16.555	3.062.342
2009	0	1.600.472	71.342	138.161	51.747	127.316	505.436	1.071.454	21.970	3.587.897
2010	0	1.538.802	1.328.878	3.941	81.333	102.983	483.608	799.827	262.743	4.602.115
2011	195.376	2.294.140	3.020.672	126.257	108.109	132.387	449.641	802.136	541.787	7.670.508

It is important to mention that dredging through alternative dredging techniques such as the sweapbeam are not included in the statistics mentioned in Table 4 - Table 6. The sweapbeam is a kind of plough that pushes the settled mud towards the main river channel were it is transported further naturally. The quantity of mud transported using the sweapbeam is difficult to assess.

Santermans (2013) and IMDC (2013) show the distribution among disposal zones in the Scheldt (Figure 11). The figure clearly shows that until 1999 most of the mud was deposited on the Plaat van Boomke. From 2000 Punt van Melsele and Oosterweel are the most important deposition sites. The three disposal zones are located in the same vicinity. Oosterweel is located on the right bank and is used for disposal during ebb. Plaat van Boomke is located on the right bank and is used for disposal during flood. Punt van Melsele is located on the left bank and is used for disposal during flood.

From 2000 onwards, the disposed volumes have increased fourfold. From 1981-1999 the disposed volume rarely exceeds 10^6 V' [m³], but from 2000 onwards the amount is never less.

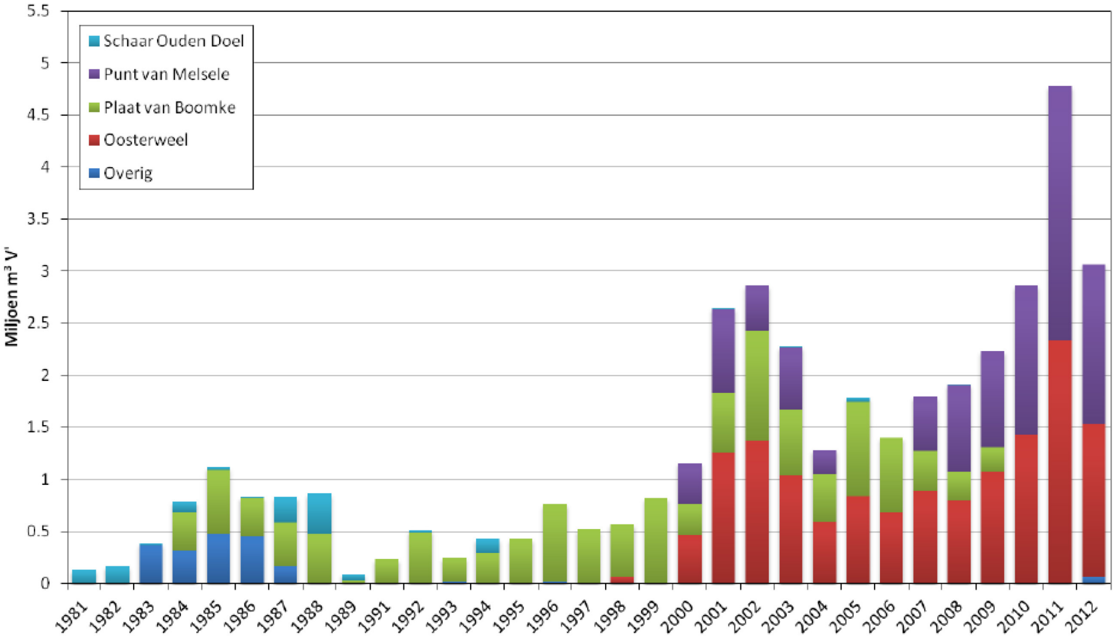


Figure 11 – Disposed volumes of mud in V' [m³] in the Lower Sea Scheldt 1981 - 2012. Data source: maritime access division. Visualisation in IMDC (2013).

Figure 12 shows the most important dredging locations in the lower Sea Scheldt. From 1999 onwards, more mud is dredged in maintaining the sills (Zandvliet, Lillo, Frederik are the main ones). This might be related to the second deepening. Since 2005 Deurganckdok is opened, which also led to an increase in maintenance dredging

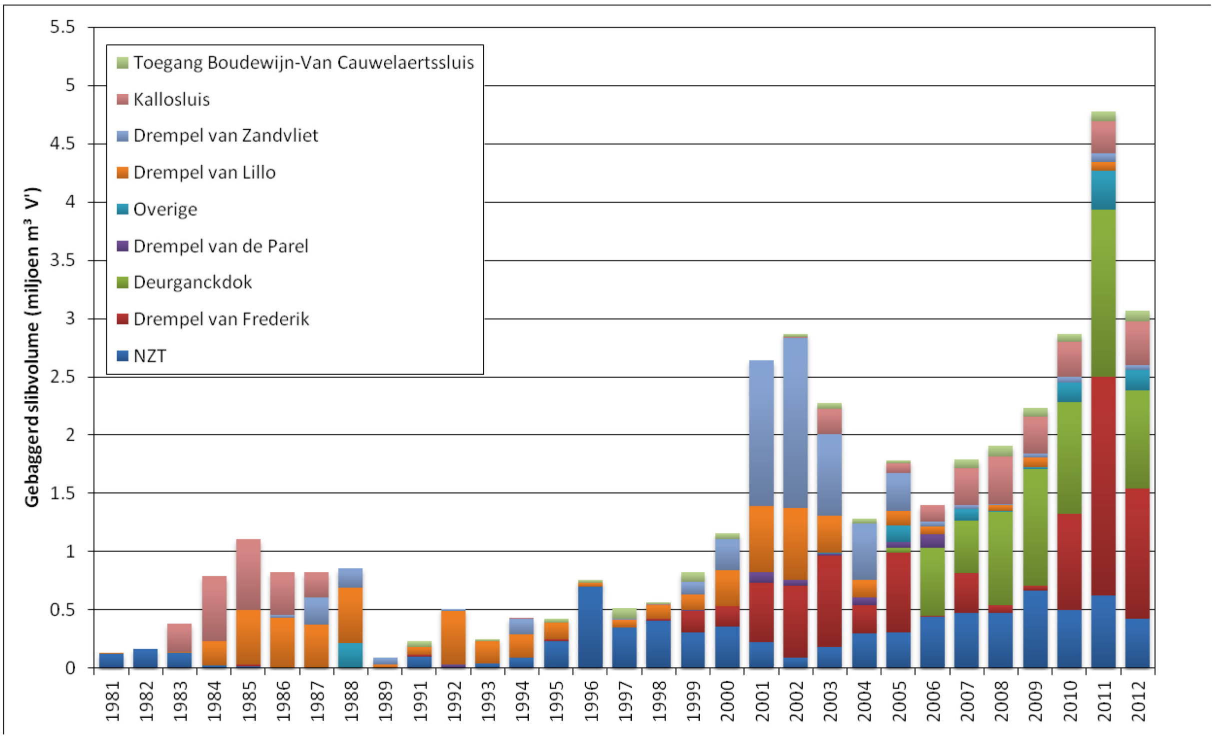


Figure 12 – Dredged volumes of mud in V' [m³] in the Lower Sea Scheldt 1981 - 2012. Data source: maritime access division. Visualisation in IMDC (2013).

4.2.4 Port of Antwerp harbour basins

Due to the low flow velocity and turbulence harbours are preferential sedimentation areas for mud. The mass of mud that is yearly deposited in the harbour basins of the port of Antwerp can be estimated from the dredging volumes or from the flux through the locks combined with suspended sediment concentration data. It should be noted that the mud transported towards the harbours is a mixture of fluvial and marine mud. Based on the information in §7 the marine fraction in the bottom sediments around the Antwerp harbours is around 40-50%.

A certain amount of mud enters the harbour every time a ship passes the locks. The Flemish government is authorized for the dredging in the Sea Scheldt and the maritime access channel in the docks, however dredging at the berthing areas is under the jurisdiction of the Antwerp port authority.

In the IMDC (1993) report a mud percentage of 95% is chosen for the locks and turning basins in the Antwerp harbour and 50% for other locations. Based on their calculations, between 1980 and 1989 about 230.000 ton/y of the total dredged mass of mud (300.000 ton/y) in the harbour of Antwerp is permanently removed from the morphological system.

Over time there have been some changes in the disposal strategy. Before 1986 most of the dredging material in the harbours was pumped back into the river. Verlaan *et al.* (1997) estimates the quantity at 100.000 ton/y. After 1990 no more mud is disposed back from the harbours at the Lower Sea Scheldt to the river. Since the Berendrecht lock (1987-1989) and Kallolock (1983-1986) became operational, the amount of mud transported to the harbours drastically increased (Verlaan *et al.*, 1997).

Spronk (1994) shows that after 1984 the quantity of mud dredged from the Antwerp harbours at the right bank back into the Scheldt gradually decreases until 1990 (Table 4).

The reports of Claessens (1993;1994) and Taverniers (1995-2001) report for the period between 1992 and 2000 a removal of on average 203.610 ton of mud per year. In 1998 the mud removal was maximum (425.387 ton), while in 1999 and 2000 almost no mud was removed because there was no permit to store the dredging material on land. The dredging material of 1999 and 2000 was therefore stored in depths of other docks such as the B1-B2 canal, 5th harbour dock etc.

A report of the Afdeling Waterwegen en Zeekanaal reports an average removal of mud in the Antwerp harbours around 235.000 ton/y (Ministerie van de Vlaamse Gemeenschap, 2000).

Depositing sites for the dredged mud are scarce: between 2003 and 2007 the Delwaide dock has been used to dispose 1.500.000 ton of dredging material of the harbours at the right bank but it is filled up since 2007. Since 2008 the Churchill dock, also situated on the right bank of the Scheldt is used for disposal of dredging material. The Churchill dock has a capacity of about 1.000.000 ton. The port of Antwerp had a permit for disposal on land on the site in Zandvliet until April 2012. In order to create a more sustainable solution of the dredged material the Port of Antwerp decided to construct a recycling installation called AMORAS. The AMORAS installation will turn the dredged mud into filtercakes, which are currently still disposed on a landfill. The AMORAS installation is able to process about 500.000 ton per year. The AMORAS plant is in operation since December 2011.

Table 7 – Amount of mud transported from the Scheldt towards the Antwerp Harbours (mainly through the Zandvliet-Berendrechtlocks). [ton/y]

<table>
<tr><th></th><th>van Maldegem et al. (1993)</th><th>Verliefde et al. (1994)</th><th>Vereeke (1994)</th><th>Spronk (1994)</th><th>Spronk (1994)</th><th>Verlaan et al. (1997)</th><th>Verlaan et al. (1997)</th><th>Winterwerp (1997)</th><th>Cleassens (1993,1994) and Taverniers (1995-1997)</th></tr>
<tr><td>1964</td><td></td><td></td><td></td><td></td><td></td><td rowspan="23">150.000 (from which 100.000 is pumped back)</td><td></td><td></td><td></td></tr>
<tr><td>1965</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>1966</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>1967</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>1968</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>1969</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>1970</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>1971</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>1972</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>1973</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>1974</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>1975</td><td rowspan="11">40.000-230.000 (120.000)</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>1976</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>1977</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>1978</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>1979</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>1980</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>1981</td><td></td><td></td><td rowspan="10">175.000</td><td></td><td></td><td></td><td></td></tr>
<tr><td>1982</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>1983</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>1984</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>1985</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>1986</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>1987</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>1988</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>1989</td><td></td><td rowspan="6">400.000</td><td rowspan="4">150.000-350.000</td><td></td><td></td><td rowspan="9">350.000-400.000</td><td></td><td></td></tr>
<tr><td>1990</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>1991</td><td></td><td></td><td rowspan="4">390.000</td><td></td><td></td><td></td></tr>
<tr><td>1992</td><td></td><td></td><td></td><td></td><td rowspan="5">221.000</td></tr>
<tr><td>1993</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>1994</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>1995</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>1996</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>1997</td><td></td><td></td><td></td><td></td><td></td><td></td><td>300.000-500.000</td><td></td></tr>
</table>

Yearly dredging masses from the Antwerp harbours from 1992-2000 were reported by Claessens (1993 and 1994) and Taverniers (1995-2000) (Table 4). Claessens (1993b) wrote that (at least until 1993) most mud passed through the Berendrecht- and Zandvlietlocks to the harbours at the right bank. Since the Kallolock is used much less, less mud is transported to the Waasland harbour at the left bank.

Verliefde *et al.* (1994) studied the difference in mud content in the harbour at the right bank between 1989 and 1994. Accounting for the dredging he concluded a yearly accumulation of 400.000 ton of mud in the harbour at the right bank.

Based on the dredging mass and the report of Verliefde *et al.* (1994), van Maldegem et al. (1993); Vereeke (1994); Spronk (1994) Verlaan *et al.* (1997) and Claessens (1993 and 1994) and Taverniers (1995-2000) estimated the transport of mud towards the Antwerp harbour as presented in Table 7.

Winterwerp (1997) did a calculation based on the water flux transported through the locks each time a ship passes and the corresponding suspended sediment concentration in the water column. He found the yearly mud flux towards the harbour between 300.000-500.000 ton. Winterwerp (1997) verified this range using a mass balance for the harbours. Francken *et al.* (2000) argued that the mud concentration applied by Winterwerp is too high (200 mg/l on average for the Berendrechtlock and 350 mg/l for the Zandvlietlock) and most likely less than 100% of river and dock water is exchanged (as assumed by Winterwerp) when the lock is used.

In a recent presentation (Heylen, 2013) the environmental manager of the Port of Antwerp mentions an annual dredging of about 500.000 ton of dry matter per year in the docks on the right bank of the Antwerp harbour. Most of this deposition is mud. This mud is taken out of the system: it is dewatered in the AMORAS (Antwerpse Mechanische Ontwatering, Recyclage en Applicatie van Slib) plant and stored on land. The AMORAS plant became operational in 2011. Before, dredged material was either stored on land or in underwater cells in docks. In the docks on the left bank only limited maintenance dredging was required in 2000-2010.

A recent calculation by GHA for total dredging activity in the docks on the right bank confirms the estimate of 500.000 TDM/yr for siltation in the docks on the right bank in the port of Antwerp (Teuchies, pers. comm.).

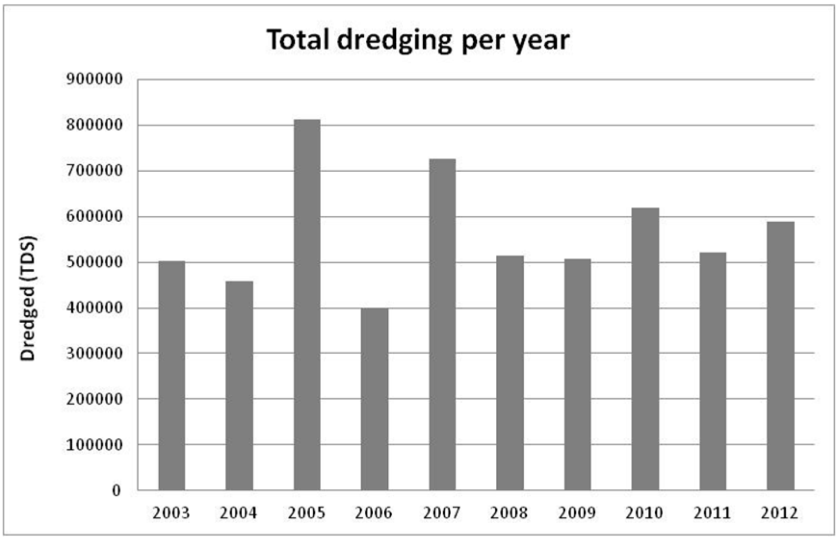


Figure 13 – Total dredging [TDM/yr] for docks on right bank in the port of Antwerp (Teuchies, pers. comm.).

4.2.5 Upstream Schelle

The Upper Sea Scheldt, the Rupel and the Leie are also dredged in order to ensure drainage and in some cases allow navigation. Only limited data is available on dredging activities upstream Schelle. In (IMDC, 1993) an estimation is made for the total quantity of mud dredged upstream Schelle. From a limited number of samples of dredging material the mud content was assumed 70% of the dredging volume. To account for the uncertainty of the density, calculations are made assuming a density of 1.2, 1.4 and 1.6 ton/m³. Results are shown in Table 8. Note that a large part of the water (and mud) from the Leie is drained through the canal Gent-Terneuzen.

Table 8 – Estimated dredged mud mass during 1 year (1989) upstream Schelle [ton/y] (IMDC, 1993)

Assumed density [ton/m³]	Leie	Upper Sea Scheldt	Rupel	Total upstream Schelle
1.2	79.000	169.000	104.000	274.000
1.4	158.000	339.000	208.000	548.000
1.6	237.000	508.000	312.000	823.000

Ten Brinke (1992) calculates with the same dredging volumes and mud percentage, but assumes the density between 1.2 and 1.3 ton/m³. This results in a dredging mass upstream Schelle between 280.000 and 410.000 ton/y.

IMDC (2015) tries to estimate the historical dredging figures (both maintenance and capital) in the Upper Sea Scheldt using the scattered (but limited) different daatsources. The *documented* dredging works in the Upper Sea Scheldt amount up to 10 Mm³ over 1932-2013, or 0.12 Mm³/yr. Figure 14 shows the cumulative dredging volumes over time in the Upper Sea Scheldt. Large gaps in the dataset are apparent. It is not always clear what was done with the dredged material, but one can assume that most of it was removed from the system for infrastructural works or brought on land on disposal sites.

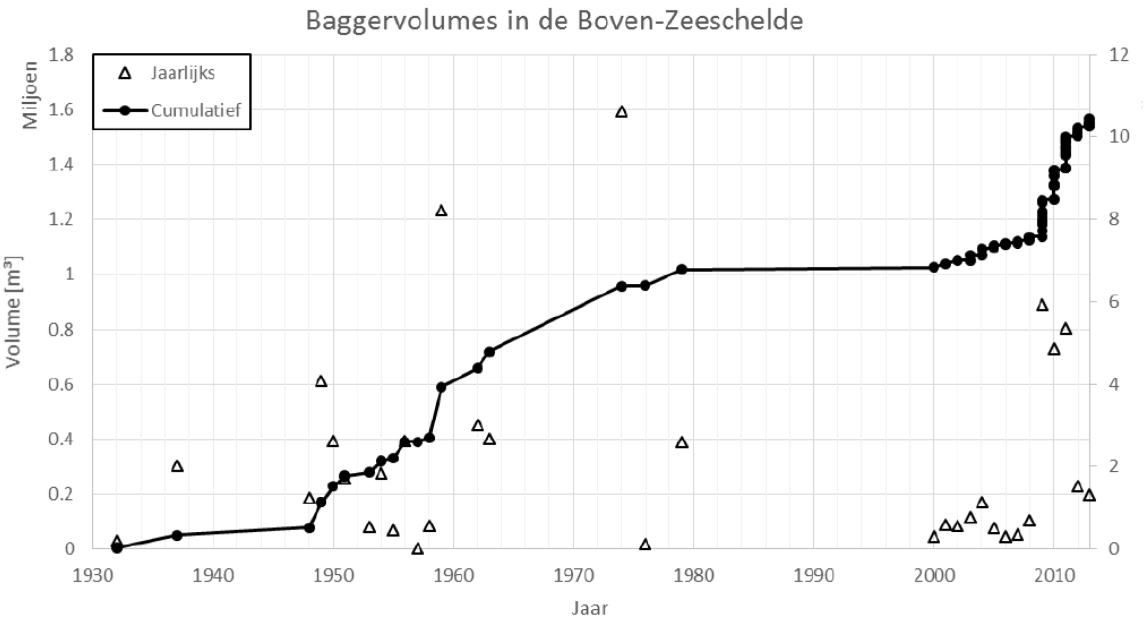


Figure 14 – Cumulative dredging volumes in the Upper Sea Scheldt. IMDC (2015)

IMDC (2015b) further specify that current maintenance is primarily done by relocation of mud (“slibslepen”), where sediment can be relocated to natural overdepths. On some locations, sediment is removed from the system to be used as building material (sand mining or building material for construction works of W&Z). Typical locations for these activities are Uitbergen and Sint-Amands. The amount of sediment extracted varies greatly in between the years, and is about 150.000m³/yr over the period 2000-2013.

4.3 Land reclamation

Both in the Western and Sea Scheldt large parts of the natural floodplain have been converted to agricultural land or urban area. Land reclamation has a very important impact on mud transport and sedimentation in the Scheldt estuary, because reclaimed land is no longer available for sediments to settle on.

After the flooding event in 1976 the Flemish government took action by developing a large-scale plan to decrease the flood risk, called Sigmaplan. In the initial version of the Sigmaplan the focus was on strengthening the embankments and establishing 13 flooding areas with a total area of 1133 ha in the Flemish part of the Scheldt. In 2005-2010 the Sigmaplan was updated. The updated plan includes the construction of an additional 4000 ha of flooding area in the future. Controlled flooding areas (FCA in English, in Dutch “gecontroleerd overstromingsgebied” or GOG) sometimes also act as controlled reduced tidal areas (CRT in English, in Dutch “gecontroleerd gereduceerd getijdengebied or GGG). Especially in the GGG’s, which will flood more often than the GOG, a strong accumulation of mud is expected. For pilot area Lippenbroek (an FCA with CRTof 8,2 ha), Peeters et al (2009) estimate the area to have a trapping efficiency of 70%. Yearly sedimentation rates between 2 and 3 cm/year are found. Averaged over the period 2006-2008, 1380 TDM/year is entrapped in Lippenbroek.

4.3.1 Western Scheldt

The current surface of the Western Scheldt is 310 km², in 1800 this was about 1.5 times larger and in 1600 even twice the current size. Figure 15 illustrates the land reclamation in the Western Scheldt between 1650-1800 and 1800-1968. Since 1930, 40 km² has been reclaimed, of which 14.5 km² after 1960. At the locations were land was reclaimed, tidal flats and marshes have disappeared (Vroon *et al.*, 1997).

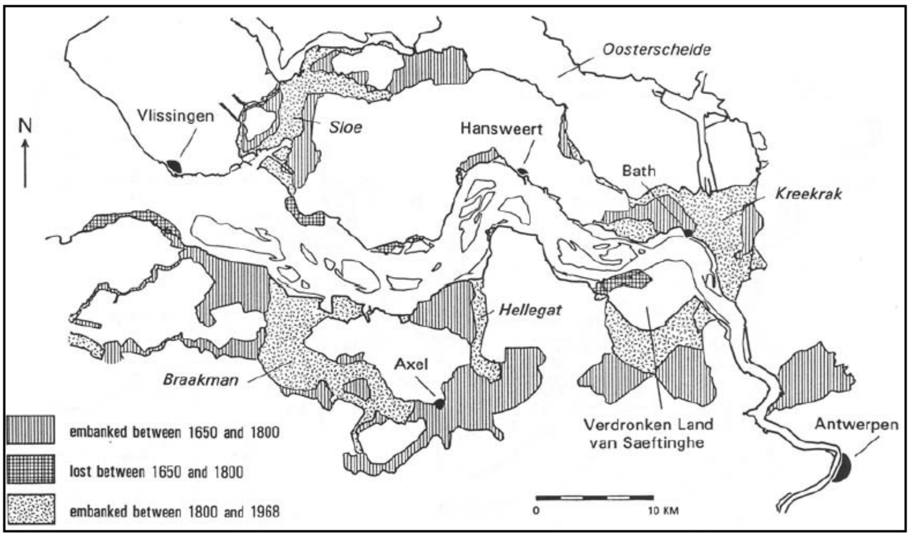


Figure 15 – Land reclamation in the Western Scheldt since 1650 (Source: Van der Spek, 1994).

Santermand (2013) also gives a detailed overview of depoldering in the Western Scheldt in the period 1851 - 1990 in his appendix F.

4.3.2 Sea Scheldt

In 2006 a detailed analysis of historical changes of the Sea Scheldt was done by Van Braeckel *et al.* (2006). Since the 19th century the river length in the fresh water zone with short retention time deceased with 10.5 km (-22%). Dike normalization induced a loss of 95% or 826 ha of the flooding area of the Upper Sea Scheldt. For a limited series of areas along the Scheldt Van Braeckel *et al.* (2006) observed a reduction in tidal flats from 309 to 296 ha and in marshes from 330 to 266 ha between 1992 and 2003.

Santermand (2013) also gives a detailed overview of depoldering in the Sea Scheldt and the tributaries in the period 1750 - 2003 in his appendix F.

4.4 Area of intertidal zones and salt marshes

4.4.1 Western Scheldt

Morphological changes of shoals ("platen" in Dutch) and subtidal areas in the Western Scheldt between 1955 and 2002 have been studied by Peters *et al.* (2003) (Figure 16). During 1955-1980 the total area of shoals in the Western Scheldt increased by 800 ha (about 20%). The increasing area of shoals is caused by an increase in both the western, central and eastern parts of the Western Scheldt. Afterwards (1980-2002) the area of shoals decreases by around 250 ha, caused by a strong decrease in shoals in the western part of the Western Scheldt. Jeuken *et al.* (2004) attributes both the increase and decrease to the origination, migration and degeneration of the connecting channels (Kuijper *et al.*, 2004).

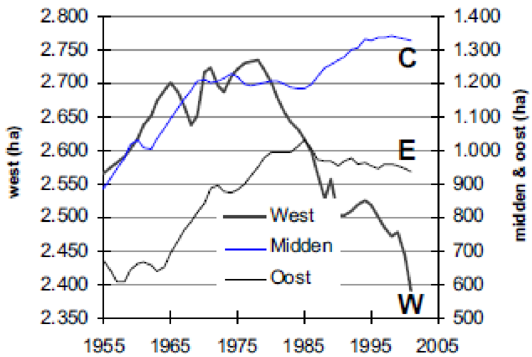


Figure 16 – Area of shoals in the Western Scheldt in the western (W), central (C) and eastern (E) part. (Source: Peters et al., 2003)

The surface area of the shallow zones (between in NAP-5m and NAP -2m in Jeuken *et al.*, 2004) has decreased from 4500 ha in 1955 to 3000 ha in 2002 (Figure 17), indicating a steepening of the channel-shoal interface (Kuijper *et al.*, 2004).There is resemblance between the sand volume extracted from the Western Scheldt due to sand mining since 1955 and the decrease of surface area of the shallow zones, however the causal relation is not proven (Kuijper *et al.*, 2004).

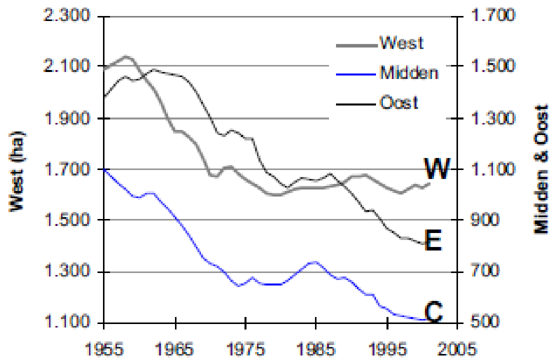


Figure 17 – Change of surface area of shallow zones in the Western Scheldt in the western (W), central (C) and eastern (E) part. (Source: Peters et al., 2003; Jeuken et al., 2004)

Between 1959 and 2001 the area of salt marshes ("schor") in the Western Scheldt decreased from 3500 ha to 2350 ha, or about 33% (Kuijper *et al.*, 2004) (Figure 18, left). This decrease occurred mainly between 1959 and 1988. The area of tidal flats ("slik") stayed relatively constant since 1988 (Figure 18, right).

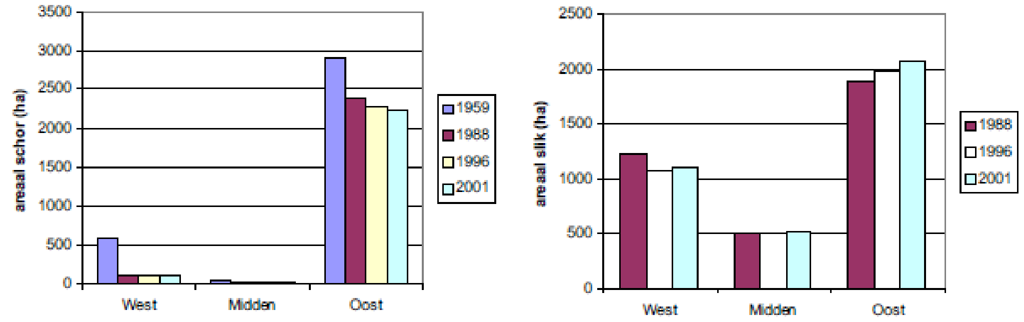


Figure 18 – Area of salt marshes (left) and tidal flats (right) in the western, middle and eastern part of the Western Scheldt (Jeuken *et al.*, 2004)

4.4.2 Sea-Scheldt

The area of both tidal flats and salt marshes in the Sea Scheldt has decreased significantly from 1850 to 2003 (Figure 19). Biologists (Van Daele *et al.*, 2007) have calculated that a minimum of 2110 ha of salt marshes is required to provide enough silica to prevent algae blooms and a minimum of 1140 ha of tidal flats is needed to nourish birds and fishes in the Sea Scheldt. The sum of those biologically minimum area of tidal flats and marshes is shown in Figure 19 by a black line. The brown bars for 2010 and 2030 show the in 2007 planned tidal flats and marshes in the framework of the new Sigmaplan.

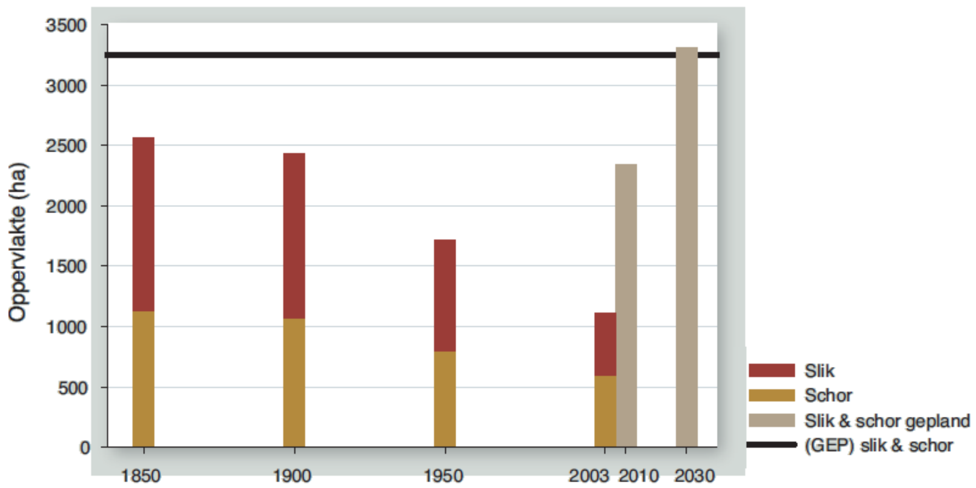


Figure 19 – Long term evolution of the area tidal flats and salt marshes in the Lower Sea Scheldt. Orange, red and brown bars represent respectively tidal flats, salt marshes and planned tidal flats and marshes. (Source: Van Daele *et al.*, 2007)

4.5 Tide

Historical documents reported no significant tidal influence near the city of Antwerp around the year 1300 (Chen *et al.*, 2007). The change in tide between 1550 and 1970 is shown inFigure 20.

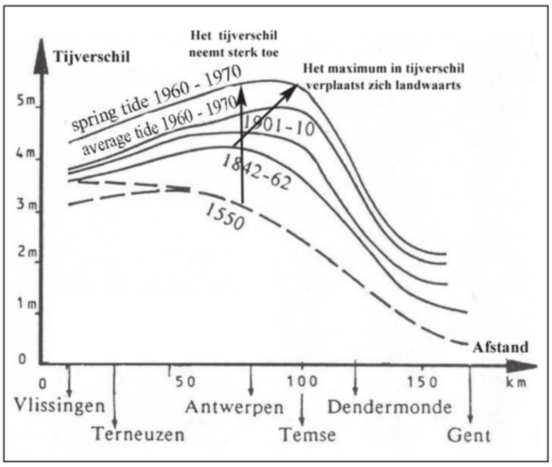


Figure 20 – Evolution of the tidal difference between 1550 to 1970 (Source: Coen, 1988)

Pieters *et al.* (2005) investigated in detail the changes of the tides in the estuary. He concluded that during the period 1890-1940 both the high and low water levels increased more or less uniform with the rise in seawater level and decreasing friction due to the increasing water depth. During the first decennia of the period 1940-1970 the tidal amplification around the border decreases, possibly due to a temporary suspension of the dredging activities during the war. After the war, the dredging activities are intensified causing an increase of the tidal change on the entire Lower Sea Scheldt. Between 1961 and 1980 a strong change of tidal amplitude occurs.

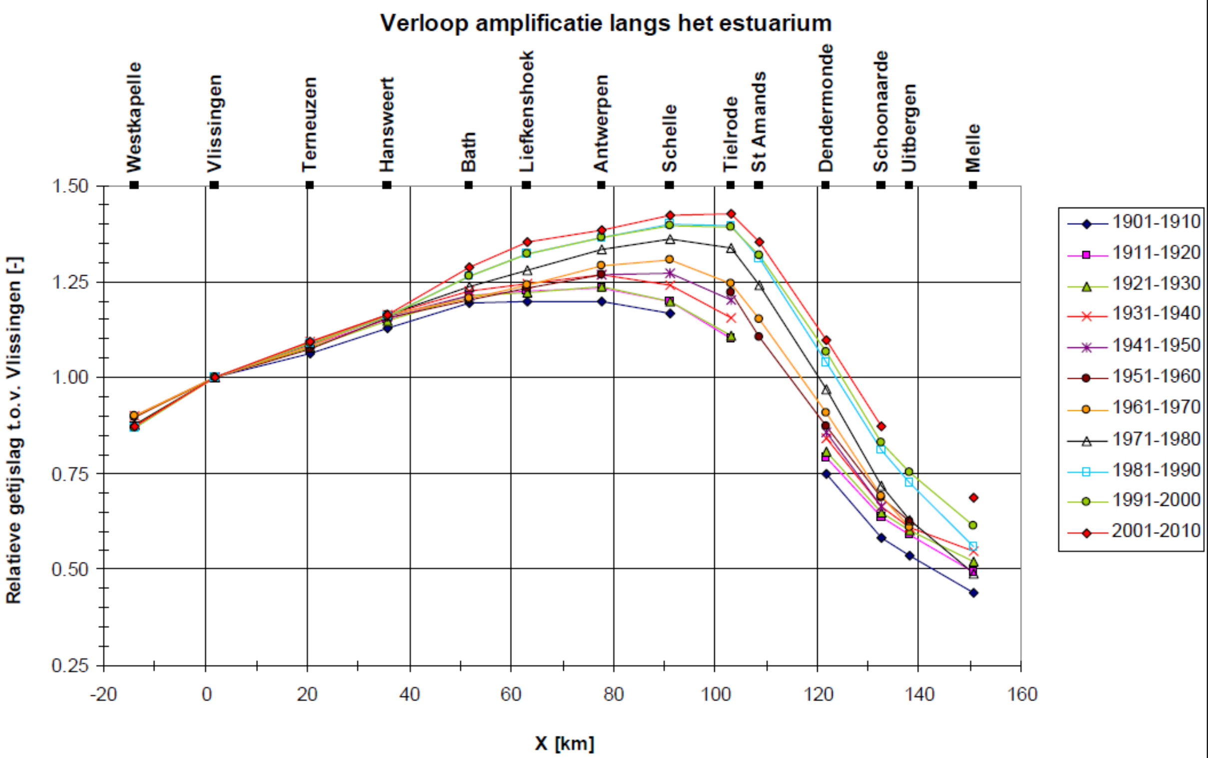


Figure 21 – Amplification of the tidal difference at average tidal over the longitudinal profile of the estuary compared to the tidal difference at Vlissingen (mouth) for different periods (Source: Kuijper, C., 2013)

Figure 22 and Figure 23 show the historical evolution in high and low water, respectively.

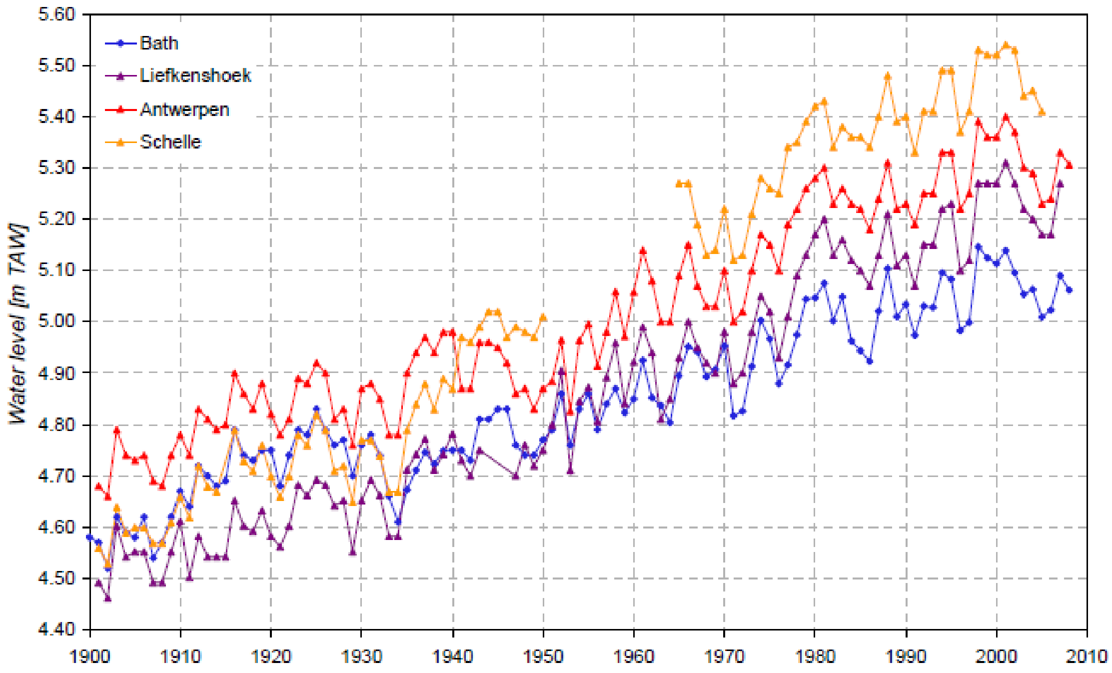


Figure 22 – Yearly-averaged high water in Bath, Liefkenshoek, Antwerpen and Schelle (Plancke et al, 2012)

In the 1970’s a strong (20 cm) decrease of low water levels can been found for all stations. This decrease can be related to a combination of several infrastructure works: e.g. sand extraction for infrastructural works, construction of guiding walls near Ouden Doel and the Ballastplaat, first deepening campaign of the navigation channel.

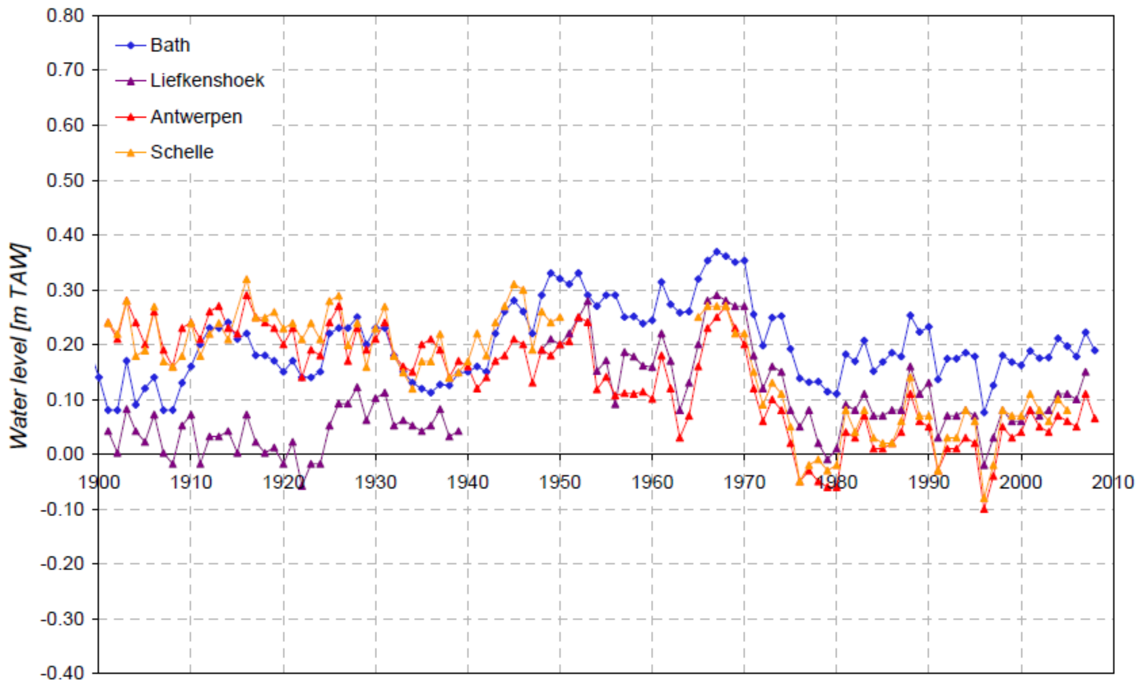


Figure 23 – Yearly-averaged low water in Bath, Liefkenshoek, Antwerpen and Schelle (Plancke et al, 2012)

Because the tidal dynamics is an important driver of mud transport in the Scheldt above discussed changes in tides potentially have an important impact on the mud transport. However, very little is known on the direct influence of changes in the vertical tide to net mud transport. It should also be noted that changes in vertical tide have been studied more in detail than changes in horizontal tide. The latter is however more important with respect to mud transport processes.

4.6 Harbours

The construction of the new docks, access channels and locks on the left and right banks of the Scheldt during the early sixties had an important impact on the mud balance of the Lower Sea Scheldt (Salden, 1998). The most important changes in the geometry of the Lower Sea Scheldt were the construction of the Zandvliet- en Berendrechtlocks on the right bank, respectively constructed in 1967 and 1988 and the Waasland-harbour with the Kallolock, constructed during the seventies and intensively used since mid-eighties. The location of the locks are shown in Figure 24, an overview of the construction of the most recent locks are given in Table 9. The locks are connected to the main Scheldt channel through the access channels of Zandvliet, Berendrecht and Kallo.

These access channels are preferred sedimentation locations for the mud. A large fraction of the mud that previously reached the Western Scheldt is now deposited into the access channels (Salden, 1998). During operating the locks, mud is transported into the docks. In order to maintain a minimum depth in the docks for the navigation of ships, dredging is required. Mud dredging activities in the harbours and access channels is discussed in paragraph 4.2.

Table 9 – Construction of locks and docks

Lock / Dock	**Year of commissioning**
Royer lock	1907
Van Cauwelaertlock	1923
Boudewijnlock	1955
Zandvlietlock	1967
Kallolock	1979 (used intensively since 1986)
Berendrechtlock	1989
Deurganckdok	2005 (CDW: 2010-2011)
Waaslandhaven - Deurganckdok	Currently under construction (since 2012)

Figure 24 – Locks in the Antwerp harbour with an important impact on the mud balance

The newest dock, Deurganckdok is in direct connection with the Scheldt, without a lock. Moreover, the depth of Deurganckdok is deeper than the river bottom of the Scheldt which prevents mud that has entered the dock to flow out again. To reduce the sedimentation of mud in Deurganckdok a current deflecting wall (CDW) was built in 2010-2011. Figure 25 shows how this wall works. The wall deflects the water in the lower part of the water column (below -7.6 m TAW) which has a high concentration of mud back to the main channel while the water layer in the upper part of the water column (above -7.6 m TAW) with a low mud concentration is conducted towards the entrance of Deurganckdok.

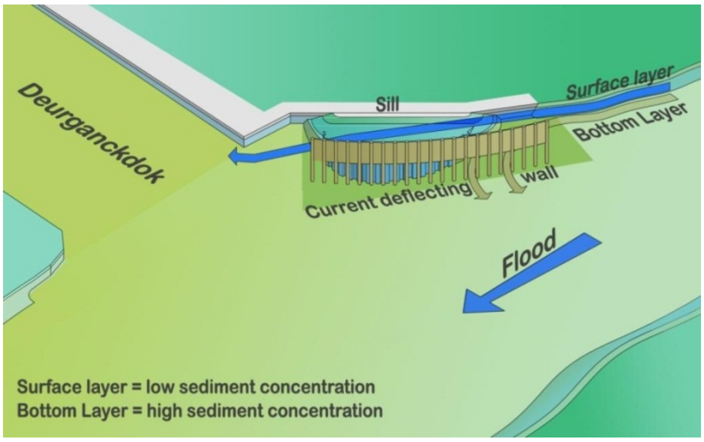


Figure 25 – Current deflecting wall at Deurganckdok (Source:IMDC)

4.7 Wastewater treatment and erosion prevention

Fluvial mud originates from both natural and anthropogenic sources. On the relative contribution of both mud sources in the Scheldt basin there has been some discussion, more details on this discussion will be given in §8.1. Furthermore, mud originating from industrial or domestic waste water is often organic and deteriorates partly during transport.

Over the last 20 years the Flemish government did a large effort to improve the water quality in the rivers by increasing the water treatment capacity and the connectivity of households to the sewer system (Peeters, 2010). The connectivity to the sewer system increased from about 80% in 1990 to around 90% in 2010, while the fraction of the water that is treated increased from 30 to 80% in the same period (Peeters, 2010). The load of domestic and industrial waste water to the rivers decreased by about 50% in the period 1990-2010. Because water treatment plants decrease the mud concentration up to 90% it is likely that the anthropogenic mud transport towards the estuary has decreased over the last 20 years.

Also the agricultural sector has taken actions to decrease erosion. These actions included adaption of management practices such as plough direction, increasing the organic matter content in the soil, planting of cover crops, etc. and the construction of buffer strips and micro topographical elements.

5 MUD STOCK IN THE BOTTOM OF THE SCHELDT ESTUARY

Large amounts of mud are stored at the bottom of the river bed, in the tidal flats and on the marshes. Mud deposited on the salt marshes is generally considered as removed from system (van Maldegem, 1993). Mud on the bottom of the river and on the tidal flats however plays an important role in the transportation of mud.

5.1 Lower Sea Scheldt

5.1.1 Mud stock

Four lithological measuring campaigns have been carried out in the Lower Sea Scheldt. The first campaign was done during 1964-1965 by Bastin. The second campaign, also executed by Bastin, was held during 1986-1987 (Bastin, 1988). The third lithological measuring campaign by Wartel (Wartel *et al.*, 2000) was done in 1999. The last lithological map was developed by a cooperation between IMDC and VUB (Wartel, Chen and De Smedt) in 2010 (IMDC & VUB, 2010).

The lithological maps of Bastin (1964 and 1986) are based on detection of natural signals emitted by bottom sediments, using an underwater probe equipped with a gamma ray detector. The data obtained from the gamma ray detector can be used to classify the river bottom into sand, sandy mud, loss mud and more compacted clay. Wartel *et al.* (2000) used the reflected signal emitted by an echosounder instead of the natural signals. The echosounder method allows the classification of the river bottom into mud, sandy mud, muddy sand, sand and hard bottom.

Based on the results of these measuring campaigns the evolution of mud stored in the Lower Sea Scheldt has been discussed by Claessens (1993), Bastin (1993), Francken *et al.* (2000) and Wartel *et al.* (2007). An overview of the calculated mud stock is shown in Table 10. From the last lithological map (2010) no analysis have been made for the mud mass within the entire Lower Sea Scheldt. Therefore, no values of mud stock are given for 2010 in Table 10.

Table 10 – Active mud stock Lower Sea Scheldt

Auteur	Bastin (1993)	Wartel et al. (2007)	Claessens (1993)	Bastin (1993)	Wartel et al. (2007)	Claessens (1993)	IMDC (1993)	IMDC (1993)	IMDC (1993)	Francken et al. (2000)	Francken et al. (2000)	Wartel et al. (2007)
Jaar	1964	1964	1964	1986	1986	1986	1989	1989	1989	1999 (meth. 1)	1999 (meth. 2)	1999
							d= 0,5 m	d = 1 m	(in Spronk, 1994)			
Kallosluis				819.000		930.000				919.000		
Zandvlietsluis				104.000						179.000		
Berendrechtsluis										90.000		
Beneden Zeeschelde (incl. tidal flats, excl, Kallo-, Zandvliet- and Berendrechtsluice)	4.757.000	3.282.000	6.100.000	6.197.241	4.259.000	7.310.000				6.385.000	4.060.000	4.406.000
Total	4.757.000	3.282.000	6.100.000	7.120.241	5.182.000	8.240.000	3.933.000 ± 2.448.000	7.867.000 ± 4.894.000	6.800.000	7.573.000	5.248.000	5.594.000
marien							104.000 ± 92.000	208.000 ± 182.000				
fluviatiel							3.829.000 ± 2.356.000	7.659.000 ± 4.712.000				

The measurements of Bastin (1964 and 1986) give information on the composition and structure of the interface water-bottom over a depth of about 25 cm. However, because it is assumed that mud stored in the first meter of the river bottom can contribute on a middle-long-term to the mud transport, Bastin extrapolates the river bottom information to a depth of 1 m. For solid clay layers an erosion of 5% to the mud content is assumed. For the access channels of the locks, mud stored below the first meter of the river bottom is also accounted for. Bastin used a mud density of 1.45 ton/m³ in the bottom and 1.3 ton/m³ in the access channels of the locks.

Claessens (1993) proposed an alternative for the fixed mud densities used by Bastin. Claessens (1993) varies the density based on the sand-mud ratio (C) which is 0 for pure sand and 1 for pure mud. The mud density (d) is defined as: d = (1.9 – 0.6 C). Significant higher masses of mud are calculated using the density based on the sand-mud ratio. The accumulation between 1964 and 1986, however is very similar using the fixed or variable mud density.

van Maldegem (1993) calculates the mass of mud in the first meter of the subsoil assuming a homogeneous vertical distribution of the mud. The mud percentage in the subsoil of the Western Scheldt were measured at the 10 cm thick top layer of the bed. These measurements had a spatial interval of approximately 1 km. The area of different morphological units (marshes, mudflats and shoals) in the estuary was taken into account. Results of calculations of van Maldegem (1993) are shown in Figure 26 and Table 11. The sections are shown in Figure 27. Note the high mud stock reported in section 8, which includes Land van Saeftinge.

van Maldegem (1993) reports the total mud stock in the total Scheldt estuary to be around 50 million ton. 40 million is stored in the upper meter of the river bottom while over 10 million is stored in the passive marshes. The estimation of the mud stock in the Lower Sea Scheldt in van Maldegem (1993) (Table 11) of 3 million ton of mud is low compared to the other values given in Table 10.

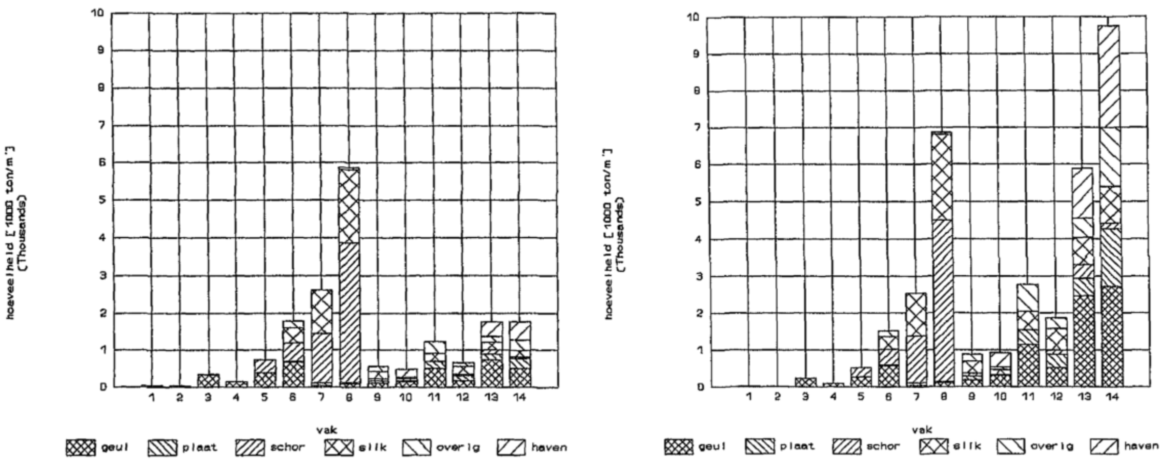


Figure 26 – Fluvial (figure on the left) and marine (figure on the right) mud storage in the upper meter along the Scheldt estuary. The number on the x-axis represent a section on the Scheldt estuary. Section 1-5 compile the Lower Sea Scheldt, section 6-10 the eastern part of the Western Scheldt and 11-14 the western part of the Western Scheldt. (source: van Maldegem, 1993)

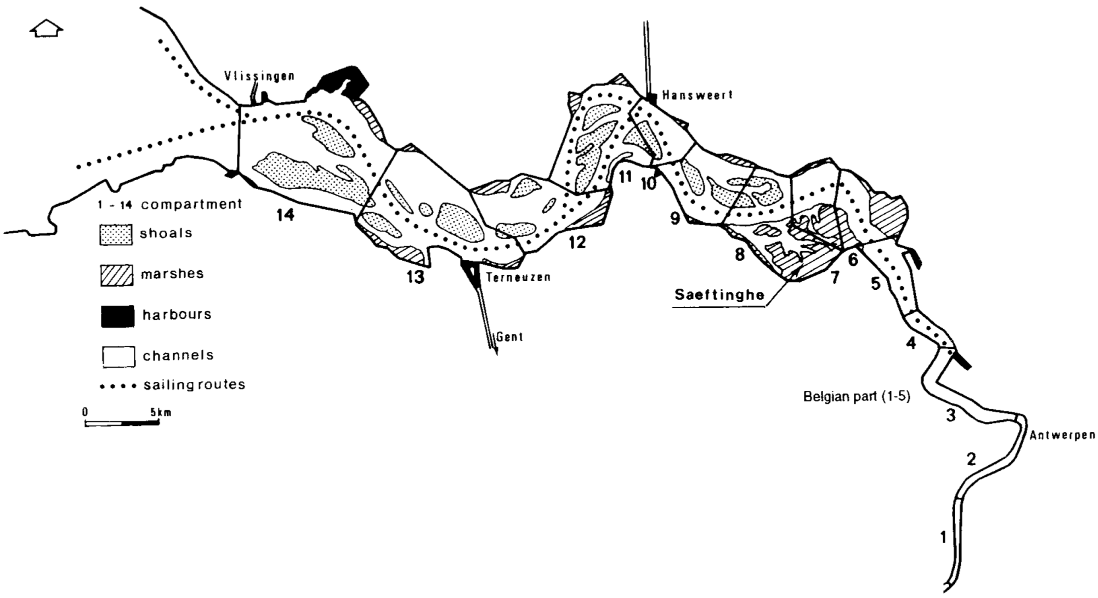


Figure 27 – 14 sections and morphological units used in van Maldegem (1993)

Table 11 – Distribution of fluvial and marine mud for a 1 m thick bed layer (Source: van Maldegem et al., 1993)

	Western Scheldt western part		Western Scheldt eastern part		Scheldt estuary Belgian part	
area [m²]	$213 \cdot 10^6$ (62%)		$103 \cdot 10^6$ (30%)		$27 \cdot 10^6$ (8%)	
mud [kg]	$26 \cdot 10^9$ (49%)		$24 \cdot 10^9$ (45%)		$3 \cdot 10^9$ (6%)	
	fluvial	marine	fluvial	marine	fluvial	marine
mud [kg]	$7 \cdot 10^9$	$19 \cdot 10^9$	$12 \cdot 10^9$	$12 \cdot 10^9$	$2 \cdot 10^9$	$1 \cdot 10^9$
subdivision [%]	25	75	50	50	65	35
channels [%]	92	5	5	5	34	18
marshes [%]	1	2	24	24	13	7
mudflats [%]	4	11	17	17		
shoals [%]	4	10	1	1		
harbours [%]	5	15	1	1		
remaining inter- tidal area [%]	4	10	2	2	18	10

IMDC (1993) also make an estimation of the available mud stock along the entire Scheldt estuary and the Durme and Rupelbasin tributaries. Based on literature an approximation is made of the mud percentage in different sections of the estuary. The mud percentage in the Lower Sea Scheldt is about 20-28±20%. To take into account the uncertainty with respect to the depth of the active river bottom calculation are done assuming both a depth of 0.5 and 1 m. A mud stock between 3.9±2.4 million and 7.9±4.9 million ton is estimated for the Lower Sea Scheldt. Only 3% of this mud is assumed from marine origin.

Bouve *et al.* (1995) mention a mud stock in the Lower Sea Scheldt of 6.4-7.7 million ton (1994). This range is in the same order of magnitude as most previously discussed estimations (Table 11). However, the exact origin of this quantity is unclear.

Francken *et al.* (2000) calculate the mud content using two different approaches. A method identical to the method used by Bastin (method 1), allowing a comparison with the results of 1964 and 1986, and a second method which they assume optimal given the available data (method 2). The lithoprobe measurements of Wartel *et al.* (2000) showed the bottom layer sensitive for erosion is smaller than the one meter assumed by Bastin. Francken *et al.* (2000) therefore use the data from the lithoprobe measurements for method 2. Based on the measurements an average penetration depth of the mud of 0.6, 0.23, 0.3 and 0.25 m is obtained for respectively mud, sandy mud, muddy sand and sand. Also the mud content in the different soil textures were redefined and the density is determined per soil texture instead of for the entire Lower Sea Scheldt.

The mean bulk-density for mud in access channels, mud in the main channel of the Scheldt, sandy mud, muddy sand and sand as measured by gamma-densitometry are respectively 1.3, 1.4, 1.45, 1.5 and 1.65 ton/m³. The significant decrease in penetration depth, although partly compensated by the higher density used in most places, causes the mud stock estimation using method 2 to be only 69% of the mud stock obtained using method 1.

The conversion factor of 69% obtained by Francken *et al.* (2000) due to the difference between method one and two for the mud stock of 1999 was applied by Wartel *et al.* (2007) to update also the mud stock calculated by Bastin for 1964 and 1986.

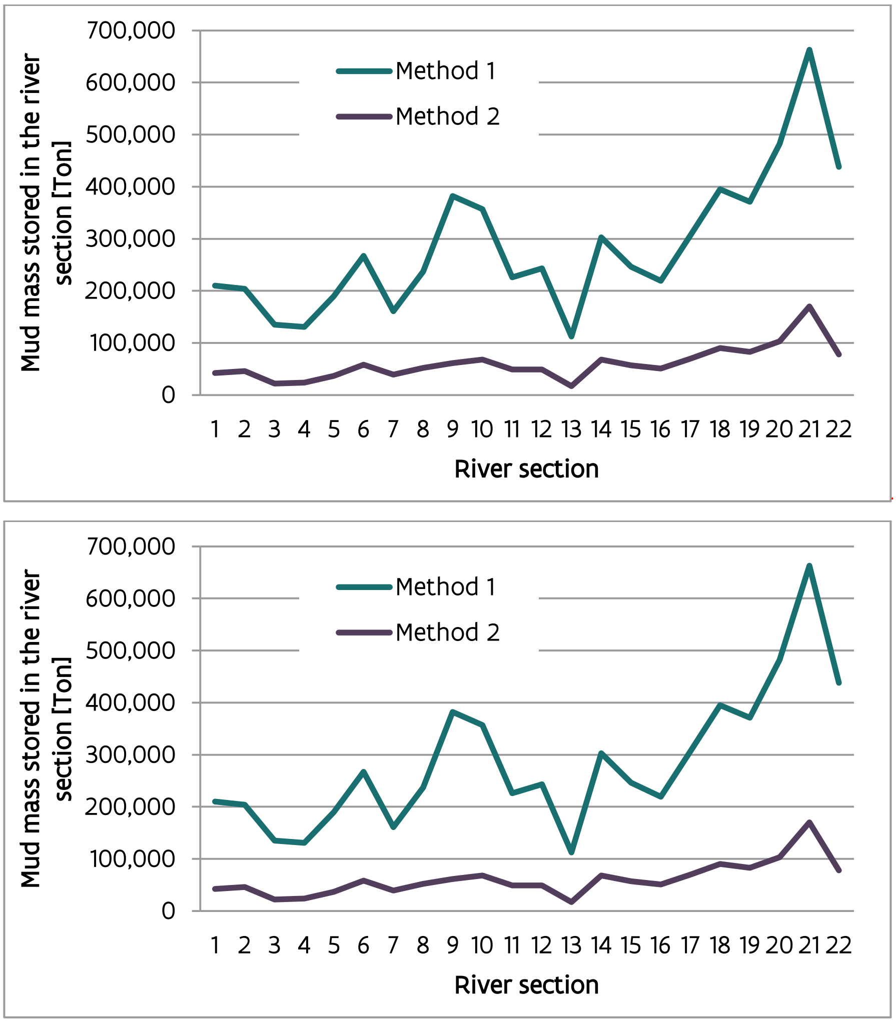


Figure 28 – Mud stock for the year 1999 along a longitudinal profile of the Lower Sea Scheldt from Galgenweel, just downstream of Antwerp (1) and the Dutch-Belgian border (22) based on data of Francken et al. (2000).

Figure 28 shows the mud stock in along a longitudinal profile of the Lower Sea Scheldt. The mud stock represents the year 1999 and is calculated using both method 1 and 2 of Francken *et al.* (2000).

A mud stock of 2.620.000 ton on the tidal flats was calculated by Francken *et al.* (2000), the access channels of the Royerslock and Van Cauwelaert- and Boudewijnlocks contain respectively 12.000 and 94.000 tons of mud.

5.1.2 Changes in mud stock

Comparing the mud stock calculated for 1964 and 1986 shows an important accumulation of mud in the Lower Sea Scheldt. The largest increase in mud stock is found in the access channels for the locks constructed during the considered time interval. The access channels of the Kallo- and Zandvietlocks store respectively about

819.000 and 104.000 ton of mud. Even without the mud stored in the access channels there is an increasing mud stock in the Lower Sea Scheldt. Francken *et al.* (2000) found that especially downstream the Kallolock more mud is stored in 1986 compared to 1964.

Also between 1986 and 1999 there was an increase in mud stored in the Lower Sea Scheldt. Comparing the mud stock calculated by Bastin (1993) for 1986 and Francken et al. (2000) using method 1 in 1999 results in an estimated increase of about 600.000 ton of mud. The Kallo- and Zandvlietlock store respectively 100.000 and 75.000 ton of mud more in 1999 compared to 1986. The newly constructed Berendrechtlock stores about 90.000 ton of mud. Smaller increases of the mud stock occur upstream the Kallolock, while minor decreases occur downstream Kallo, with the exception of the region of the Berendrechtlock.

Francken *et al.* (2000) calculated that, if the mud deposits on the access channels are excluded, the mud stock along the longitudinal profile of the Lower Sea Scheldt (averaged over a sufficiently large river section) is relatively constant. Values range between 0.4 and 0.7 m³ of mud per m².

The differences in mud stock between 1964, 1986 and 1999 provide important information on the accumulation of mud in the Lower Sea Scheldt. However, to derive the accumulation rates form these mud stocks it is important to take into account sediment removal that have taken place during the time interval. Claessens (1993) reports dredging of 4.200.000 ton of mud from the Lower Sea Scheldt and 2.300.000 ton of mud from the Antwerp harbours into the Scheldt. Resulting in a net abstraction of 1.900.000 ton of mud. Wartel *et al.* (2007) accounts for 1.187.000 ton of mud dredged from the Kallolock access channel between 1986 and 1999.

Based on the measurements of Bastin (1988), an annual increase in mud stock about 100.000 ton/y is observed between 1964 and 1986. Despite the removal of large amounts of mud from the system in the nineties the mud stock continued to increase between 1986 and 1999. The growth is slower than before 1986, about 35.000 ton/y.

5.1.3 Changes in mud percentage of the soil

Except for some exceptions such as the access channels of the locks most mud in the Scheldt estuary is stored as a mixture with sand. Estimations on the total mud stock are thus, especially in the Western Scheldt, very sensitive to the assumed percentage of mud in the bottom. Observed changes in the mud percentage of the soil are an important indicator for an altered mud stock in the estuary.

Van Ledden (2003) analysed the mud concentration in both the Western Scheldt and the Lower Sea Scheldt. He found that the average mud concentration of the Lower Sea-Scheldt is 44.3±36.2%.

Salden (1998) analysed river bottom data measured by the Vlaamse Mileumaatschappij (VMM) between 1990 and 1997. Results are shown in Figure 29. The graph on the left in Figure 29 shows the mud percentage of different sand banks along a transect in the neighbourhood of the Belgian-Dutch border. The graph on the right in Figure 29 shows a clear decreasing trend of the mud percentage on the sand banks in the Lower Sea Scheldt from 1991 to 1997. Also in the access channels Salden (1998) found a decreasing mud percentage between 1991 and 1997. However, with an average decrease of the mud percentage around 10% (on average from 90 to 80%) the reduction is much less pronounced that for the sand bars.

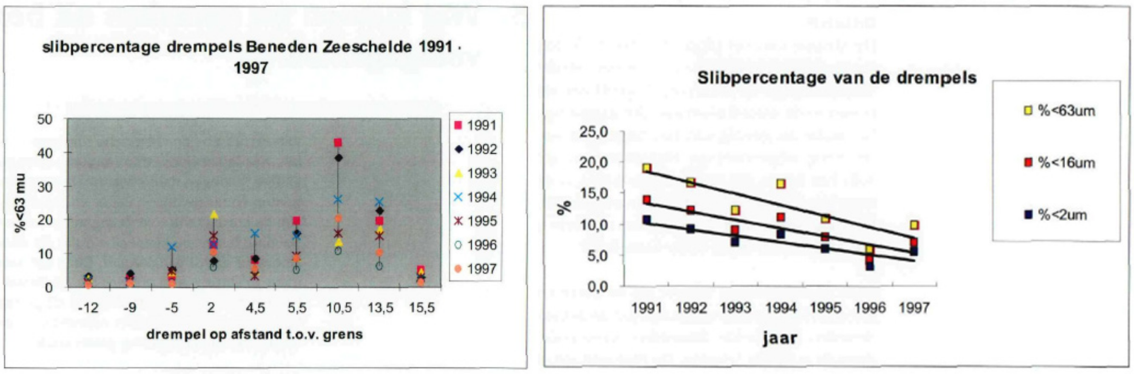


Figure 29 – Evolution of mud percentage of the sand banks of the Lower Sea Scheldt during 1991-1997 (left) and Trend in the average mud percentage of the sand banks in the Lower Sea Scheldt (right) (Source: Salden, 1998)

More recent Chen *et al* (2005) showed a similar rising trend of the sand fraction in the river bottom of the Scheldt (Figure 30).

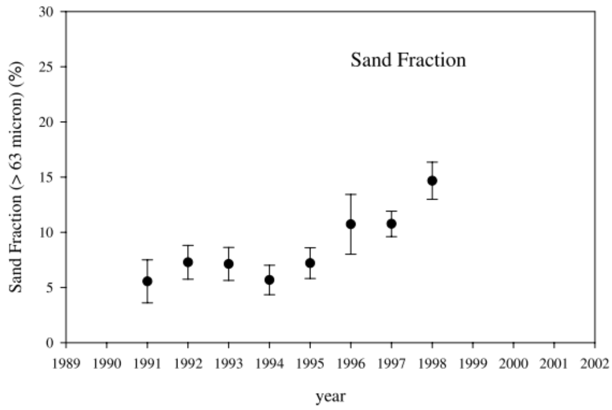


Figure 30 – Sand fraction of suspended matter from samples (60-80 per year) collected along the axis of Scheldt between 20 and 100km from the mouth (Source: Chen et al., 2005).

Santermans (2013) saw that the mud and clay content of the sills of Zandvliet, Frederik and Lillo strongly increased after 1997 to about 30-40% and afterwards decreased again to ±10%. After 2009 the mud and clay content increased again to 30-40%. Analysis of bottom sediments in Deurganckdok showed a decreasing trend in sand content over the recent years (Santermans, 2013).

More recent data for the Western Scheldt can be found in the series of reports "Jaarlijks waterbodemonderzoek in de Westerschelde" (Vereecken et al., 2014 and 2013; Vanlierde et al., 2013, 2011, 2010) which describe the sampling campaigns and VMM (2009, 2010, 2011, 2012, 2013) which describe the analysis of the samples.

Vos et al. (2011) describe a lithological map of the Lower Sea Scheldt for 2011, based on 260 sediment samples. Their analysis show the large spatial variation of the mud fraction along the thalweg.

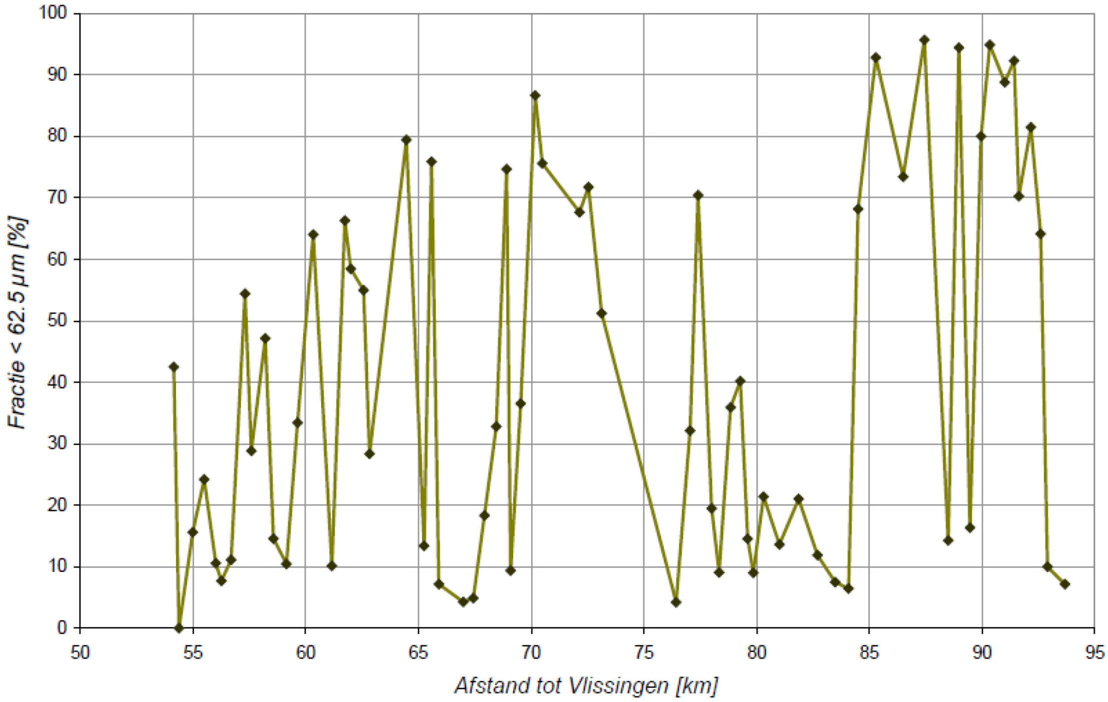


Figure 31 – Mud fraction (<62.5µ) along the thalweg in the Lower Sea Scheldt. Taken from (Vos et al., 2011)

5.2 Western Scheldt

De Looff determined the sediment composition in the eastern (De Looff, 1978) and western (De Looff, 1980) part of the Western Scheldt. Maps were created which indicated for example the mud content in the upper layer of the entire Western Scheldt. In 1996 McLaren also mapped the mud content of the Western Scheldt. The mud content indicated by McLaren is significantly larger that the mud contents determined by De Looff. However, this difference in mud content is mainly caused by differences in sampling, measuring techniques and the definition of mud (<16µm by De Looff and <63µm by McLaren) (Dam & Cleveringa, 2013).

According to McLaren (1994) less than 6% of the area of the Western Scheldt is covered with mud (<20% sand). Sand (>80% sand) covers around 71% of the river bottom, muddy sand (between 80-50% sand) about 12% and sandy mud (between 50-20% sand) 10%. Based on an analysis of the data of De Looff en McLaren, Van Ledden (2003) calculated the average mud content in the Western Scheldt at 16.4±23.9%. In the IMDC report (1993) the mud percentage of the river bottom in the Western Scheldt down-estuary of Hansweert is taken as 8-11% with a standard deviation between 11 and 14%. In the section between Hansweert and "Verdronken land van Saeftinghe", the river bottom contains only 2±3% mud. The river bottom in "de bocht van Bath" has a mud percentage of 20±17%. Van Eck (1999) indicates the mud percentage in the Western Scheldt per morphological unit. According to Van Eck (1999) the mud percentage in the channel and on shoals is less than 10% while on tidal flats and marshes the mud content is higher than 10%.

Assuming a 1 meter thick active bottom layer van Maldegem (1993) estimates the total mud stock in the western and eastern part of the Western Scheldt at respectively 26 and 24 million ton. Accounting the mud to a depth of 10 to 50 cm, van Maldegem *et al.* (1999) estimates the total mud mass in the Western Scheldt around 10 million ton. Most of this mud is stored in the marsh areas, especially in the Land of Saeftinghe. The river channel and shoals contains between 1 and 10 million ton of mud spread over a depth of 10 to 50 cm (Van Maldegem *et al.*, 1999). The mass of mud in suspension is only a fraction of this total mass. In summer about 60.000 ton of mud is in suspension, in winter this is three times as much (180.000 ton) (Van Maldegem *et al.*, 1999). Harbours in the Western Scheldt store around 1 million ton of mud (Van Maldegem *et al.*, 1999).

The data analysis by IMDC (1993) result in a total under water mud stock between 15.9 and 31.8 million ton for the western part and between 1.7 and 3.5 million ton for the eastern part of the Western Scheldt.

Dam & Cleveringa (2013) performed a detailed analysis on the contribution of mud in volumetric changes observed between 1980-1992, 1992-2000 and 2000 and 2010. Dam & Cleveringa (2013) simulated a yearly increase in mud volume in the entire Western Scheldt of 100.000, 150.000 and 580.000 m³/y for respectively 1980-1992, 1992-2000 and 2000-2010. For all periods these changes occur in the deeper parts. The method assumes a fixed mud percentage over time. Middelgat, a channel just downstream of Hansweert is an important location for mud storage in the Western Scheldt. During the period 2000-2010 the mud content of the sedimentation in Middelgat is around 13-14%. Middelgat accounts for about 43%, 167% and 73% of the sedimentation in the Western Scheldt for respectively 1980-1992, 1992-2000 and 2000-2010.

Converting the mud volumes to mud mass is not so straight forward because the density depends on the mud/sand ratio in the bottom. Migniot (1989) found that the density of mud increases fast during the first 40 days after deposition. After 3 months the dry density was about 0.3 ton/m³. After 3 years the dry density of mud in the Scheldt is about 0.5 ton/m³. Dam & Cleveringa (2013) propose a dry density of fine sediments of 0.45 ton/m³. Using the density of 0.45 ton/m³ the mass of mud that according to Dam & Cleveringa (2013) is deposited yearly in the Western Scheldt between 1980-1992, 1992-2000 and 2000-2010 is respectively, 45.000 ton/y, 67.500 ton/y and 261.000 ton/y.

6 MUD CONCENTRATION IN THE WATER COLUMN

The suspended mud concentration has a high spatial variability. The mud concentration varies along the longitudinal profile of the river but also vertically there is a large gradient. van Maldegem (1987) indicates that the average mud concentration in the total water column can be 1 to 3, sometimes even up to 10, times higher than the concentration at the surface. Measuring data of the Antwerpse Zeehavendienst at Oosterweel and Liefkenshoek was analysed (Zeehavendienst, 1993). At Oosterweel the mud concentration at the surface was about 90% of the mud concentration TAW-4m (considered as a representative of the average mud concentration). At Liefkenshoek a relation of 1.9 was found for the ratio bottom concentration/average concentration (IMDC, 1993). Turbulence with sufficiently high tidal currents cause a strong mixing of the mud in the water column. During periods with low tidal currents larger mud particles will sink to the bottom while the smaller particles will stay in suspension.

Also the temporal variability of the suspended mud concentration is high. During one tidal cycle the depth averaged mud concentration varies with a factor around 2 (van Eck *et al.*, 1991) to 5 (Sas *et al.*, 2007). The long-term measurements at Liefkenshoek (IMDC, 1989) showed a ratio between the average mud concentration and the maximum value during flood and ebb at respectively, 1.65 and 2.3.

Chen *et al.*, (2005) closely monitored the vertical suspended matter evolution during one tidal cycle (Figure 32). The SPM concentration along the vertical profile develops two-layers during the first 3-4 hours of the flood tide. A uniform suspension layer with low SPM concentration extends about 60% of the upper water column. Below a graded-suspension layer is found with high SPM concentration close to the bottom. During ebb tide the high concentration bottom layer gradually extends towards the water surface, covering up to 85% of the vertical water profile (Figure 32b). Note that Chen et al. (2005) give little details on the measurement campaign the dataset was collected in (meteo conditions, phase in spring neap cycle, fresh water inflow, …), so that it is hard to extrapolate this data from 1 campaign to general conclusions on the vertical structure of suspended sediment in the Scheldt Estuary. The location mentioned in the title (70km) suggest a measurement location in the vicinity of Kallo Sluice.

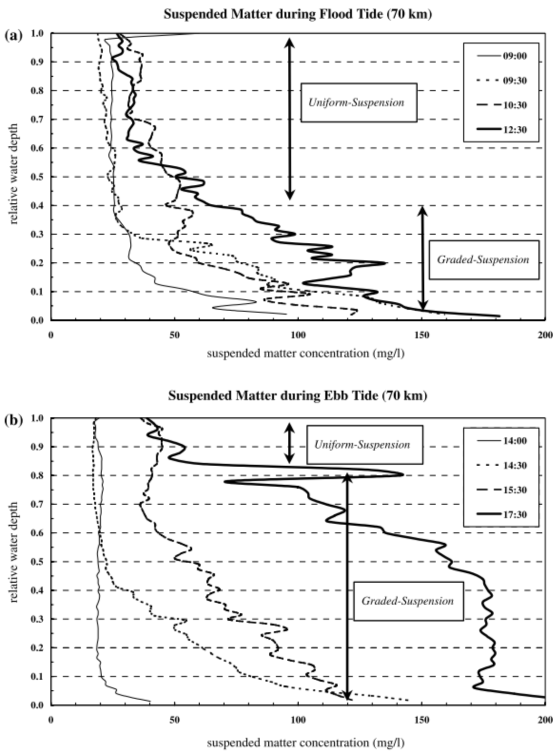


Figure 32 – Vertical distribution of suspended matter during a tidal cycle. An example of measurements carried out at an anchored station near to 70 km from the mouth. Y-axis indicates relative water depth, where 1 is water-surface and 0 is bottom. (Source: Chen et al., 2005)

Also at Liefkenshoek the depth averaged mud concentration during neap tide is only about 50% of the average mud concentration, during spring tide this is about 125% (IMDC, 1989). Fettweis (1995) found spring-tide concentration at Prosperpolder (near the Dutch – Belgian border) to be 1.3-1.7 times higher than during neap tide.

The seasonal factor for mud concentration in the Western Scheldt is around 2 to 3. In summer the mud concentration is low due the lower river discharge (Fettweis, 1995), the high accumulation of mud on the tidal flats (van Eck *et al.*, 1991) and storm events in the Dutch and Belgian coastal zone leading to considerable erosion of bottom sediment (Verlaan, 1998).

According to Verlaan (1998) longer term variations are usually related to human interventions. The most important interventions identified by Verlaan (1998) are: (1) removal of mud upstream of Rupelmonde, (2) removal of mud-rich bottom sediment from the access channels to the harbours of Antwerp and (3) the deepening of the main fairway of the Western Scheldt.

Nihoul & Wollast (1976) reported mud concentrations around 30 mg/l between Vlissingen and Bath, going up to 150 and 200 mg/l at Rupelmonde (IMDC, 1993). Swart (1982) gave similar values for the Western Scheldt between het ”Verdronken land van Saeftinghe” and the mouth of the estuary based on weekly samples of suspended matter between 1969 and 1980. At the Dutch-Belgian border Swart (1982) measured a yearly averaged mud concentration of about 60 mg/l.

van Maldegem (1987) looked for trends in the monthly averaged mud concentration measured at the water surface between 1969 and 1985. At sea a slightly rising mud concentration (±2%/y) was noticed while at the border of the sea and the river a slight decrease (1-3%/y) was observed. At the Western Scheldt the mud concentration at the surface rises again (1-5%/y). At the river border a clear decrease in mud concentration at the surface is measured (±4%/y).

van Eck *et al.* (1991) performed an analyses on the series of mud concentration measurements between 1970-1990 along the longitudinal profile of the Scheldt (extended data set as used by Swart (1982). Figure 33 summarizes the outcome of these measurements. The figure clearly illustrates the sharp rise in turbidity between Doel and Kallo. The figure of van Eck *et al.* (1991) is also shown by van Maldegem (1993). The depth average mud concentration for the Sea Scheldt, western part of Western Scheldt and eastern part of the Western Scheldt is respectively 115±30, 76±30 and 72±27 mg/l. van Maldegem (1993) reports no clear trends in the mud concentration of the water surface over the years.

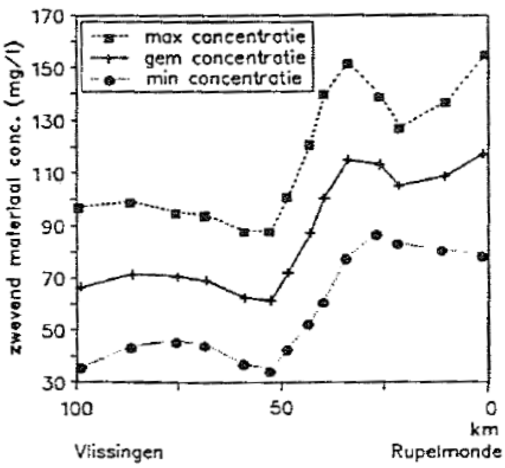


Figure 33 – Depth average mud concentration [mg/l] between Vlissingen and Rupelmonde (1970-1990) (Source: van Eck et al., 1991)

In the framework of the SAWES project Holland *et al.* (1991) also established a profile of the mud concentration along the Scheldt estuary (Figure 34). Significant differences were found average mud concentration in the two years. Most probably these changes are caused by the significantly higher river discharges in 1988 compared to 1985. On a long term the profile is most likely closer to the profile with a turbidity maximum of 150-200 mg/l around Antwerp.

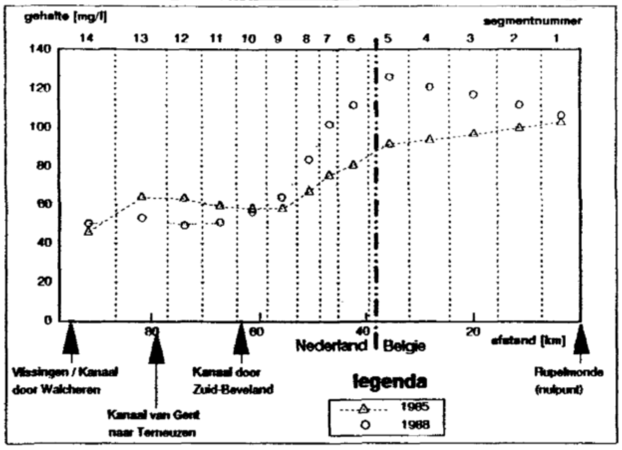


Figure 34 – Comparison of the depth averaged mud concentration profile along the Scheldt (Source: Holland et al., 1991)

Temmerman *et al.* (2004) showed the time-averaged suspended sediment concentration measured in surface water samples collected between January 1996 and January 2002 at 29 locations in the main stream (**Fout! Verwijzingsbron niet gevonden.**). Measurements were taken at different stages of the tidal cycle..

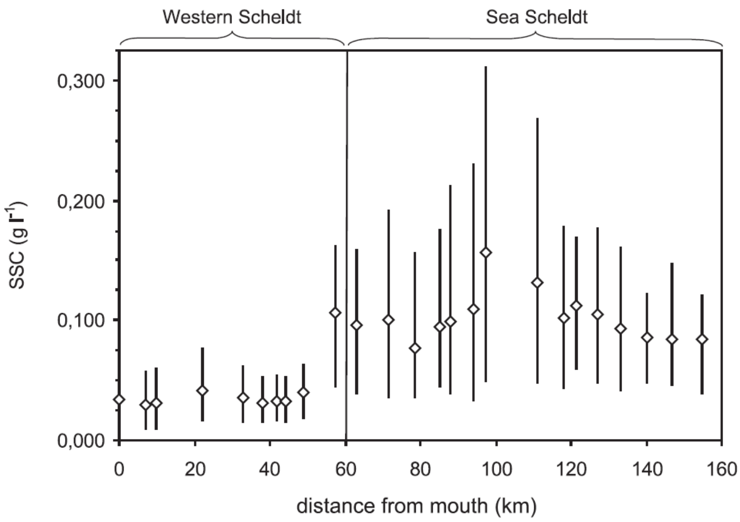


Figure 35 – Time-averaged longitudinal variation in surface suspended sediment concentration along the Scheldt estuary, calculated from monthly monitoring data between 1996-2001. Error bars represent the 10-90 percentiles of all SSC measurements at the stations. (Source: Temmerman et al., 2004)

Van Damme *et al.* (2005) studied spatial and temporal patterns of water quality parameters in the Scheldt estuary based on the results of 7 years (1996-2002) of intense monitoring along the Scheldt estuary. Results for the surface suspended particulate matter (SPM) are shown in Figure 36. The figure shows the higher SPM in the Sea Scheldt compared to the Western Scheldt. Also the seasonal trend of the SPM is clearly visible in Figure 36.

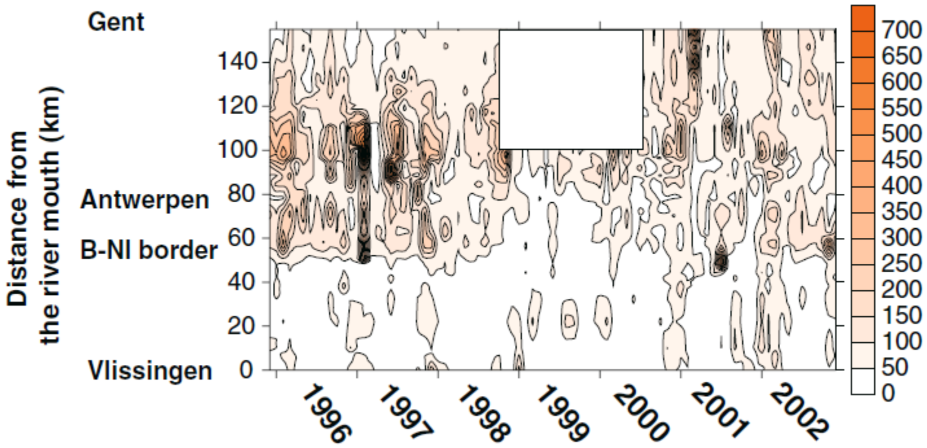


Figure 36 – Surface suspended particulate matter (SPM) along the estuarine axis of the Scheldt [mg/l] (Source: Van Damme et al., 2005).

van Kessel *et al.* (2006) summarized results of Verlaan (1998) and Chen *et al*. (2005) on the SPM concentration along the estuary axis, distinguishing the upper 10% and 25% upper water layer and the lower 10% of the water layer (Table 12). van Kessel *et al.* (2006) also analysed the SPM concentration in the Western Scheldt based on data from the MWTL (Monitoring Waterstaatkundige Toestand des Lands) dataset and measurements taken in Terneuzen. Figure 32 shows for different locations in the Western Scheldt the overall, winter and summer mean SPM concentration. The SPM concentration in Terneuzen show almost no vertical gradient. The tidal component has a strong impact on the fluctuations of SPM in Terneuzen. Seasonal fluctuations appear to be caused by a combination of freshwater discharge and wind climate (van Kessel *et al.*, 2006). For the Sea Scheldt van Kessel *et al.* (2006) give a complete overview of available datasets.

Table 12 – Typical SPM concentrations in the Scheldt estuary according to Verlaan (1998) and Chen et al. (2005) [mg/l]. (Source: van Kessel et al., 2006)

	Lower estuary	Middle	Upper estuary
25% upper water layer	< 50	100 ± 70	110 ± 50
10% upper water-layer	50	82 ± 65	110 ± 65
10% lower water-layer	50	150 ± 2.5	100-1000

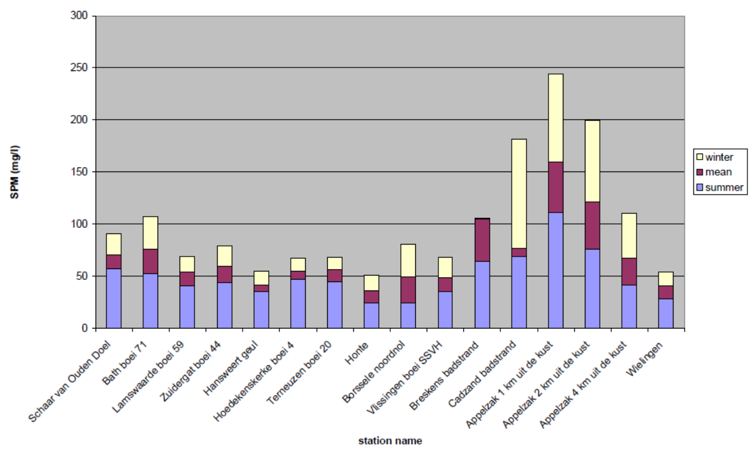


Figure 37 – Mean, mean winter and mean summer observed SP concentration in the Western Scheldt. Measuring locations on the left side are closer to the Belgian – Dutch border, the bars on the right are closer towards the sea. (Source: van Kessel et al., 2006)

Sas *et al.* (2007) applied the Slib3D model, which was briefly discussed in §3.5, to assess the effects of a third deepening of the fairway and alternative dredging and disposal practices. The Slib3D model allows the simulation of mud concentration for the whole longitudinal river profile under different circumstances. Figure 39 presents the simulated depth and tidal averaged mud concentration for an average neap and spring tide event. The mud concentration profile is also calculated for high and low river discharge events. The Slib3D also accounts for vertical differences, allowing to compare the mud concentration at the bottom and at the surface under different events as illustrated in Figure 39.

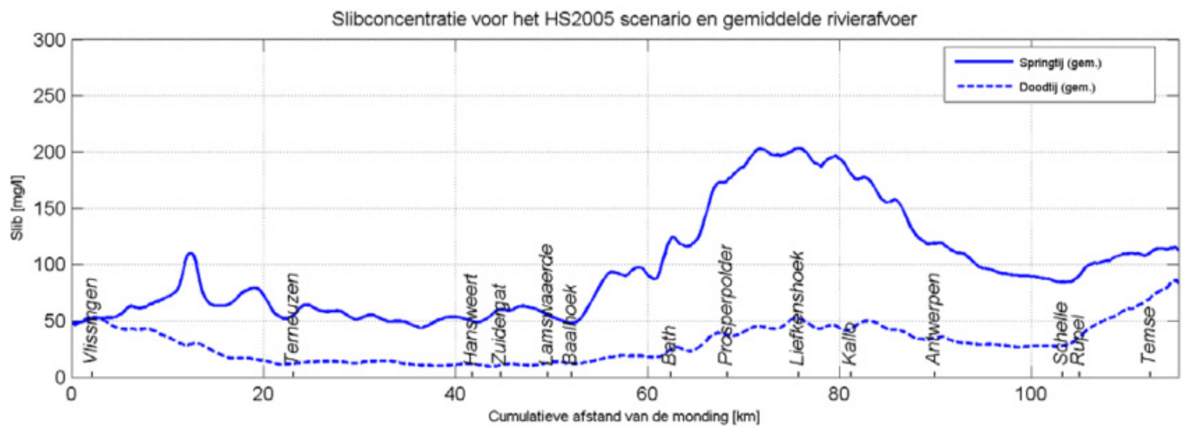


Figure 38 – Tidal and depth averaged mud concentration for average neap (dotted line) and spring tide (solid line) simulated for the year 2005 under average river discharge conditions (Source: Sas et al., 2007)

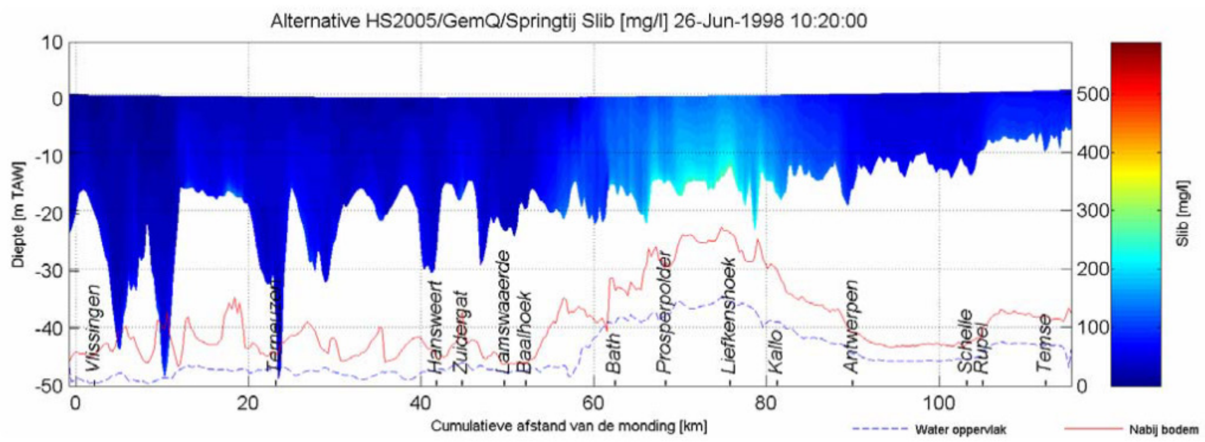


Figure 39 – Mud concentration during maximum ebb current (spring tide and average discharge) (Source: Sas et al., 2007)

Note that more recent data on SSC concentrations comes available under the MONEOS monitoring programme. There are the measurements during ebb half tide (e.g. Levy et al., 2015) and 13h measurements where SSC is inferred from ADCP backscatter (e.g. Levy et al (2014), the limitations of that technique are briefly discussed in §3.7).

In a more recent effort, Vandenbruwaene et al (2015) did a meta-analysis on a tide-independent set of databases of surface SPM data (DONAR, OMES and CEME datasets). By correlating each data point with the tidal phase, the tidal variation of surface SPM can be reconstructed *for the entire Scheldt Estuary*.

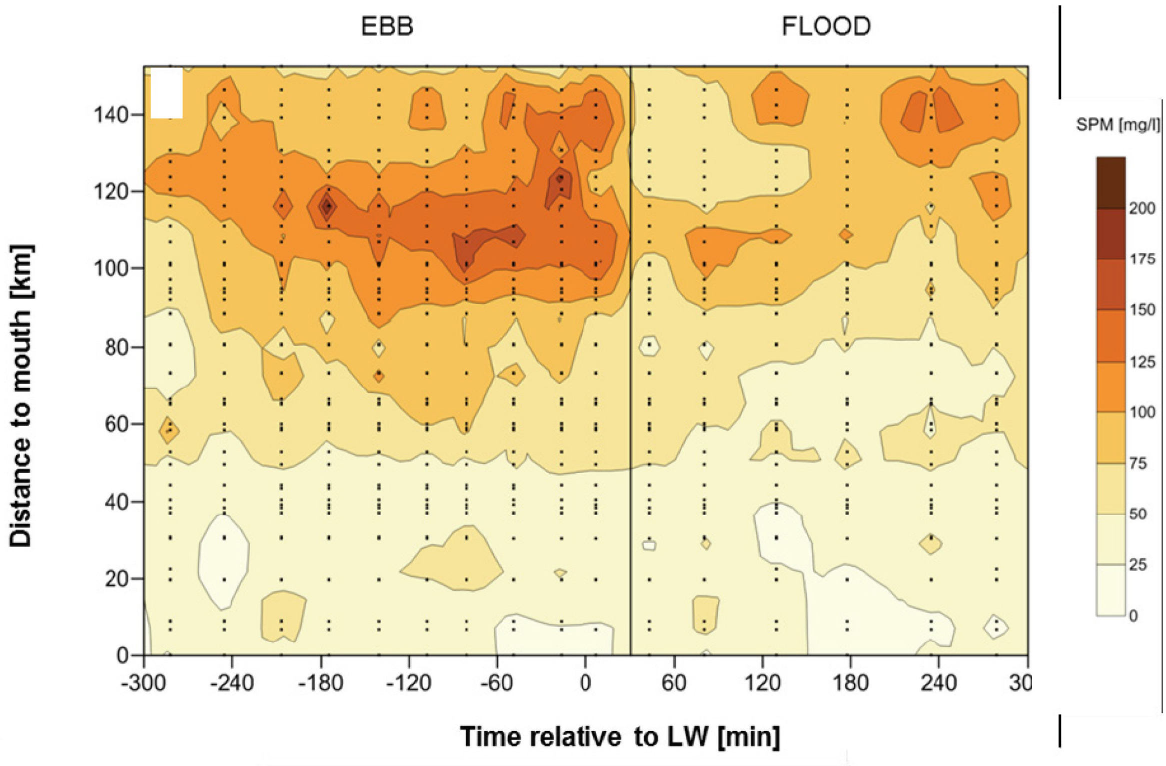


Figure 40 – Relationship between the tidal phase (relative to LW) and the surface SPM along the Scheldt estuary. Vertical line which separates the ebb and flood phase represents the time of low water slack. From Vandenbruwaene et al. (2015)

Similarly, the spring-neap variation of the surface SPM signal can be reconstructed for the entire Scheldt Estuary.

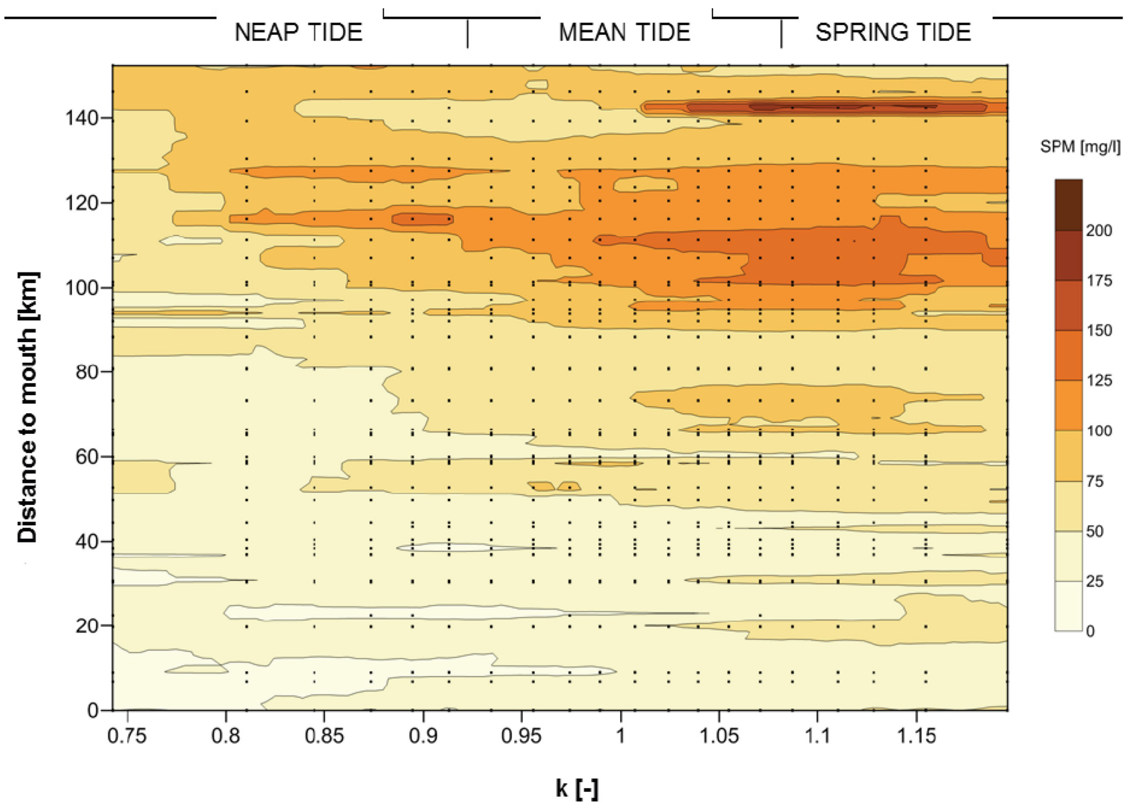
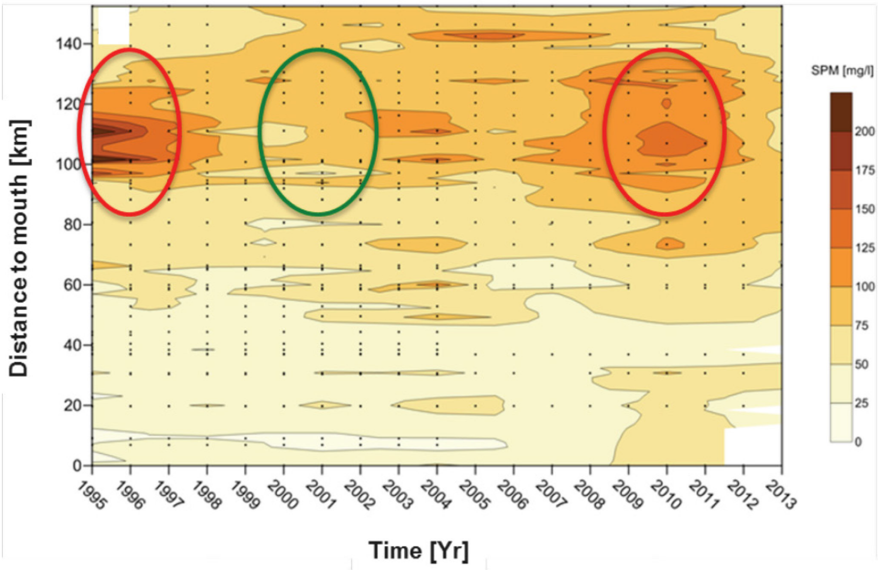


Figure 41 – Relationship between the k-value (i.e. the ratio between the observed tidal range and the mean tidal range) and the surface SPM along the Scheldt estuary.

Interestingly, Vandenbruwaene et al. (2015) found a clear relation between fresh water inflow at Melle (inflow in the Upper Sea Scheldt) and the occurrence of a classical ETM in the surface SPM in the Upper Sea Scheldt. They observe an alternation of periods with higher and lower suspended sediment concentrations (red and green circles). Higher SPM values are hereby associated with periods of lower riverine discharge and vice versa.



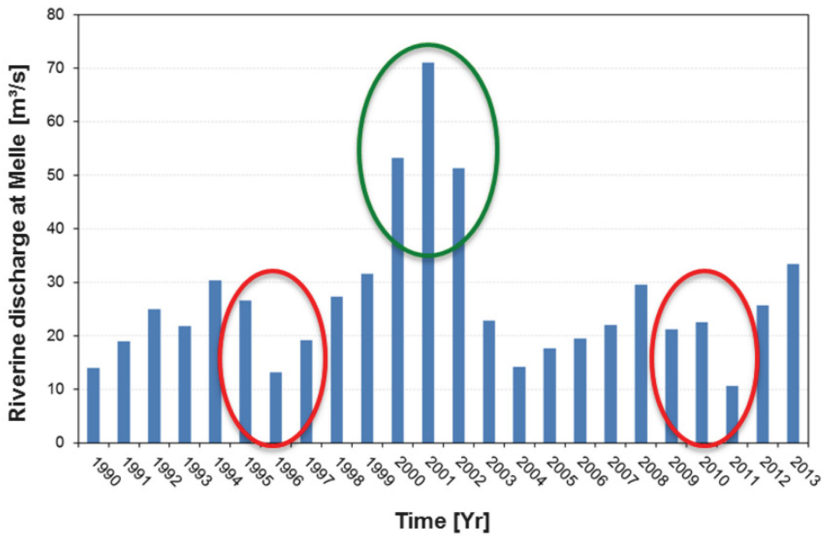


Figure 42 – top panel: Evolution of surface SPM along the Scheldt estuary over the time period 1995-2013. Red circles indicate periods with higher SPM values in the upstream part of the estuary, the green circle indicates a period with lower SPM values. Lower panel: Yearly riverine discharge at Melle.

7 RATIO FLUVIAL-MARINE MUD

7.1 Ratio fluvial-marine mud in the river bottom

7.1.1 Measurements

It is well known that part of the mud in the Scheldt estuary originates from upstream natural or anthropogenic sources while another part is transported towards the estuary from the North sea. Because especially the marine mud transport is difficult to measure, the ratio of fluvial and marine mud found in the estuary is an important term in developing a mud balance. Furthermore, changing fluvial-marine mud ratios can be an indication for important hydraulic or ecological changes in the estuary.

The fluvial marine mud ratio used in the IMDC (1993) report originate from the research done by Swart (1987). Swart (1987) measured an increase in fluvial mud percentage from almost 0% at the mouth to around 39-47% at the Belgian-Dutch border. The ratio was measured using carbon 12 and 13 isotopes.

van Maldegem (1993) also used carbon 12 and 13 isotopes to obtain the fluvial-marine mud ratio along the river bottom. Results of van Maldegem (1993) are shown in Figure 43. The average fluvial fraction at the mouth (Vlissingen), the border and Rupelmonde are respectively, 20, 60 and 70 percent. The uncertainty range indicated on Figure 43 is caused by the relatively large spread in $^{12}C^{13}C$ value for 100% marine (-21/-24) and 100% fluvial mud (-27/-31).

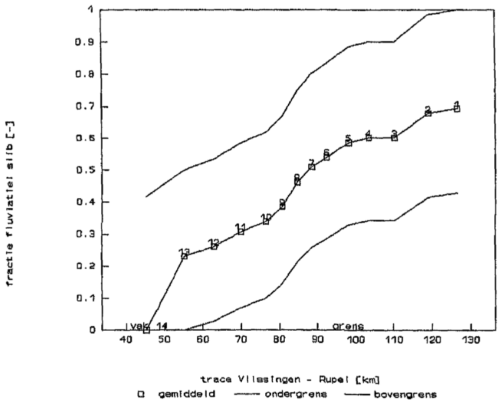


Figure 43 – Fluvial mud fraction in the bottom of the Scheldt estuary from the mouth (left) to Rupelmonde (right) (Source: van Maldegem, 1993)

Verlaan (1998) summarized the results of several measuring campaigns on the mixing of marine and fluvial mud. The fluvial fractions, presented in Figure 44, are obtained using different analyzing techniques. Point marked with crosses, triangles and diamonds are respectively obtained through analysis of carbon, plutonium and lead isotopes. The figure shows the measuring method has a significant influence on the resulting marine fraction (Verlaan, 1998). Another problem is that the method based on carbon isotopes gives information only on the organic fraction of the mud.

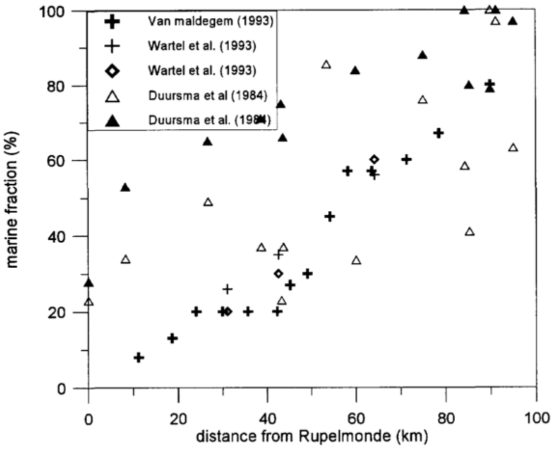


Figure 44 – Overview of marine fractions in the bottom mud of the Scheldt estuary as measured by the presented authors. The marine fraction of the organic carbon is derived from carbon isotopes indicated as crosses. The marine fraction of the inorganic fraction is derived from plutonium (triangles) and lead (diamonds). (Source: Verlaan, 1998)

Verlaan (2000) applied a factor analysis approach based on the concentration of As, Cd, Cr, Cu, Hg, Ni, Pb and Zn, to identify the fluvial-marine ratio of the bottom mud (Figure 45). Samples were collected between 1990 and 1993. Results show a sharp increase in marine fraction between Lillo (10%) to Saeftinghe (75%). Between Antwerp and Rupelmonde the marine fraction in the bottom is generally less than 10%. Downstream Saeftinghe the marine fraction increases gradually from 75% to 95% at Vlissingen.

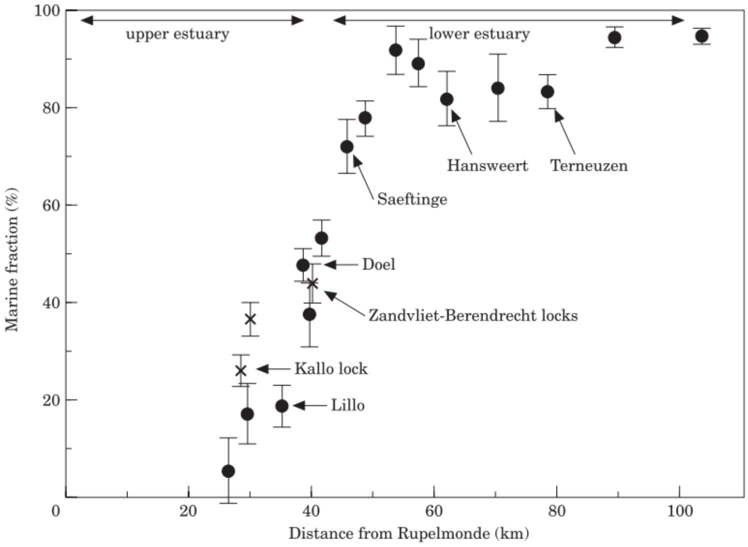


Figure 45 – Fraction of marine bottom mud versus the distance from Rupelmonde. Dots represent samples taken from the main fairway. Samples from the access channels to the Antwerp harbour are marked as crosses (Source: Verlaan, 2000).

Ten Brinke (1992) also applied the ^{13}C isotope to estimate the fluvial mud ratio along the estuary. He divided the estuary in 4 zones: Belgian part (zone 1), Bath-Hansweert (2), Hansweert-Terneuzen (3) and Terneuzen-Vlissingen (4). The fluvial mud percentage in those zones was estimated at 84±5, 64±15, 42±2 and 27±9 percent.

7.1.2 Temporal changes

Salden (1998) compared the mixing curve for the bottom sediments of van Maldegem *et al.* (1993), based on measurements in 1987 with the mixing curve of Verlaan *et al.* (1998) who used measurements between 1990 and 1993. The graph (Figure 46) shows the sharp gradient in fluvial – marine ratio between 40 and 60 km from Rupelmonde. Over the considered time interval the gradient has become stronger and moved upstream by about 5 km. It is not clear if this change could be explained by differences in river discharge (which was significantly larger in the period before 1987 than around 1990-1993) or due to the removal of mud in the upper Sea Scheldt during the nineties (Salden, 1998).

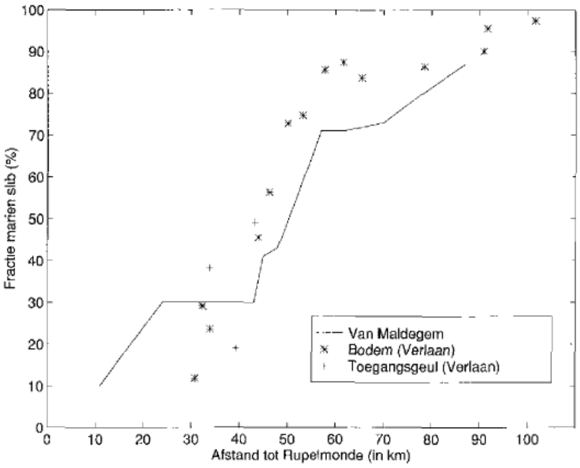


Figure 46 – Mixing curves of fluvial and marine mud in the bottom sediment for 1975-1985 (van Maldegem) and 1990-1993 (Verlaan) (Source: Salden, 1998)

Wartel *et al.* (2004) compared $\delta^{13}C$ values in the mud of the river bottom to evaluate change in the marine-fluvial mud ratio between 1993 and 1998. Results in Figure 51 indicate an increase in fluvial mud fraction between 1993 to 1998 and a reduction between 1998 and 2003. Fluvial mud fractions of 1993 were comparable with the measurements of 2003. However, it is important to take into account that due to dredging activities, bottom samples taken in a certain year not necessarily correspond to deposits of the same year.

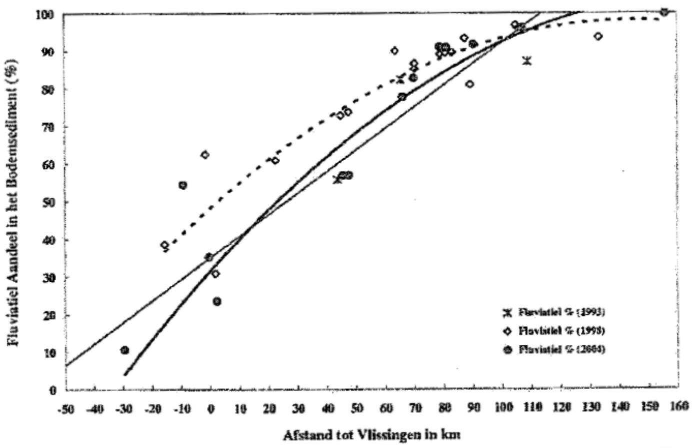


Figure 47 – Fluvial share in bottom sediment of 1993 (x and thin line), 1998 (◊ and dotted line) and 2004 (O and thicker line) (Source: Wartel et al., 2004)

7.2 Ratio fluvial-marine suspended sediments

7.2.1 Measurements

Besides the suspended sediment concentration also the fluvial-marine ratio of the suspended sediments is highly variable in time and space. Verlaan *et al.* (1998) clearly shows the impact of the river discharge on the fluvial-marine ratio of the suspended matter along the longitudinal profile of the Scheldt estuary (Figure 48). During high discharge periods, the percentage of marine suspended matter gradually increases from a few percent at Rupelmonde to around 80% at Vissingen. During low discharge periods the percentage marine suspended matter increases rapidly from a few percent at Rupelmonde to about 65% at the Dutch-Belgian border (±40 km) and 90% at Vlissingen. Figure 49 shows the marine fraction of the suspended sediments at the Belgian – Dutch border is sensitive to the river discharge while the concentration at Vlissingen is relatively stable.

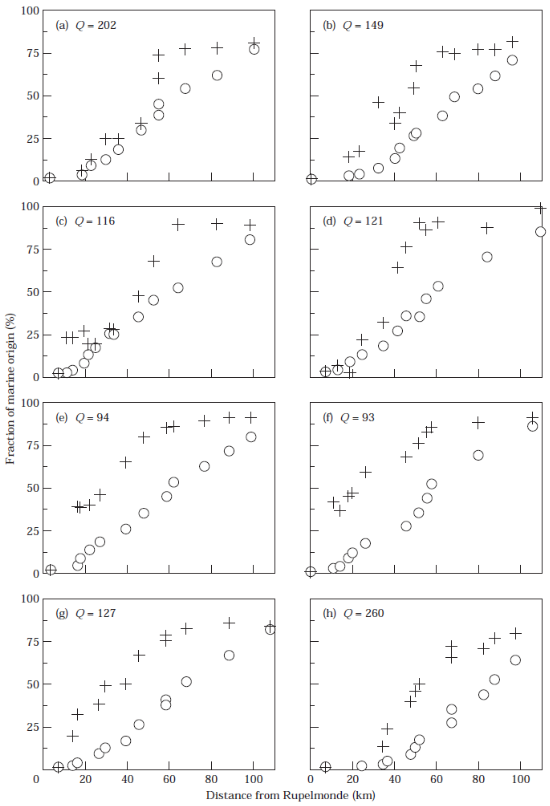


Figure 48 – The seawater fraction and the fraction of marine suspended matter versus the distance from Rupelmonde. The sample location is corrected for the tidal phase. The Scheldt discharge Q is specified for each cruise. The seawater fractions (o) are derived from measured salinities, assuming that seawater has a salinity of 34. Fractions of marine suspended matter are derived from the scores of the first factor (+). Calculations were carried out for eight cruises: (a) February 1987, (b) April 1987, (c) May 1987, (d) July 1987, (f) October 1987, (g) December 1987 and (h) February 1988. (Source: Verlaan et al., 1998)

Similar as for the fluvial – mud ratio in the bottom (P. a. J. Verlaan, 2000) Verlaan *et al.* (1998) used a factor analysis based on the concentration of Cr, Pb, Fe, Mn, Ni, Co, Ba, Zn, Cu, Cd, S, Ca, Sr, Ag, Sn and Na. This factor analysis method provides information on the origin of all the suspended matter in contrast to the methods based on carbon or nitrogen isotopic data which gives the origin of the carbonate or organic fraction only. Verlaan *et al.* (1998) argues that because the faction of fluvial suspended matter in the Scheldt is high, the carbon or nitrogen isotopic methods tend to overestimate the fluvial fraction.

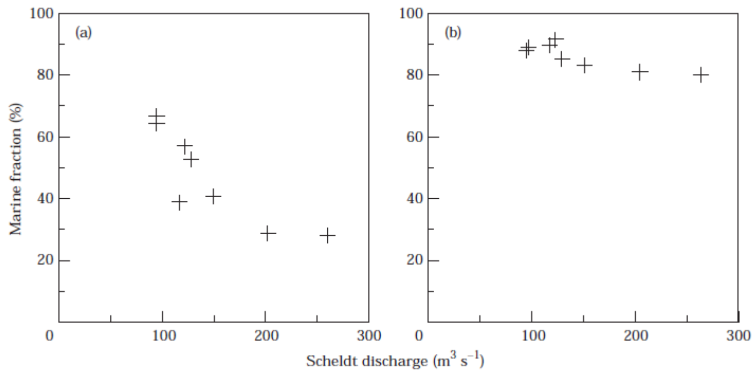


Figure 49 – The fraction of marine suspended matter versus the instantaneous Scheldt discharge Q at (a) the Dutch-Belgian border (40 km from Rupelmonde) and (b) Vlissingen (100 km from Rupelmonde). (Source: Verlaan et al., 1998)

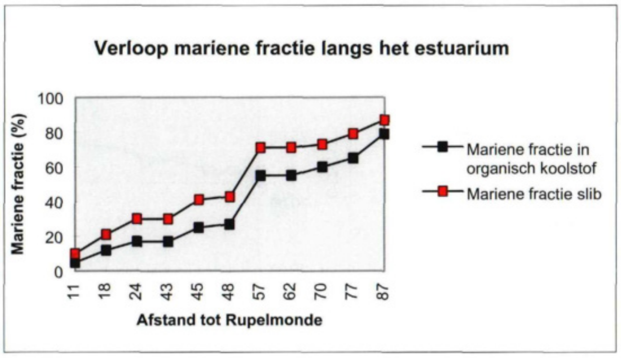


Figure 50 – Comparison of the marine fraction calculated from the organic carbon and from all suspended matter. (Source: Verlaan, 1998)

7.2.2 Temporal changes

Ministerie van de Vlaamse Gemeenschap (2000)mentions a strong increase of the marine fraction in suspended sediments at the Dutch – Belgian border from 20% (1991) to 40% (2000) .

Chen *et al.* (2005) compared $\delta^{13}C$ values in the suspended mud to evaluate change in the marine-fluvial mud ratio between 1993 and 1998. Results shown in Figure 51 indicate a clear reduction of the fluvial fraction in the suspended matter between 1993 and 1998. The reduction is most profound in the Lower Sea Scheldt. Chen *et al.* (2007) also included more recent measurements of 2004 as shown in Figure 52. The marine – fluvial ratio did not really changed between 1998 and 2004. This indicates that after 1993 the marine component in the estuary increased. (Chen *et al.*, 2007) attribute this increase to second deepening of the Western Scheldt.

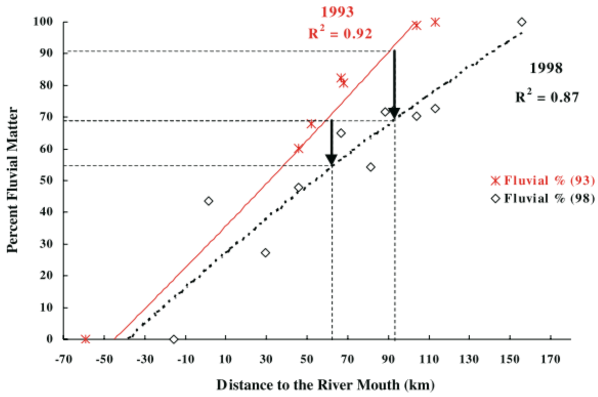


Figure 51 – Comparison of the evolution in fluvial fraction of mud in the river bed of the Scheldt between 1993 and 1998 (Source: Chen et al., 2005)

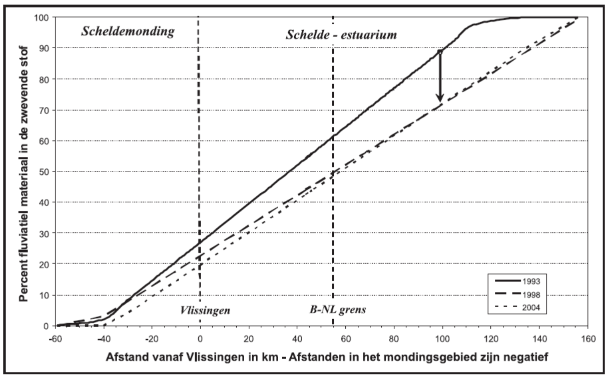


Figure 52 – Fluvial-marine ratio of suspended matter in 1993, 1998 and 2004. (Source: Chen et al., 2007)

8 FLUX ESTIMATES FOR MARINE AND FLUVIAL MUD

8.1 Fluvial mud

The quantity of fluvial mud entering the estuary is an important component of the mud balance. Fluvial mud originates from both natural and anthropogenic sources. Natural sources of mud are dominated by soil erosion. Besides this the mud originating from erosion, also precipitation naturally contains a small fraction of mud. Anthropogenic sources are domestic and industrial waste and agriculture management practices.

8.1.1 Fluvial mud load at Schelle

Table 1 gives an overview of the input of fluvial mud at Schelle reported in literature. One of the first values of input of fluvial mud at Schelle was reported by Nihoul and Wollast (1976) and Wollast and Peters (1979). Nihoul and Wollast (1976) and Wollast and Peters (1979) established the mass balances by considering: the net flow due to the river discharge for both suspended and dissolved compounds, their longitudinal turbulent dispersion (estimated from the salinity profile), their sedimentation process and their lateral input from tributaries and sewers. Nihoul and Wollast (1976) performed multiple measurements during different phases of the spring-neap tide cycle. The fluvial mud input of mud at Schelle was concluded around 970.000 ton/year.

A few years later Wollast and Marijns (1981) applied an indirect method to estimate the fluvial mud load at Schelle from different sources. Wollast and Marijns (1981) calculate the mud load from land erosion at 226.800 ton/y, from domestic waste 144.400 ton/y and from industrial waste 136.500 ton/y, resulting in a total suspended matter load produced upstream Schelle around 507.700 ton/y. These mud loads are a summation of the mud loads estimated for the different sub-basins. For the estimation of the domestic and industrial waste an inhabitant equivalent of 90 g/day was used. Mud originating from erosion was estimated from measurements executed in May and April 1981 at Bousval in the basin of the Wavre (40 km²) a sub-basin of the Dijle river. The obtained erosion (12,56 ton/ha/y) was extrapolated to the whole Scheldt basin. D'Hondt and Jacques (1982) who summarized the results of Wollast and Marijns (1981) argued that a large fraction of the organic material is degraded in the riverine system. D'Hondt and Jacques (1982) estimate the fluvial suspended matter flux at Schelle at 320.000 ton/y.

Salomons et al. (1981) applied the transport method to calculate the fluvial mud load at Schelle, which was estimated around 800.000 ton/y. This value is based on a measurement for a situation with average river discharge.

In 1987 the National Institute for Coastal and Marine Management (the Netherlands) initiated the System Analysis Western Scheldt (SAWES) project. The main goal of this project was to acquire knowledge on how to tackle pollutions problems in the Scheldt estuary. The load of suspended sediments transported from upstream to Schelle was calculated in the SAWES project using measured suspended sediment concentrations and river discharge, results were published by Holland et al. (1991). Values presented in Table 15 are read from Figure 8 (p. 29) in Holland et al. (1991).

In the framework of the same SAWES project van Maldegem (1993) developed a cohesive sediment balance for the Scheldt estuary. To estimate the fluvial input at Schelle van Maldegem (1993) used the data published by Wollast and Marijns (1981) and summarized by D'Hondt and Jacques (1982). van Maldegem (1993) however, assumes the organic part of the mud (2/3 of the domestic and industrial waste) deteriorates for a large part or is deposited in the upstream river branches of the Zenne or Durme. Furthermore van Maldegem (1993) reduces the fluvial input value of Wollast and Marijns (1981) by 18%, the fraction of the discharge which is diverted to the canal Ghent – Terneuzen. As a result van Maldegem (1993) concludes the inorganic fluvial cohesive sediment load at Schelle around 260.000 ton/y ±120.000 ton/y (standard deviation). Because publications before 1990 include both the organic and inorganic load of the mud, the value of van Maldegem (1993) should not be compared with these values in Table 15. van Maldegem (1993) compared his result of 260.000 ton/y with the inorganic fraction he estimated from earlier published results: Nihoul and Wollast (1976): 550.000 ton/y; Salomons et al. (1981): 460.000 ton/y; Manni (1986): 570.000 ton/y.

In 1993 IMDC (International Marine & Dredging Consultants) performed a detailed analysis of the input of fluvial mud to the Scheldt to improve the previously mentioned estimations by Wollast and Marijns (1981). In this report substantiated estimations are made for organic and inorganic mud originating from domestic, industrial and agricultural wastewater, erosion, precipitation and the sediment processes and dredging activities in the non-tidal zone of the estuary. In the IMDC study (1993) the mud caused by erosion is based on a study from Lamalle *et al.* (1989) Lamalle et al. (1989). Lamalle et al. (1989) measured a much higher erosion for their study compared to the experiments used by Wollast and Marijns (1981). As a consequence the IMDC study estimates erosion to induce about 82% of the total suspended sediment transport, versus about 36% predicted by Wollast and Marijns (1981). The total fluvial mud produced upstream Schelle is estimated between 888.000 and 915.000 ton/y. Unlike Wollast and Marijns (1981) the IMDC report takes into account dredging of canals and rivers outside the tidal zone. It is assumed that 70% of the dredged volume is mud and the mud has a density between 1.2 and 1.4 ton/m³. This results in a dredged quantity of mud between 274.000 and 548.000 ton/y. Taking into account the uncertainties in suspended sediment caused by the load of industrial and agricultural wastewater and the density of the dredged mud, the IMDC study estimates the fluvial mud load at Schelle between 340.000 and 640.000 ton/y.

Around the same time that the IMDC report was written, ten Brinke (1992a; 1992b) published his two reports on mud in the Scheldt estuary. The main goal of these reports was not to develop a mud balance for the Scheldt but to quantify the uncertainties and knowledge gaps with respect to the mud balance in the estuary. For the fluvial mud input ten Brinke (1992a) based himself on the preliminary results of the IMDC report (1993). On two points ten Brinke (1992a) adapted the fluvial input data of IMDC (1993): the matter eroded from loam soils was assumed to be mud for 50-100%, compared to 100% in the IMDC report and a fixed density is used for the dredged material. Ten Brinke (1992a) estimates the fluvial input of mud at Schelle between 100.000 and 601.000 ton/y.

Vereeke (1994) updated the mud balance of van Maldegem (1993). For the fluvial input Vereeke used the data of Ten Brinke (1992) and information of the measured mud transport (Claessens, 1993a). An average input of fluvial mud at Schelle of 350.000 ton/y is assumed. Vereeke (1994) warns for the high spread both between years and within a year. Yearly average values vary between 200.000 and 600.000 ton/y.

Table 13 – Sources of terrestrial mud in the Scheldt catchment area [10³ ton/y] based on (IMDC, 1993). 1Upper Scheldt + Dender + Upper Sea Scheldt basin; 2Dijle + Zenne + Nete + Demer basin (Source: Verlaan, 1998)

Sources of fluvial mud	Leie basin	Scheldt basin[1]	Rupel basin[2]	Lower Sea Scheldt basin	Total mud production
Domestic	31	36	67	13	147
Industrial	14-24	14-20	28-35	12-25	68-104
Agriculture	2-18	0	2-16	0	4-34
Atmospheric	0.2	0.3	0.3	0.4	1.2
Erosion	65-130	209-418	161-322	1.5-3	436-873
Total	112-203	259-474	258-440	27-41	656-1159

Table 13 and Table 14 represent the terrestrial mud production, dredging amounts and the terrestrial mud available for transport as calculated by IMDC (1993) and updated by Ten Brinke (1992) and Verlaan (1998). Ten Brinke (1992) increased the uncertainty of the erosion part (50-100% mud). Verlaan (1998) fixed the average density of the dredging material based on the consolidation time at 1.3 ton/m³ or 0.45 ton dry matter per m³.

Table 14 – Terrestrial mud production, dredging amounts and terrestrial mud available for transport [10^3 ton/y] based on IMDC (1993) (Source: Verlaan, 1998)

	Leie basin	Scheldt basin	Rupel basin	Mud entering the mixing zone
Mud production	112-203	259-474	258-440	
Dredging	118	254	156	
Available for transport	0-85	5-220	102-284	107-589

Based on literature Taverniers (1999) estimated the average fluvial mud supply to the Scheldt at Schelle slightly above 400.000 ton/y. According to Taverniers (1999) the fluvial mud supply of 970.000 ton/y proposed by Nihoul and Wollast (1976), 507.700 ton/y proposed by Wollast and Marijns (1981) and the upper limit of 640.000 ton/y suggested by the IMDC report (1993) overestimate the real value.

Between 1992 and 1999 the division maritime Scheldt of the Flemish government (Claessens, 1992, 1993; Taverniers 1994, 1995, 1996, 1997, 1998, 1999) yearly published the fluvial mud balance of the Lower Sea Scheldt. Reported values are based on continue discharge measurements and weekly measurements of suspended matter. Water samples to determine the suspended matter concentration are taken at the position of the discharge stations in Merelbeke (the upper end of the tidal influenced estuary) and Dendermonde (Appels), Eppegem, Haacht, Itegem and Grobbendonk, on the five most important tributaries of the River Scheldt. Values are included in table 14.

Table 15 – Overview of the fluvial input of mud at Schelle. Early reported values (indicated with *) do not account for decomposition of the organic fraction in the mud. [ton/y]

Jaar	Nihoul en Wollast (1976)	Wollast en Marijns (1981)	Salomons et al. (1981)	Holland e.a. 1991 (SAWES-invent.)	van Maldegem (1993)	IMDC (1993)	ten Brinke (deel1) 1992	Vereeke (1994)	Taverniers (1999)	Claessens en Taverniers (1992-1999) (Methode 2)	Van Hoestenberghe et al. 2013 (Interpolation)	Van Hoestenberghe et al. 2013 (method 1)	Van Hoestenberghe et al. 2013 (method 2)
1964-1972											239.166	211.573	191.099
1973											244.425	204189	190.970
1974											836.040	729.448	573.679
1975											326.918	321.687	327.889
1976	970.000*										250.636	233.724	219.384
1977											332.456	266.912	282.087
1978											324.171	268.073	249.759
1979			800.000*		260.000 - 300.000			350.000			417.321	348.816	313.363
1980				400.000					400.000 - 450.000		376.947	301.304	278.838
1981		507.700*		470.000							439.129	353.342	373.751
1982				360.000							368.117	305.348	275.615
1983				350.000							250.641	232.983	228.041
1984				440.000							413.048	341.549	390.259
1985				351.000							282.341	250.310	244.847
1986				370.000							266.286	261.312	205.573
1987				490.000							336.923	281.439	241.519
1988				552.000							420.680	382.657	278.598
1989						340.000 - 640.000	100.000 - 601.000				195.776	177.083	167.388
1990											131.503	119.954	134.812
1991											170.505	142.830	150.975
1992										230.000	203.417	183.240	185.711
1993										202.000	225.323	186.161	187.114
1994										189.000	218.690	183.347	183.235
1995										163.250	191.785	170.950	162.344
1996										88.000	103.464	84.572	88.305
1997										94.000	102.928	97.015	93.997
1998										250.000	276.766	239.840	254.588
1999										320.000	433.125	338.085	327.919
2000											295.772	256.822	269.740
2001											504.090	429.955	431.874
2002											420.918	367.264	366.777
2003											199.150	166.479	170.098
2004											170.614	138.428	139.875
2005											155.007	138.953	133.129
2006											156.865	128.191	133.876
2007											213.431	176.325	184.397
2008											232.494	200.756	192.909
2009											185.736	159.101	148.394

8.1.2 Fluvial mud load input Lower Sea Scheldt

The total input of fluvial mud in the Lower Sea Scheldt is determined by the fluvial input at Schelle, discussed above, and the lateral mud supply in the zone between Schelle and the Belgian-Dutch border.

Nihoul and Wollast (1976) first estimated a lateral mud influx in the Lower Sea Scheldt of around 550.000 ton/y. Later Wollast and Marijns (1981) calculated the additional lateral input of mud to be 245.000 ton/y of which 47.000 ton originates from domestic waste, 154.000 ton from industrial waste and 44.000 ton from natural sources. Baeyens et al. (1998) estimates that from the 245.000 ton/y about 111.000 ton/y (the inorganic fraction) reaches the estuary.

The value of 1.000.000 ton/y given by Manni (1986) is based on a literature review including the work of Nihoul and Wollast (1976), Wollast and Marijns (1981) and Salomons et al. (1981).

van Maldegem (1993) based also the lateral supply of mud in his mud balance on the data given by Wollast and Marijns (1981). From the total amount of 245.000 ton mud that is yearly produced in the Lower Sea Scheldt basin downstream Schelle, 111.000 ton/y is inorganic. The organic part is estimated to deteriorate for 2/3 before entering the Lower Sea Scheldt, resulting in a lateral supply of 155.000 ton/y.

Table 16 – Overview of the total fluvial input of mud at Lower Sea Scheldt (Schelle + lateral inflow Lower Sea Scheldt). Early reported values (indicated with *) do not account for decomposition of the organic fraction in the mud. [ton/y]

Jaar	Nihoul en Wollast (1976)	Wollast en Marijns (1981)	Manni (1986)	Van Maldegem (1993)	IMDC (1993)	Vereeke (1994)	Verlaan (1995)	Claessens en Taverniers (1993-2000)	Bouve et al. (1995)	Cauwenberghs (1999)	Sas et al. (2007)	Claus et al. (2009) method 1	Claus et al. (2009) method 2
1964-1972													
1973													
1974													
1975													
1976	1.520.000*												
1977													
1978													
1979							375.000						
1980				420.000		390.000			400.000				
1981		753.000*											
1982													
1983													
1984													
1985													
1986			1.000.000 *										
1987													
1988													
1989					300.000 - 681.000								
1990													
1991													
1992								250.000				230.496	236.216
1993								210.000				191.131	201.569
1994								200.000				184.129	189.042
1995								172.610		310.000		167.612	158.899
1996								94.000				83.883	89.708
1997								100.200				99.188	91.898
1998								265.000				237.522	257.875
1999								336.500				313.264	328.272
2000											310.000	264.682	287.881
2001											482.000	429.717	452.016
2002											425.000	372.269	384.461
2003											200.000	165.211	177.588
2004											165.000	136.161	144.943
2005											160.000	136.716	137.189
2006												162.209	141.262
2007												200.277	189.937
2008													
2009													

In the SAWES report of Holland et al. (1991) the lateral mud inflow between Schelle and the border from 1980 and 1988 is estimated between 45.000 – 50.000 ton/y. Because the exact values are difficult to read from the graph in Holland et al. (1991) is was chosen not to include them in Table 16.

In the IMDC report (1993) the total mud supplied to the Lower Sea Scheldt is between 300.000 – 680.000 ton/y. Compared with the supply at Schelle, a lateral input between 10.000 and 42.000 ton/y is assumed. This input is smaller than what was reported in the SAWES report (Holland, 1991). According to the IMDC report (1993), this is due to an overestimation of the contribution from the polder water and the fact that dredging activities are not taken into account in the SAWES report.

The lateral mud input to the Lower Sea Scheldt proposed by Vereeke (1994) is 40.000 ton/y. Vereeke obtained this value from the SAWES and IMDC (1993) reports. Both projects report similar values for the lateral mud input, however, the SAWES method used an extrapolation of measuring data, while the IMDC method summed all sources of mud in the estuary.

Verlaan (1995) measured the suspended matter concentration and the freshwater discharge every month at six locations on the edge of the estuarine zone. The transport of fluvial material was derived from the quarterly average suspended matter concentration multiplied by the quarterly averaged river discharge, with corrections for peak discharge and extra mud supply within the Lower Sea Scheldt. In the period 1973-1986 the annual mud discharge varied between 300.000 and 800.000 ton with a mean of 390.000 ton/y. In the period 1964-1986 the mean annual mud discharge was 375.000 ton/y.

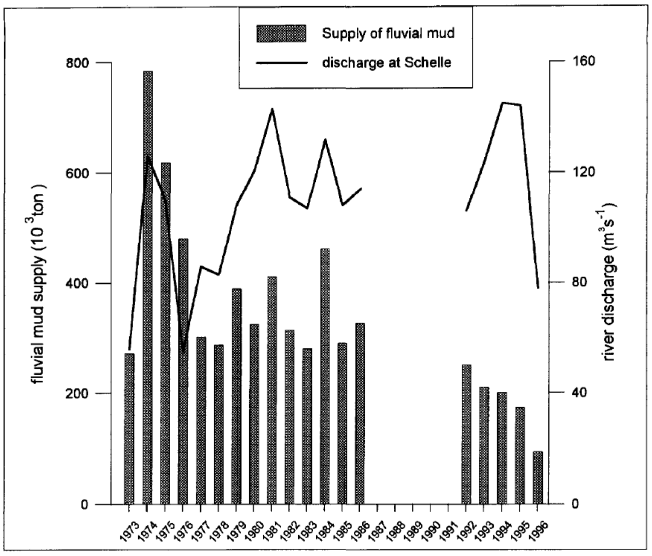


Figure 53 – Annual fluvial mud supply to the Lower Sea Scheldt based on monthly SSC and discharge measurements between 1973-1986 and weekly measurements since 1992. (Source: Verlaan, 1998)

From 1973 to 1986 the suspended matter concentration and freshwater discharge were measured monthly at six location on the edge of the estuarine zone. By multiplying the quarterly average suspended matter concentration with the quarterly averaged river discharge an estimation was made for the total fluvial mud supply (Figure 53). Corrections were made for the peak discharges and supply of the Lower Sea Scheldt (Claessens, 1993a).

The yearly reports of the fluvial mud balance of the Sea Scheldt published by Claessens and Taverniers between 1992 and 1999 calculate the lateral supply of mud between Schelle and the Belgian-Dutch border based on the suspended sediment transport of the Rupel basin. The Rupel basin is assumed to have similar characteristics than the lateral basin of the Lower Sea Scheldt. Therefore, the lateral mud supply is calculated as 12%, being the ratio between the area of the lateral Lower Sea Scheldt and the Rupel, of the mud discharge of the Rupel. Between 1992 and 1999 the average the lateral mud supply of the Lower Sea Scheldt was 11.500 ton/y, with a minimum of 6000 for the year 1996 and a maximum of 20.000 for the year 1992.

Based on erosion, waste water discharge and overflow of sewer system data collected between 1994 and 1998, the first report of the working group “duurzame ontwikkeling” in the framework of the policy plan “sanering van de waterbodem Beneden-Zeeschelde” (Cauwenberghs, 1998) presented a new calculation of the fluvial mud import into the Lower Sea Scheldt. Based on an average erosion value of 7.5 ton/ha/y Cauwenberghs (1998) estimates the sediment load originating from erosion on about 185.000 ton/y. The load from waste water is calculated as 125.000 ton/y, resulting in a total load of 310.000 ton/y.

Finally Sas et al. (2007) and Claus *et al.* (2009) applied a similar methodology as used by Taverniers (1999) to calculate the fluvial mud load imported in the Lower Sea Scheldt for the years between 2000 and 2007 and 1992 and 2007, respectively. Results can be read from Table 16.

8.1.3 Mud transport towards the Antwerp harbours

8.1.4 Sedimentation of fluvial mud in Lower Sea Scheldt

An overview of the sedimentation in the Lower Sea Scheldt presented in literature for different time periods is shown in Table 17. Below the origin of the different values is briefly explained.

The estimations of Nihoul & Wollast (1976) and Salomons *et al.* (1981) are based and discharge and turbidity measurements at Rupelmonde and the Dutch-Belgian border. A short clarification is given in section 8.1.5. From the difference between mud flux in Rupelmonde and at the border results in an estimation of the sedimentation in the Lower Sea Scheldt.

Manni (1986) estimates the sedimentation of mud in the Lower Sea Scheldt to be minimum 10%, maximum 50% and on average 30% of the fluvial import. Based on the fluvial mud import of 1.000.000 ton/y he projects the sedimentation in the Lower Sea Scheldt is around 300.000 ton/y.

Van Eck (1991) proposes a sedimentation of fluvial mud in the Lower Sea Scheldt of 67.000 ton/y. The calculation method for this quantity is not specified.

van Maldegem (1993) did a detailed study on the sedimentation on the different morphological units (shoals, channel, tidal flats and marshes) in the Scheldt estuary. For the marshes van Maldegem (1993) took a mud accumulation of 13 cm/y, resulting for the Lower Sea Scheldt (170 ha) in 22.000 ton/y (F+M). Additionally van Maldegem (1993) took into account a net removal of 60.000 ton/y in the Lower Sea Scheldt due to dredging (dredging: 112.000 ton/y; disposal 52.000 ton/y). Including the mud accumulated in the harbours (±120.000 ton/y), 120.000 ton/y of the fluvial mud is retained in the Lower Sea during the period 1975-1985, or about one third of the fluvial load imported in the Sea Scheldt.

In the updated balance of Vereeke (1994) the mud percentage of the material deposited in the marshes is taken 50% (against 100% by van Maldegem 1993, the deposition rate was kept at 13 cm/y) reducing the deposition to 8.000 ton/y (5/8 is fluvial, 3/8 is marine mud). The net dredging amount is chosen at 240.000 ton/y, about 170.000 ton is of fluvial and 70.000 ton is of marine origin.

In the IMDC (1993) report the sedimentation in the Lower Sea Scheldt was calculated using a mathematical model based on critical shear stress for erosion, critical shear stress for deposition, erodibility constant and the settling velocity. A sedimentation of 510.000 ton/y (F+M) was obtained for the Sea Scheldt.

The total sedimentation value of Verlaan et al. (1997) is determined by comparing the bottom maps of Bastin for 1964 and 1986. Based on the difference in mud stock between these maps a sedimentation of 100.000 ton/y was found. Accounting for a dredging of about 150.000 ton/y results in a total sedimentation of around 250.000 ton/y (F+M).

The budgets of Salden (1998) aim to estimate the amount of mud removed from the bottom of the estuary due to the intensive dredging in the nineties and are therefore not ideally suited to estimate the sedimentation. However, in the Kallolock (the most important area of mud accumulation in the Lower Sea Scheldt) a sedimentation of 240.000 ton of fluvial and 60.000 ton of marine mud was assumed.

In the particulate matter flow balance of Baeyens *et al.* (1997) a sedimentation of 279.000 ton/y of fluvial and 85.000 ton/y of marine mud is given. The mass transport is based on turbidity and water flows.

Finally Wartel *et al.* (2007) used again the bottom maps of Bastin (1964 and 1986) and the bottom map of Wartel *et al.* (2000). The bottom maps of 1964 and 1986, updated with the information of Wartel *et al.* (2000), indicated a yearly increase of 82.000 ton of mud, of which about 55% is deposited in the access channels of the Zandvliet but especially the Kallolock. An additional 12.000 ton mud is deposited on the marshes in the Lower Sea Scheldt. Unlike Verlaan *et al.* (1997), Wartel *et al.* (2007) did not correct for dredging during this period. For the period 1986-1999 Wartel *et al.* (2007) calculated an increase in bottom mud of 131.000 ton/y (including 91.000 ton/y removed by dredging) the deposition of mud on the salt marshes was kept constant (12.000 ton/y).

Table 17 – Sedimentation of mud in the Lower Sea Scheldt. Fluvial mud (F) is shown in green, marine mud (M) is shown in blue. The total amount of mud (F+M) is shown in black [ton/y].

Year	Nihoul en Wollast (1976)	Salomons et al. (1981)	Manni (1986)	Van Eck (1991)	van Maldegem (1993)	IMDC (1993)	Vereeke (1994)	Verlaan et al. 1997	Salden (1998)	Baeyens (1998)	Wartel et al. (2007)
1964-1972											
1973											
1974											
1975											
1976	1.200.000 (F) 800.000 (M)	460.000 (F) 200.000 (M)									
1977											
1978								250.000 (F+M)			94.000 (F+M)
1979					120.000 (F) 80.000 (M)						
1980											
1981											
1982										279.000 (F) 85.000 (M)	
1983											
1984				67.000 (F) 16.000 (M)							
1985											
1986			300.000 (F) 0 (M)								
1987											
1988											
1989						510.000 (F+M)					
1990											
1991											
1992							174.000 (F) 74.000 (M)				142.000 (F+M)
1993									240.000 (F) 60.000 (M)		
1994											
1995											
1996											
1997											
1998											
1999											

8.1.5 Fluvial mud transported across the Belgian - Dutch border

Because of the importance of mud in the transportation of pollutants and heavy metals, the mud load transported over the Belgian-Dutch border has been an political issue between Belgium and the Netherlands. Moreover, the border roughly coincides with the downstream end of the maximum turbidity zone were the mud is kept under influence of the tidal wave coming from downstream and upstream river flow. As a result a number of authors have tried to quantify the mud load transported over the Belgian-Dutch border.

Bakker (1975) and Swart (1983) used stream velocity and mud concentration measurements at the border to estimate the net transport of mud by advection and diffusion. The transports of mud were in the order of 600.000 to 800.000 ton/y.

Based on measurements (4 times a year during 5 days for 3 years) of suspended and dissolved compounds at different locations along the estuary, Nihoul and Wollast (1976) estimate the transport of mud over the Belgian-Dutch border around 320.000 ton/y. Because Nihoul and Wollast (1976) calculated the fluvial input in the Lower Sea Scheldt at 1.520.000 ton/y (Table 16), this implies a sedimentation of 1.200.000 ton of fluvial mud per year.

Salomons et al. (1981) evaluates the mud transport using indirect measurements of turbidity at different locations along the estuary. The transportation of fluvial mud from the Lower Sea Scheldt to the Western Scheldt is calculated as 340.000 ton/y. Previously the fluvial mud supply at Schelle was determined 800.000 ton/y, resulting in a sedimentation of fluvial mud in the Lower Sea Scheldt of 460.000 ton/y.

Other authors (Table 18) calculated the transportation of fluvial mud across the Dutch-Belgian border as the difference between the fluvial input and the mud sedimentation in the Lower Sea Scheldt. An exception is Salden (1998) who assumed a transport of only that part of the mud that stays in suspension (estimated at one third).

Table 18 – Mud transported across the Dutch-Belgian border. For Salden (1998) two values are presented, A is based on the data of Claessens (1993,1994) and Taverniers (1995-1997), B is updated using additional field data. [ton/y]

Year	Bakker (1975) - Swart (1983)	Nihoul en Wollast (1976)	Salomons et al. (1981)	Manni (1986)	Van Eck (1991)	v. Maldegem (1993)	IMDC (1993)	Vereeke (1994)	Verlaan et al. 1997	Salden (1998) A	Salden (1998) B	Baeyens (1998)	Wartel et al. (2007)
1964-1972									175.000 (F) 100.000 (M)				306.000 (F) -
1973													
1974													
1975	600.000-800.000 (F)					300.000 ±160.000 (F) 80.000 ± 50.000 (M)							
1976		320.000 (F) 800.000 (M)	340.000 (F) 200.000 (M)										
1977													
1978													
1979													
1980					365.000 (F) 16.000 (M)							153.000 (F) 85.000 (M)	
1981													
1982													
1983													
1984													
1985													
1986				700.000 (F) 0 (M)									
1987													87.000 (F) -
1988													
1989							0 - 190.000 (F) 9.000-20.000 (M)						
1990													
1991													
1992								121.000 (F) 130.000 (M)					
1993										73.000 (F) 53.000 (M)	100.000 (F) 80.000 (M)		
1994													
1995													
1996													
1997													
1998													
1999													

Cleveringa & Dam (2013) and Dam & Cleveringa (2013) also present values for an estimated flux over the Dutch-Belgian border. Their work is covered in §10.17.

8.1.6 Lateral inflow in the Eastern side of Western Scheldt

The lateral inflow of fluvial mud in the eastern part of the Western Scheldt is relatively low. Some previous studies therefore do not take it into account. Since 1988 part of the Zoommeer in the Netherlands drains to the Scheldt estuary. In 1988 the mass of mud transported through this connections was estimated at 16.000 ton/y (IMDC, 1993). About 70% of the mud of the Zoommeer is discharged in Dutch area (Bath) and 30% flows into the Antwerp harbours at the right bank. Other lateral sources are the polders and some industrial discharge. The entire Western Scheldt drains about 1410 km² of polder area.

Table 19 – Lateral inflow of fluvial mud in the eastern side of the Western Scheldt [ton/y]

Year	van Maldegem (1993)	IMDC (1993)	Vereeke (1994)
1975			
1976			
1977			
1978			
1979			
1980	20.000		
1981			
1982			
1983			
1984			
1985			
1986			
1987			
1988			
1989		16.000	
1990			
1991			
1992			
1993			5.000
1994			

8.1.7 Sedimentation of fluvial mud in the eastern side of the Western Scheldt

The eastern side of the Western Scheldt is an important sedimentation area, especially on the salt marshes of the Verdronken land of Saeftinghe large amounts of mud are deposited. More details on the sedimentation in the salt marsh will be given in §9.4.

Manni (1986) assumes the average sedimentation of fluvial mud on tidal flats, shoals and in the channel at respectively 5, 5 and 10% of the fluvial input. The maximum sedimentation of fluvial mud on tidal flats, shoals and in the channels is about 15, 10 and 10%, respectively. Starting from a fluvial input to the Western Scheldt of 700.000 ton/y, the sedimentation of fluvial mud in the eastern part of the Western Scheldt proposed by Manni is 140.000 ton/y.

The fluvial mud deposition proposed by Van Eck (1991) of 212.000 ton/y is high. This is caused by the fact that van Eck (1991) assumes 50% of the fluvial mud supply to deposit on the Verdronken Land van Saeftinghe.

Also Van Maldegem (1993) calculated a high sedimentation (170.000-510.000 ton/y) in the Verdronken land van Saeftinghe. For the different morphological units in the eastern side of the Western Scheldt Van Maldegem (1993) concluded erosion of 126.000 and 15.000 ton/y for respectively the channel and shoals. During the same period there was a sedimentation on the tidal flats and salt marshes of respectively 142.000 ton/y and 323.000 ton/y. Resulting in a net sedimentation of 324.000 ton of mud per year, of which about half is of fluvial origin. About 18.000 ton of mud per year (1975-1985) is removed by dredging in the eastern side of the Western Scheldt.

Table 20 – Erosion and sedimentation of mud in the eastern side of the Western Scheldt (SAWES zones: 11-14) calculated by Vereeke (1994). Negative values represent sedimentation, positive values represent erosion. [ton/y]

Morphological units	**Fluvial mud**	**Marine mud**
Channels	+44.000	+47.000
Shoals	+15.000	+3.000
Tidal flats	-105.000	-102.000
Marshes	-60.000	-61.000
sum	-106.000	-113.000

The sedimentation or erosion on the different morphological units in the eastern side of the Western Scheldt proposed by Vereeke (1994) are given in Table 20.

The value presented by Dam & Cleveringa (2013) is based on the difference between the volume transported to the Sea Scheldt and "Verdronken land van Saeftinghe" (boundary condition) and the volume transported between macrocell 4 and 5. A dry density of 0,45 ton/m³ is used to convert the mud volume to mass. Because the boundary condition contains also the mud sedimentation on the salt marsh of "Verdronken land van Saeftinghe" this mass is not included in the presented term.

Table 21 – Sedimentation of mud in the eastern side of the Western Scheldt [ton/y]. The value presented by Dam & Cleveringa (*) is excluding the sedimentation on the "Verdronken land van Saeftinghe".

Year	Manni (1986)	Van Eck (1991)	van Maldegem (1993)	Vereeke (1994)	Dam & Cleveringa (2013)
1964-1972					
1973					
1974					
1975					
1976					
1977					
1978					
1979					
1980			160.000 (F) 160.000 (M)		
1981					
1982					
1983					
1984		212.000 (F) 70.000 (M)			
1985					
1986	140.000 (F) 245.000 (M)				
1987					
1988					
1989					
1990					
1991					
1992					
1993				106.000 (F) 113.000 (M)	
1994					
1995					
1996					
1997					
1998					
1999					
2000					
2001					
2002					52.000 (F+M)*
2003					
2004					
2005					
2006					
2007					
2008					
2009					
2010					

8.1.8 Lateral inflow in the Western side of Western Scheldt

The canal between Gent and Terneuzen drains a large part of the Leie and part of the Durme river. The average discharge of the canal is between 20 and 22 m³/s. Measurements indicate a suspended matter concentration of 10 mg/l, resulting in a yearly input of approximately 7.000 ton/y. Together with the mud input from domestic and industrial deposits and the drainage from the polders, the total lateral inflows of mud is as shown in Table 22.

Table 22 – Lateral inflow of fluvial mud in the eastern side of the Western Scheldt [ton/y]

Year	van Maldegem (1993)	IMDC (1993)	Vereeke (1994)
1975			
1976			
1977			
1978			
1979			
1980	90.000		
1981			
1982			
1983			
1984			
1985			
1986			
1987			
1988			
1989		29.000	
1990			
1991			
1992			
1993			25.000
1994			

8.1.9 Fluvial mud transported between the eastern and western side of the Western Scheldt

Based on the previously described mass balance terms, the transportation of fluvial mud from the eastern side to the western side of the Western Scheldt can be calculated. The boundary between the eastern and western part is chosen on a hypothetical North-South axis near Hansweert. The values of mud transportation from the eastern to the western side of the Western Scheldt are reported in Table 23.

The values reported in Table 23 include the anthropogenic transportation of mud due to dredging and disposal. The disposal strategy has changed over time: from disposal locations near the dredging locations before the second deepening campaign, to the oost-west-strategy after the second deepening at the end of the 1990's, back to a strategy where close the dredging locations is disposed after the third deepening (2010). Van Maldegem (1993) and (Vereeke, 1994) report the average yearly net dredging or disposal mass in the eastern and western part of the Western Scheldt. According to Van Maldegem (1993) a yearly net disposal of 18.000 ton/y took place from 1975-1985 in the eastern part, while in the same period 24.000 ton/y was disposed in the western part. Vereeke (1994) reports a net dredging in the eastern part of 27.000 ton/y (14.000 ton fluvial and 13.000 ton marine mud) during 1992-1994 and a net disposal in the western part of 31.000 ton/y (11.000 ton fluvial and 20.000 ton marine mud).

Dam and Cleveringa (2013) suggest a transport of 500.000 m³/y mud (fluvial and marine) from the western to the eastern part of the Western Scheldt. Assuming a dry density of the mud of 0,45 ton/m³ this corresponds with 225.000 ton/y.

Table 23 – Transportation of mud from the eastern to the western side of the Western Scheldt. All fluvial fluxes go in the direction of the western part. The marine fluxes go in the direction of the eastern part. [ton/y]

<table>
<tr><th>Year</th><th>Manni (1986)</th><th>Van Eck (1991)</th><th>v. Maldegem (1993)</th><th>Vereeke (1994)</th><th>Dam & Cleveringa (2013)</th></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>1964-1972</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>1973</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>1974</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>1975</td><td></td><td></td><td rowspan="11">240.000 ± 120.000 (F)
160.000 ± 120.000 (M)</td><td></td><td></td></tr>
<tr><td>1976</td><td></td><td></td><td></td><td></td></tr>
<tr><td>1977</td><td></td><td></td><td></td><td></td></tr>
<tr><td>1978</td><td></td><td></td><td></td><td></td></tr>
<tr><td>1979</td><td></td><td></td><td></td><td></td></tr>
<tr><td>1980</td><td></td><td rowspan="9">154.000 (F)
86.000 (M)</td><td></td><td></td></tr>
<tr><td>1981</td><td></td><td></td><td></td></tr>
<tr><td>1982</td><td></td><td></td><td></td></tr>
<tr><td>1983</td><td></td><td></td><td></td></tr>
<tr><td>1984</td><td></td><td></td><td></td></tr>
<tr><td>1985</td><td></td><td></td><td></td></tr>
<tr><td>1986</td><td>560.000 (F)
208.000 (M)</td><td></td><td></td><td></td></tr>
<tr><td>1987</td><td></td><td></td><td></td><td></td></tr>
<tr><td>1988</td><td></td><td></td><td></td><td></td></tr>
<tr><td>1989</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>1990</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>1991</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>1992</td><td></td><td></td><td></td><td rowspan="3">6.000 (F)
250.000 (M)</td><td></td></tr>
<tr><td>1993</td><td></td><td></td><td></td><td></td></tr>
<tr><td>1994</td><td></td><td></td><td></td><td rowspan="17">225.000 (F+M)</td></tr>
<tr><td>1995</td><td></td><td></td><td></td><td></td></tr>
<tr><td>1996</td><td></td><td></td><td></td><td></td></tr>
<tr><td>1997</td><td></td><td></td><td></td><td></td></tr>
<tr><td>1998</td><td></td><td></td><td></td><td></td></tr>
<tr><td>1999</td><td></td><td></td><td></td><td></td></tr>
<tr><td>2000</td><td></td><td></td><td></td><td></td></tr>
<tr><td>2001</td><td></td><td></td><td></td><td></td></tr>
<tr><td>2002</td><td></td><td></td><td></td><td></td></tr>
<tr><td>2003</td><td></td><td></td><td></td><td></td></tr>
<tr><td>2004</td><td></td><td></td><td></td><td></td></tr>
<tr><td>2005</td><td></td><td></td><td></td><td></td></tr>
<tr><td>2006</td><td></td><td></td><td></td><td></td></tr>
<tr><td>2007</td><td></td><td></td><td></td><td></td></tr>
<tr><td>2008</td><td></td><td></td><td></td><td></td></tr>
<tr><td>2009</td><td></td><td></td><td></td><td></td></tr>
<tr><td>2010</td><td></td><td></td><td></td><td></td></tr>
</table>

8.1.10 Sedimentation of fluvial mud in the western side of the Western Scheldt

The deposition of mud on the shoals, tidal flats and salt marshes in the western side of the Western Scheldt is on average 47.500 ton/y and maximum 165.000 ton/y (Manni, 1986). In one of the secondary channels (Middelgat) large amounts of mud are deposited (200.000 ton/y). The maximum deposition of mud is thus 365.000 ton/y. The fluvial mud concentration is about 20% in the western part of the Western Scheldt.

Due to the relatively low fluvial input (caused by including only the organic fraction of the mud) and high sedimentation of mud in the eastern side of the Western Scheldt, van Eck (1991) proposes a low sedimentation, about 18.000 ton/y, in the western part of the Western Scheldt.

For the western side of the Western Scheldt Van Maldegem (1993) calculated an erosion of 22.000 ton/y for the channel and 11.000 ton/y for the shoals. Sedimentation on the tidal flats and marshes was respectively 69.000 ton/y and 38.000 ton/y. The sum of the erosion and sedimentation adds up to a net sedimentation of 74.000 ton/y. Additionally there is net disposal of 24.000 ton/y of mud in dredging material. About 30.000 ton of the yearly sedimentation is of fluvial origin.

No major changes in the mud budget of this part of the Scheldt are reported by Vereeke (1994) in his updated version of the balance of van Maldegem (1993). The erosion and sedimentation on the different morphological units is presented in Table 24.

Table 24 – Erosion and sedimentation of mud in the western side of the Western Scheldt (SAWES zones: 11-14) calculated by Vereeke (1994). Negative values represent sedimentation, positive values represent erosion. [ton/y]

Morphological units	**Fluvial mud**	**Marine mud**
Channels	-11.000	+22.000
Shoals	+7.000	+10.000
Tidal flats	-14.000	-91.000
Marshes	-3.000	-11.000
sum	-21.000	-70.000

The value proposed by Dam & Cleveringa (2013) is based the volumetric change in the western part of the Western Scheldt and is converted to mass using a dry density of 0,45 ton/m³.

Table 25 – Sedimentation of mud in the western side of the Western Scheldt [ton/y]

<table>
<tr><th>Year</th><th>Manni (1986)</th><th>Van Eck (1991)</th><th>van Maldegem (1993)</th><th>Vereeke (1994)</th><th>Dam & Cleveringa (2013)</th></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>1964-1972</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>1973</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>1974</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>1975</td><td></td><td></td><td rowspan="11">30.000 (F)
80.000 (M)</td><td></td><td></td></tr>
<tr><td>1976</td><td></td><td></td><td></td><td></td></tr>
<tr><td>1977</td><td></td><td></td><td></td><td></td></tr>
<tr><td>1978</td><td></td><td></td><td></td><td></td></tr>
<tr><td>1979</td><td></td><td></td><td></td><td></td></tr>
<tr><td>1980</td><td></td><td rowspan="9">18.000 (F)
8.000 (M)</td><td></td><td></td></tr>
<tr><td>1981</td><td></td><td></td><td></td></tr>
<tr><td>1982</td><td></td><td></td><td></td></tr>
<tr><td>1983</td><td></td><td></td><td></td></tr>
<tr><td>1984</td><td></td><td></td><td></td></tr>
<tr><td>1985</td><td></td><td></td><td></td></tr>
<tr><td>1986</td><td>73.000 (F)
292.000 (M)</td><td></td><td></td><td></td></tr>
<tr><td>1987</td><td></td><td></td><td></td><td></td></tr>
<tr><td>1988</td><td></td><td></td><td></td><td></td></tr>
<tr><td>1989</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>1990</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>1991</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>1992</td><td></td><td></td><td></td><td rowspan="3">21.000 (F)
70.000 (M)</td><td></td></tr>
<tr><td>1993</td><td></td><td></td><td></td><td></td></tr>
<tr><td>1994</td><td></td><td></td><td></td><td rowspan="17">108.000 (F+M)</td></tr>
<tr><td>1995</td><td></td><td></td><td></td><td></td></tr>
<tr><td>1996</td><td></td><td></td><td></td><td></td></tr>
<tr><td>1997</td><td></td><td></td><td></td><td></td></tr>
<tr><td>1998</td><td></td><td></td><td></td><td></td></tr>
<tr><td>1999</td><td></td><td></td><td></td><td></td></tr>
<tr><td>2000</td><td></td><td></td><td></td><td></td></tr>
<tr><td>2001</td><td></td><td></td><td></td><td></td></tr>
<tr><td>2002</td><td></td><td></td><td></td><td></td></tr>
<tr><td>2003</td><td></td><td></td><td></td><td></td></tr>
<tr><td>2004</td><td></td><td></td><td></td><td></td></tr>
<tr><td>2005</td><td></td><td></td><td></td><td></td></tr>
<tr><td>2006</td><td></td><td></td><td></td><td></td></tr>
<tr><td>2007</td><td></td><td></td><td></td><td></td></tr>
<tr><td>2008</td><td></td><td></td><td></td><td></td></tr>
<tr><td>2009</td><td></td><td></td><td></td><td></td></tr>
<tr><td>2010</td><td></td><td></td><td></td><td></td></tr>
</table>

8.1.11 Fluvial mud exported to North Sea

Finally all fluvial mud that is not deposited in the Western Scheldt is discharged into the North Sea. Published values are presented in Table 26.

Table 26 – Fluvial mud discharged into the North Sea [ton/y]

Year	Nihoul en Wollast (1976)	Wollast and Marijns (1981)	Salomons et al. (1981)	Manni (1986)	Van Eck (1991)	v. Maldegem (1993)	IMDC (1993)	Vereeke (1994)	Baeyens (1998)	van Maldegem (1999)
1964-1972										
1973										
1974										
1975										
1976	120.000		100.000							
1977										
1978										
1979						220.000 ±160.000				
1980										
1981		300.000								
1982										
1983									133.000	
1984					136.000					
1985										
1986				487.000						
1987										
1988										
1989							0-191.000			
1990										
1991										
1992										
1993								22.000		
1994										
1995										
1996										
1997										
1998										10.000
1999										

8.2 Marine mud

8.2.1 Import of marine mud from North Sea

Based mainly on the hydrodynamics, Terwindt (1967) estimate the marine input of mud into the Scheldt to be around 1.000.000 ton/y. In the same year Wollast (1976) estimate the contribution of coarse sand transported upstream by strong bottom currents to the suspended solids mass balance by comparing the chemical composition of suspended matter carried by freshwater and by the bottom currents. Wollast (1976) concluded a load of 800.000 ton/y marine mud was transported through the lower zone and deposited in the upper zone of the Scheldt estuary. Salomons et al. (1981) projected a similar value of 930.000 ton/y of marine mud entering from the North Sea based on the sedimentation rate in different parts of the Scheldt and the ratio of fluvial and marine mud in those sections.

Manni (1986) wrote that the relatively high values of marine mud entering the Scheldt estuary mentioned by the previous authors might have been possible in the past, however in the configuration of the basin around 1986 the deposition possibilities are reduced considerably resulting in a lower import of marine mud. Using a mass balance approach Manni (1986) estimated the maximum input of marine mud to be around 500.000 ton/y.

Van Alphen (1990) discusses the mud balance in the Belgian-Dutch coastal waters. Based on empirical and mathematical modeling done by Steyaert and van Maldegem (1987), Van Alphen (1990) estimates the net deposition of marine mud in the Western Scheldt to be about 600.000 ton/y.

ten Brinke (1992a) calculated the marine mud import from the fluvial mud import, net mud accumulation in the system and the ratio between marine and fluvial mud in suspension. Accounting for uncertainties due to sedimentation rate on the marshes, yearly erosion/sedimentation from the intertidal areas and channels, net dredging from Lower Sea Scheldt and methods to determine the marine-fluvial ratio of the mud, ten Brinke (1992a) determines the import of marine mud into the Scheldt between -270.000 and 530.000 ton/y.

Also van Maldegem (1993), Vereeke (1994), Verlaan (1998) and van Maldegem (1999) use the import of marine mud from the North sea as a closing term of the mud balance. Their results for the marine mud import can be read from Table 27.

Lefèvre (2000) calculated a mud balance based on a 3D mud model. The model shows an import of mud in the order of 700.000 ton/y after the second deepening of the Scheldt. This is about double of the marine input simulated before the second deepening.

Dam & Cleveringa (2013) calculated the net transport between the North Sea and Scheldt estuary based on bathymetric changes and lithological maps of the Western Scheldt.

Table 27 – Overview of amount of marine mud [ton/y] yearly imported into the Scheldt estuary estimated by different authors.

Jaar	Terwindt (1976)	Wollast (1976)	Salomons et al. (1981)	Manni (1986)	Van Alphen (1990)	van Eck (1991)	Ten Brinke (1992)	v. Maldegem (1993)	Vereeke (1994)	Verlaan (1998)	v. Maldegem (1999)	Levèvre (2000)	Dam & Cleveringa (2013)
1964-1968													
1969					600.000								
1970-1975	1.000.000	800.000			600.000					50.000-350.000			
1976-1980													
1981-1985			930.000		600.000			320.000 ±120.000					
1986				<500.000	600.000	79.000							
1987													
1988													
1989							-270.000 - 530.000						
1990-1993									297.000				
1994-1997													
1998											130.000		333000 (M+F)
1999													
2000-2010												700.000	

8.2.2 Sedimentation of marine mud Western Scheldt and transportation to Lower Sea Scheldt

The transportation of marine mud upstream towards the Lower Sea Scheldt is caused by the tidal asymmetry of the flow in the estuary and the gravitational circulation.

The marine mud transportation and sedimentation in the Western Scheldt was included in Table 18, Table 21, Table 23, Table 24 and The value proposed by Dam & Cleveringa (2013) is based the volumetric change in the western part of the Western Scheldt and is converted to mass using a dry density of 0,45 ton/m³.

. The sedimentation and erosion and transportation quantities were obtained using the same methodology as for the fluvial mud. The fluvial-marine ratio was used to determine the quantity of fluvial and marine sedimentation or erosion.

8.2.3 Sedimentation of marine mud in Lower Sea Scheldt

The sedimentation of marine mud in the Lower Sea Scheldt as simulated by different authors is given in Table 17.

9 EXCHANGE OF MUD BETWEEN THE MORPHOLOGICAL UNITS

van Maldegem (1993) (Table 28) and Wartel & Van Eck (2000) (Table 29) present an overview of the distribution of mud on the different morphological units. In the Lower Sea Scheldt the major part of the mud is of fluvial origin. Most of this mud is stored in the bottom of the channels. On the tidal flats in the Lower Sea Scheldt there is most of the time a gradient from moderate fine sand near the water to loose mud near the marsh border. Claessens (1993a) concluded that at least 2 million ton of the mud in the Lower Sea Scheldt (6.3-7.7 million ton in 1993) is stored in tidal flats. In the access channels of the locks the bottom is covered with a layer of loose mud up to several meters. Little is known about the sediments in the upper estuary according to Wartel & Van Eck (2000).

In the eastern part of the Western Scheldt the fluvial-marine ratio is around 50%, large parts of the mud is here stored in the tidal flats and marshes ("Verdronken Land van Saeftinghe"). In the Western Scheldt most mud is stored in the channels. Nevertheless, the channels (Dutch: "geulen") and shoals (Dutch: "platen") contain over 90% sand. Concentrated bottom mud in the Western Scheldt occurs mainly at the borders of the tidal flats, marshes and harbours. The harbours in the Western Scheldt contain up to 75% of mud (Wartel & Van Eck, 2000).

Table 28 – Percentage of the bulk quantity of mud in the different morphological units (Source: van Maldegem, 1993)

Gebied	Beneden Zeeschelde		Westerschelde oost		Westerschelde west	
Morf. eenh.	fluv	mar	fluv	mar	fluv	mar
1.Geulen	31	21	5	5	7	27
2.Slikken	-	-	16	18	3	11
3.Platen	-	-	1	1	3	11
24.Havens	0	0	1	2	3	16
5.(*)	-	-	2	2	3	12
Schorren	12	8	23	26	1	3

* Overig intergetijdegebied   18 Maatgevende morfologische eenheid

The lower Sea Scheldt has predominantly mud from fluvial origin (predominantly buffered in the channels), where the Western part of the Western Scheldt has more mud of marine origin (predominantly buffered in the channels), with the Eastern part of the Western Scheldt acting as an intermediate zone with most mud buffered on tidal flats.

Table 29 – Estimated percentage of the quantity of resuspendable mud in the different morphological units. The sum per column is 100% (Source: Wartel & Van Eck, 2000)

Morfoeenheid	Westerschelde Totaal	Beneden Zeeschelde	Boven Zeeschelde
Geulen	20	61	?
Platen	10	0	0
Slikken	25	26	?
Schorren	25	7	?
Ondiepwater gebieden	10	0	0
Havens	10	6	?

An indication for the mud concentration per morphological unit in the Scheldt estuary is presented inFigure 54.

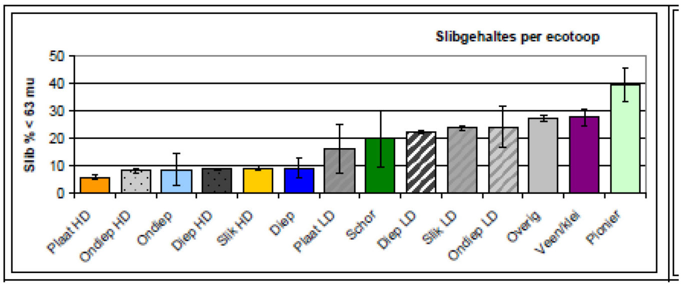


Figure 54 – Mud concentration per morphological unit and per high- and low dynamic state for the entire Western Scheldt (Source: Nolte, 2012)

Table 30 – Net sedimentation and erosion of mud in the morphological units including the dredging effects in the Scheldt estuary (Source: van Maldegem, 1993)

Morfologische eenheid	Beneden Zeeschelde	Westerschelde oost	Westerschelde west
geul	-	+126	+22
plaat	-	+ 15	+11
slik	-	-142	-69
schor	-23	-323	-38
baggeren	-60	+18	-24
	-=sedimentatie; +=erosie		

Table 30 presents the sedimentation and erosion of the mud in the morphological units as calculated by van Maldegem (1993). The erosion and sedimentation data of van Maldegem (1993) is used as a reference in many other mud balance studies.

9.1 Shoals

Quantitatively, shoals are not so important for the accumulation of mud. Less than 10% of the bulk quantity of mud in the Scheldt is stored on shoals (van Maldegem, 1993). The mud content on the shoals also varies with the seasons (at least for the area around Middelgat). In summer the shoals around Middelgat maintain relatively large and in winter relatively small quantities of mud. Because shoals are generally flooded from upstream the origin of the mud stored on the shoals is more marine than the origin in its neighbouring channels (van Maldegem, 1993).

9.2 Tidal flats

The sedimentation on the shoals and tidal flats in the western and eastern side of the Western Scheldt is shown in Table 31.

Table 31 – Yearly sedimentation of mud on the shoals and tidal flats of the Western Scheldt [ton/y] (Source: Manni, 1986)

Shoals/Tidal flats	Minimum	Average	Maximum
Western Scheldt west		18.000	90.000
Western Scheldt east		24.000	112.000

Tidal (mud) flats contain large quantities of mud, around 20% of the mud stock in the Scheldt estuary. The mud percentage varies between 20-50%, the highest concentrations are found east of Hansweert (Van Maldegem, 1993). Van Maldegem (1993) calculated changes in mud storage based on morphological changes and mud content of the bottom material. Van Maldegem (1993) assumes a dry density of 1 ton/m³. Vereeke (1994) uses the data of Van Maldegem (1993) but assumed the dry density on the tidal flats to be 1,5 ton/m³.

Ten Brinke (1992) calculated the average yearly accumulation of mud on the tidal flats and shoals between 1975-1985 and between 1975-1990. The calculated accumulation is based on yearly erosion values suggested by other authors (Van Maldegem (1993) for the period 1975-1985). For the period 1975-1985 the measured mud content on the different shoals and mud flats were used. For the period 1975-1990 these mud contents were average and a standard deviation was used. The dry bulk density of the shoals and tidal flats was assumed 1.5 ton/m³. Results are shown in Table 32.

Table 32 – Yearly mud accumulation in the tidal flats and shoals of the Western Scheldt (Source: Ten Brinke, 1992)

Vak	Accumulatie ($*10^4$ t jr^{-1}) 1975-1985	Slibgehalte %	Accumulatie ($*10^4$ t jr^{-1}) 1975-1990
1 (België)	0	-	0
2 (Hansweert-Bath)	19.0	26±20	20.8±16.0
3 (Terneuzen-Hansweert)	-1.8	20±14	6.0±4.2
4 (Vlissingen-Terneuzen)	10.5	25±19	-5.0±3.8

Wartel & Van Eck (2000) determined the accumulation rate of mud over a period from 50 to 100 years based on the depth and activity of the 210Pb isotope in the bottom sediment. Tidal flats in the Western Scheldt (Konijnenschor and Emanuelpolder) and between Tielrode and Zandvliet were examined. The accumulation rates measured by Wartel & Van Eck (2000) vary between 2.1 mm/y in the neighbourhood of Antwerp up to 17 mm/y downstream the Dutch-Belgian border (Figure 55). The average value is slightly above 6 mm/y.

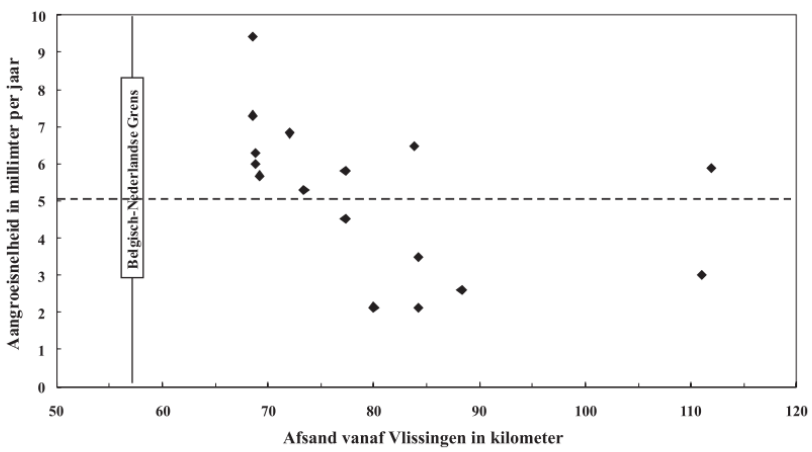


Figure 55 – Accumulation rate of sediment on the tidal flats in function of the distance to the mouth (Vlissingen) (Source: Wartel & Van Eck, 2000)

The Flemish research institute for nature and forest (INBO) closely monitored the mud accumulation in the Groot Buitenschoor since 1993. During that time the "Noordelijke Containerkaai" was constructed. Measurements show an increase around 10 cm during the considered period and a slower growth during the latest years (Verbessem *et al.*, 2010).

Chen *et al.* (2007) compared the accumulation rate of mud on the shoals and tidal flats with the average sea-level rise and rising tidal difference. The observed accumulation rates, between 0.2 and 0.7 cm/y, were higher than the sea-lever rise (about 0.1-0.2 cm/y) but correspond well with the changes in mean high water level due to the tide (around 0.5 cm/y).

Temmerman…

Lippenbroek …

9.3 Channel

9.3.1 Lower Sea Scheldt

Van Maldegem (1993) calculated the sedimentation/erosion in the channels in the same way as the sedimentation/erosion on the tidal flats, based on bathymetric changes and lithological maps. For the Lower Sea Scheldt Van Maldegem (1993) assumes no erosion or sedimentation in the channel. All mud is transported to the harbours, deposited on the marshes or removed by dredging.

As previously mentioned, the access channels retain large amounts of mud. The area of the access channel of the Kallolock is approximately 30 ha. The sedimentation in the area has been closely monitored. During the late eighties, a daily accumulation of mud around 4.000 m³/d (1,4 cm/d or 1.500.000 m³/y) were observed between (IMDC, 2004; Sas *et al.*, 2007). Assuming a dry density of 0.48 ton/m³ as proposed by (Francken *et al.*, 2000) this corresponds with a mass of 720.000 ton/y. These sedimentation values are much higher than the values proposed by Francken *et al.* (2000): 819.000 ton between 1964 and 1986 (excluding dredging).

Also in the access channel of the Berendrechtlock (35 ha) there is a significant accumulation of mud. During the construction in 1987 and 1989 sedimentation values up to 2 cm a day were observed. Francken *et al.* (2000) observed an accumulation of 184.000 m³ of mud in the access channel between 1986 and 1999 (excluding dredging).

Siltation rates at dredging locations are higher due to the continuous dredging activities, allowing repetitive siltation at these locations. In general it is assumed that siltation rates will decrease in time if the “overdepth” reduces automatically through siltation.

The long term average accumulation of mud on the bottom of the Lower Sea Scheldt is much lower, around 2 mm/y (Francken *et al.*, 2000).

9.3.2 Western Scheldt

Van Maldegem (1993) calculated a net erosion of the channels in the eastern part of the Western Scheldt of 56.000 ton of fluvial mud and 70.000 ton of marine mud. For the western part of the Western Scheldt there was an erosion of 9.000 ton of fluvial mud and a sedimentation of 29.000 of marine mud.

Ten Brinke (1992) calculated again the average yearly accumulation of mud in the channels of the Western Scheldt between 1975-1985 and between 1975-1990. The 1975-1985 data originates from van Maldegem (1993). Results are shown in Table 34.

Especially in the areas were the gradient from marine to fluvial mud is high, the flood channels contain more marine mud than the ebb channels (Van Maldegem, 1993).

The values suggested by (Manni, 1986) for the sedimentation of mud in the channels of the Western Scheldt are presented in Table 34. Especially the deposition of mud in Middelgat is significant, given the high mud concentration (up to 30%).

Table 33 – Yearly sedimentation of mud in the secondary channels [ton/y] (Source: Manni, 1986)

Secondary channels	Minimum	Average	Maximum
Western Scheldt west	100.000	200.000	300.000
Western Scheldt east	40.000	70.000	100.000

Table 34 – Yearly mud accumulation in the channels of the Western Scheldt (Source: Ten Brinke, 1992)

Vak	Accumulatie (*10^4 t jr^{-1}) 1975-1985 ongecorr.	Accumulatie (*10^4 t jr^{-1}) 1975-1985 baggercorr.	Accumulatie (*10^4 t jr^{-1}) 1975-1990 ongecorr.	Accumulatie (*10^4 t jr^{-1}) 1975-1990 baggercorr.
1 (België)	0	44.7±28.9/ 28.5±23.5	0	44.7±28.9/ 28.5±23.5
2 (Hansweert-Bath)	-20.4	-14.8±3.4	-20.7±31.3	-13.3±31.6
3 (Terneuzen-Hansweert)	26.0	19.9±3.7	6.6±6.6	-0.3±7.8
4 (Vlissingen-Terneuzen)	-29.6	-29.6	-19.1±21.8	-19.0±21.8

9.4 Salt marshes

9.4.1 Western Scheldt

The sedimentation of mud on the salt marshes can be calculated by multiplying the area of the salt marshes with their accumulation rate. Because 2730 ha of the about 3000 ha of salt marshes in the Western Scheldt are situated in the Verdronken land van Seaftinge, the accumulation rate in that area will dominate the sedimentation on salt marshes.

Four different methods have been used to estimate the sedimentation rate (Ten Brinke, 1992a):

- Based on the height of the early sandbank at the moment of planting the marsh (early thirties)
- Using calculations of changes of the amount of water stored in the marsh area during high water minus what remains during low water (Dutch: “komberging”)
- Via leveling of the topography of the marsh
- Based on radioactive isotopes

Values for yearly sedimentation on the salt marshes suggested by Manni (1986) are presented in Table 35. These values are estimated based on an average and maximum deposition of respectively 5 and 15% of the mud transported towards the Scheldt on the salt marshes.

Table 35 – Yearly sedimentation of mud on the marshes in the Western Scheldt [ton/y] (Source: Manni, 1986)

Marshes	Minimum	Average	Maximum
Western Scheldt west	7.500	29.500	75.000
Western Scheldt east	21.500	85.500	215.000

Berger & Eisma (1988) determined in 1987 the age of bottom sediments at different depths in the Emanuel marsh and at two locations in the Verdronken Land van Saeftinghe. Sedimentation rates of 1.09±0.36 cm/y were reported. Ten Brinke (1992) warns that possibly the data of Berger & Eisma (1988) was not corrected for “excess” ^{210}Pb, causing an overestimation of the sedimentation rate.

Also in 1987 the elevation of a number of cross-sections in the Verdronken Land van Saeftinghe were measured. Comparison with available profiles from 1962 and 1931 indicated a sedimentation rate between 1-2 cm/y.

van Eck & van Maldegem (1990) determined the level of the sandy sub-surface for a location in the Verdronken Land van Saeftinghe at 80 cm. Knowing the development of the marsh started in the thirties with the planting of *Spartina anglica*, the average yearly sedimentation rate is 1.38 cm/y.

Due to the sedimentation in the marshes the storage capacity for water that can flow in during high tide and back out during low tide decreases over time. Based on changes in the water storage capacity of the Verdronken Land van Saeftinghe a sedimentation rate of 2.6 cm/y is calculated (B. van Eck & Van Maldegem, 1990). The changing water storage capacity could however be influenced by the strong deposition of sand in the marsh creeks and natural levees, which implies the actual sedimentation is likely to be lower than the calculated value (Ten Brinke, 1992a). The accumulation rate used in the mud balance of van Maldegem (1993), 2,6 cm/y (assuming a mud concentration of 50% and a density of 1 ton/m³) resulting in a sedimentation of 170-510.000 ton/y could be too high (Ten Brinke, 1992a). Vereeke (1994) used a lower accumulation rate of 1.3 cm/y and a lower dry density of 0.75 ton/m³. The mud concentration was kept at 50%.

In the IMDC (1993) report the calculation using an average mud sedimentation of 340.000 ton/y resulted in unrealistic low mud concentrations in the water column. Calculation with half of this sedimentation (170.000 ton/y) gave much better results.

Table 36 – Mud deposition on the tidal marshes of the Western Scheldt, assuming a dry density of 0.75±0.13 ton/m³, a mud percentage of 50% and two assumptions for the sedimentation rate. (Source: Ten Brinke, 1992)

Vak	Oppervlakte ($*10^3$ m^2)	Accumulatie (1.09 ± 0.36 cm jr^{-1}) ($*10^4$ t jr^{-1})	Accumulatie (1.64 ± 0.66 cm jr^{-1}) ($*10^4$ t jr^{-1})
1 (België)	1800	0.7±0.2	1.1±0.2
2 (Hansweert-Bath)	24880	10.2±3.7	15.3±3.3
3 (Terneuzen-Hansweert)	720	0.2±0.1	0.5±0.1
4 (Vlissingen-Terneuzen)	2240	1.0±0.2	1.4±0.3

Dam & Cleveringa (2013) assume the sedimentation in the Verdronken Land van Saeftinghe between 300.000-600.000 m³/y. Assuming a density of 0.75 ton/m³ as proposed by ten Brinke (1992) and Vereeke (1994) and a mud percentage of 50% the annual deposition of mud is 125.000-250.000 ton/y. These values are used as a boundary condition in their calculations.

9.4.2 Sea Scheldt

Van Maldegem (1993) calculated a sedimentation of 23.000 ton/y on marshes in the Lower Sea Scheldt.

The dynamics of tidal marshes in the Sea Scheldt was studied by Temmerman (Temmerman, Govers, Meire, *et al.*, 2003; Temmerman, Govers, Wartel, *et al.*, 2003; Temmerman *et al.*, 2004). Some of the results are visualized in Figure 56. During 1931-1955 there is a strong accumulation of the young tidal marshes in the Western Scheldt, the accumulation on the older tidal marshes is significantly smaller. During 1955-2002 the sedimentation rate is lower. The sedimentation rate of the older marshes is similar to the mean high water level rise, the sedimentation on the young marshes is only slightly higher.

Based on sedimentation data obtained from Temmerman, Govers, Meire, *et al.* (2003), Wartel *et al.* (2007) estimated the annual deposition on 12.000 ton/y on the tidal marshes in the Lower Sea Scheldt.

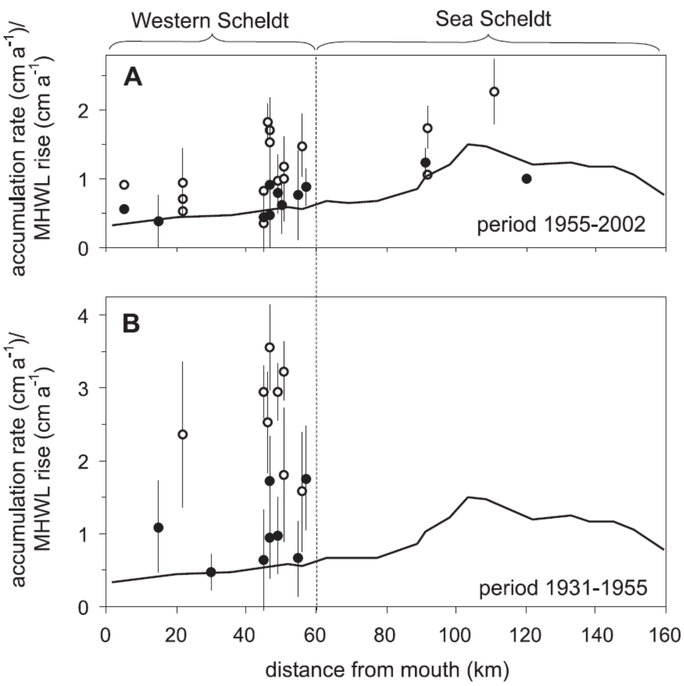


Figure 56 – Observed marsh accumulation rates (mean values in symbols and standard deviations in error bars) in relation to mean high water level (MHWL) rise (in black line) along the Scheldt estuary, for the period (A) 1955–2002 and (B) 1931–1955. Old marsh surfaces in black symbols, young marsh surfaces in white symbols. (Source: Temmerman et al., 2004)

9.5 Harbours

The mud transport towards the Antwerp harbours is discussed in chapter 8.1.3. All the mud dredged in the harbours of the Western Scheldt is pumped back into the Western Scheldt. These harbours are thus just a temporary stock of mud.

10 OVERVIEW OF REPORTED MUD BALANCES

This chapter presents an overview of published mud balances for the Scheldt estuary. Most of the individual terms have been discussed and compared in the previous chapters. In order to understand the knowledge gained since the first balances were developed, mud balances are ranked according to their publication date.

10.1 Wollast and Peters (1979)

This mud balance is sometimes also referred to as Nihoul & Wollast (1976, chapter 4) who first published the results. The values in this mud balance are based on turbidity measurements. The marine sediment transport of 800.000 ton/y occurs over the bottom of the river bed and is evaluated based on the composition of the sediments. The balance is shown in Figure 57. The lower zone extends from the sea to 50km (corresponding to the Western Scheldt), where the upper zone extends from 50km to 100km (corresponding to the Lower Sea Scheldt).

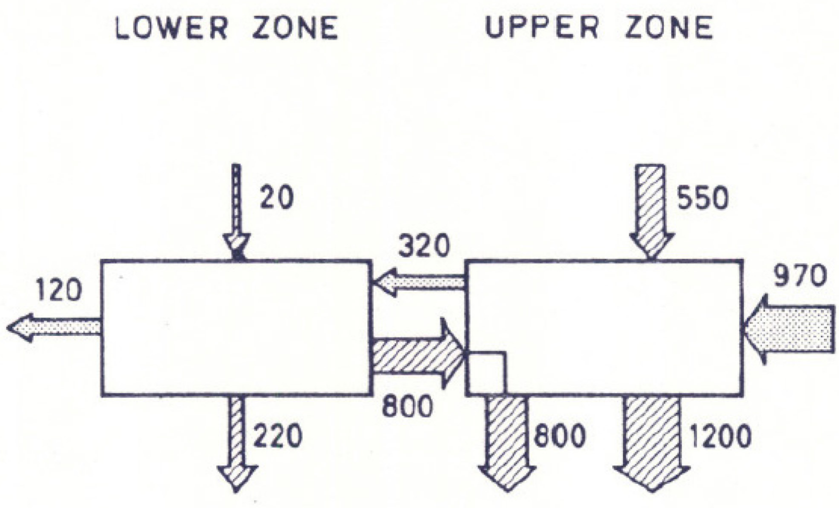


Figure 57 – Suspended matter transport in the Scheldt estuary [103 ton/y] (Source: Wollast and Peters, 1979). Values in represent fluxes in 10^3 TDS/yr. Middle arrows represent material in suspension, bottom arrows represent sedimentation.

10.2 Wollast and Marijns (1981)

The mud balance of Wollast & Marijns (1981) is based on theoretical quantities of natural, domestic and industrial sources of mud. The discharge towards the sea is estimated from about thirty turbidity profiles measured over 6 different years. Figure 58 shows the mud balance according to Wollast & Marijns (1981), values in brackets are derived from the mud balance of Nihoul & Wollast (1976).

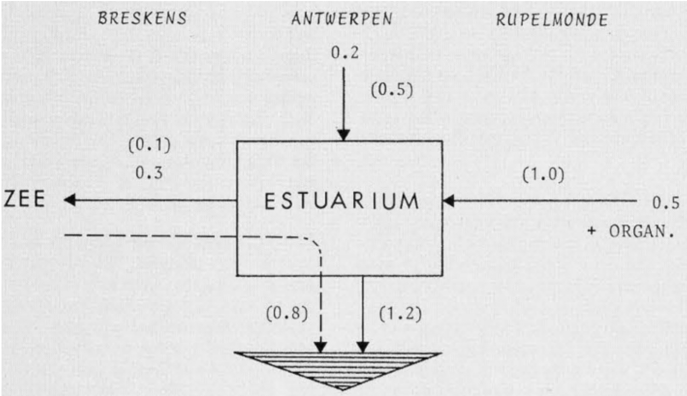


Figure 58 – Mud balance of the Scheldt estuary [106 ton/y] (Source: D'Hondt & Jacques, 1982)

10.3 Salomons et al. (1981)

The mud balance of Salomons *et al.* (1981) illustrated in Figure 59 is based on suspended sediment concentration measurements. The transport of marine and fluvial mud is indicated using respectively a dotted and full arrow.

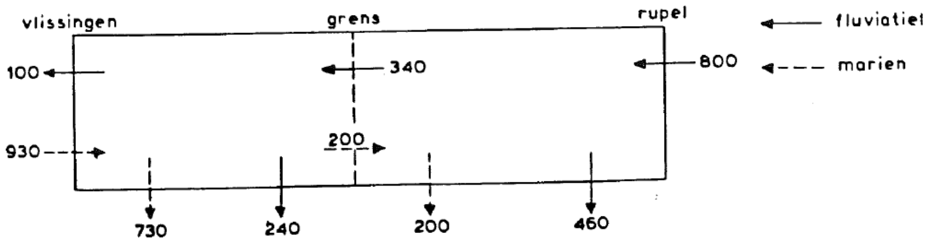


Figure 59 – Fluvial and marine suspended matter transport [103 ton/y] (Source: Salomons et al., 1981)

10.4 Manni (1986)

Based on a literature review and some own calculation Manni (1986) proposed a mud balances as shown in Figure 60. Manni (1986) applied a high fluvial input, including also organic material. Manni argued that the import of marine mud from the North sea up to 1000.000 ton/y as proposed by other authors exceeds the maximum deposition in the eastern part of the Western Scheldt. Counting back from a maximum deposition of 245.000 ton of marine mud in the eastern part of the Westeren Scheldt, Manni proposed a maximum input of 500.000 ton/y of marine mud in the Scheldt estuary.

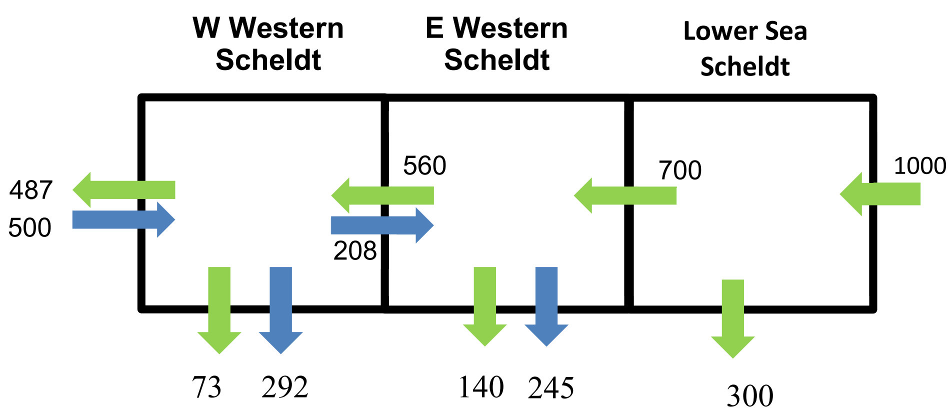


Figure 60 – Mud balance after Manni (1986) [103 ton/y]

10.5 Van Eck (1991)

van Eck (1991) considers only the inorganic part of the fluvial input, reducing the value considerably. The Western Scheldt is divided into two parts: an eastern and a western part. The Verdronken Land van Saeftinghe is the most important sedimentation area. Fifty percent of the fluvial mud is deposited on the Verdronken Land van Saeftinghe. The mud balance is shown in Figure 61.

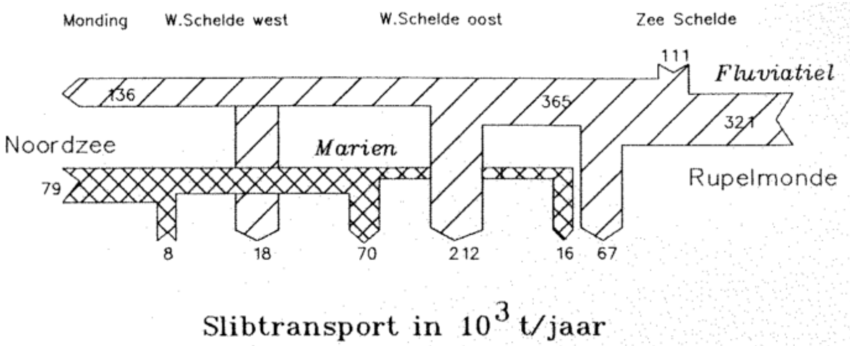


Figure 61 – Mud balance in the Scheldt estuary [103 ton/y] (Source: van Eck, 1991)

10.6 van Maldegem (1993)

The mud balance of van Maldegem (1993) represents the period 1975-1985. The balance terms are presented in Figure 62. Upper and lower limits are shown respectively above and below the arrows. According to van Maldegem (1993) about one third of the fluvial input sediments in the Lower Sea Scheldt, one third sediments in the eastern part of the Westerns Scheldt. The resulting part (also about one third) is transported towards the North Sea. Almost half of the marine mud imported from the sea is deposited in the eastern part of the Western Scheldt.

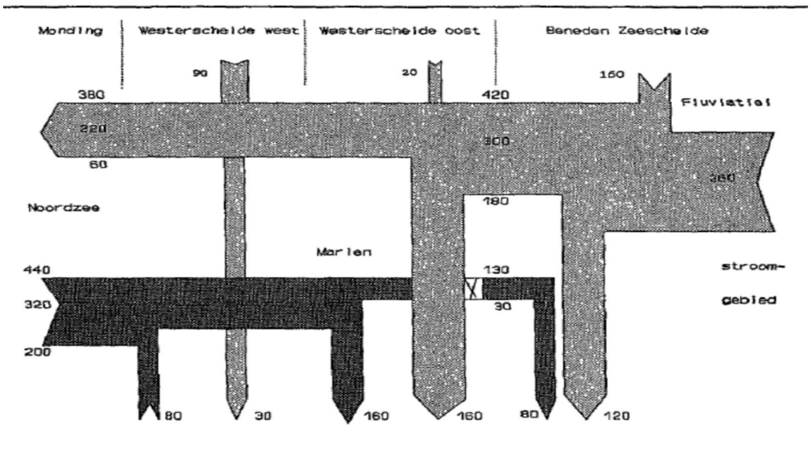


Figure 62 – Mud balance for the period 1975-1985 according to van Maldegem (1993). [103 ton/y]

The transportation of marine and fluvial mud along the longitudinal profile of the estuary as calculated by van Maldegem (1993) is shown in Figure 63. The markers present the estimated values, while the lines indicate the uncertainty interval. Note that based on a mass balance, one would expect the marine and fluviatile mud fluxes to decrease monotonically from Rupelmonde to Vlissingen. The figure below generally follows the expected trend, with the exception of transect 1314. van Maldegem (1993) attributes this to errors in the original (tracer) data.

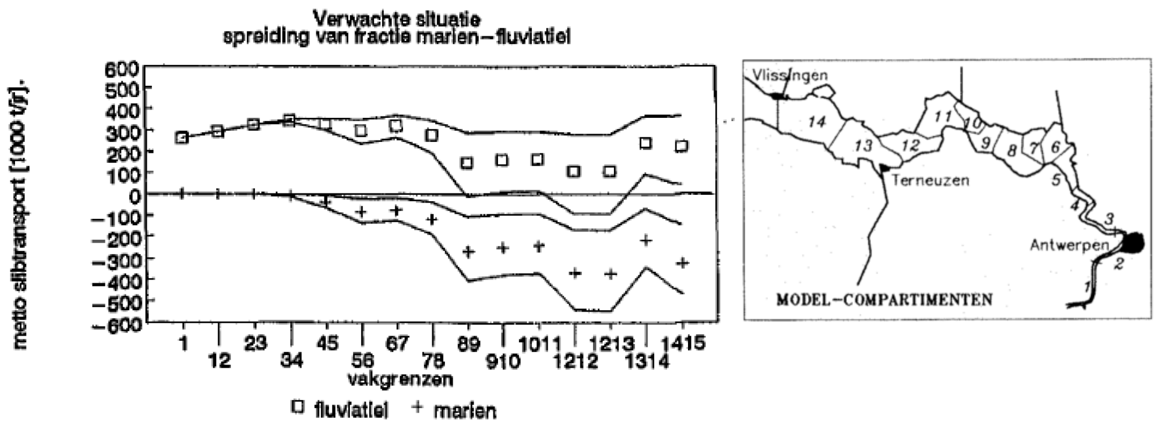


Figure 63 – Transport of fluvial and marine mud along the longitudinal profile of the Scheldt Estuary. Section 1 starts at Rupelmonde, the border between the Lower Sea Scheldt and the Western Scheldt is at 56, the mouth of the Scheldt is at 1415. (Source: van Maldegem, 1993)

10.7 IMDC (1993)

The mud balance developed by IMDC (1993) is shown in Figure 64. The main focus of the study was to improve the estimation of fluvial mud input to the Lower Sea Scheldt. The presented range (300.000-681.000 ton/y) includes the lateral inflow along the Lower Sea Scheldt estuary.

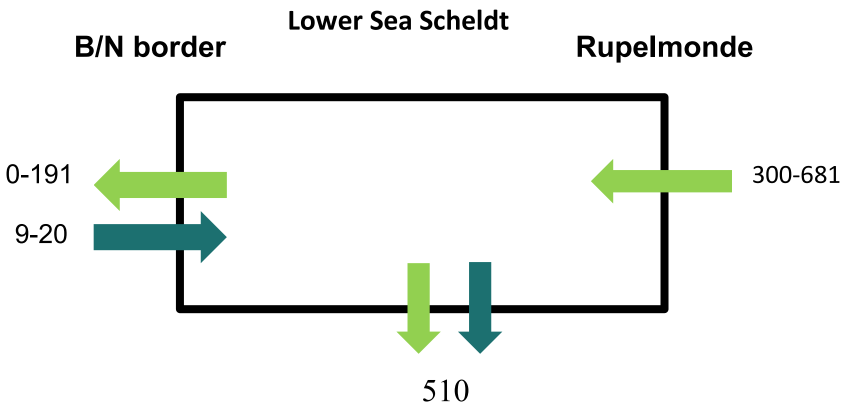


Figure 64 – Mud balance of the Lower Sea Scheldt for 1989 as developed by IMDC (1993) [103 ton/y]

10.8 Vereeke (1994)

Vereeke (1994) made an update of the mud balance of van Maldegem (1993), the balance is valid for the period after 1991 (1991-1994) when large amounts of mud were abstracted from the Antwerp harbours and Lower Sea Scheldt. The 14 (SAWES) sections were used by Vereeke. To allow comparison with other mud balances presented in this literature review the 14 zones were aggregated to 3 zones in Figure 65. Separate erosion and deposition values for the channels, shoals, tidal flats and marshes in each section are given by Vereeke (1994) but not included in Figure 65.

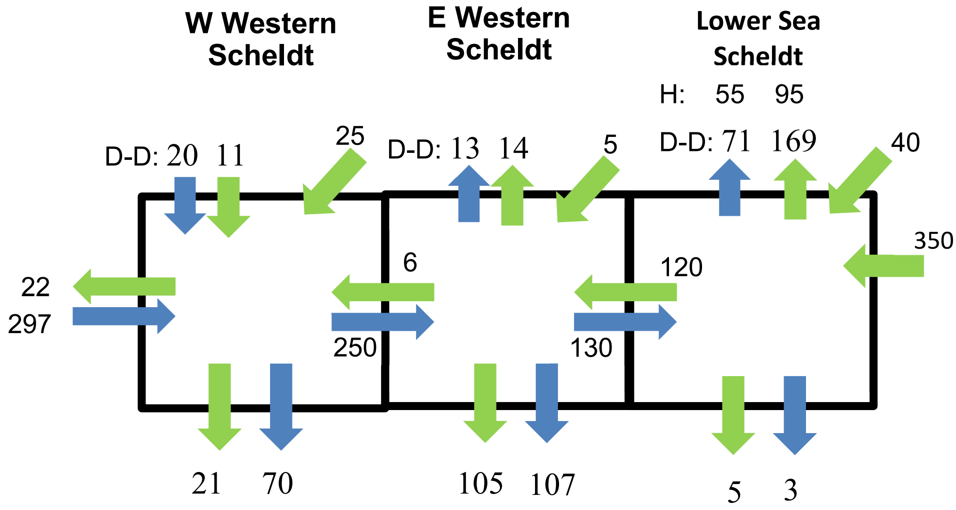


Figure 65 – Mud balance as proposed by Vereeke (1994). Arrows in blue represent marine mud, green arrows fluvial mud. H: mud abstracted to the harbours, D-D is the net balance between dredging and disposal. [103 ton/y]

10.9 Verlaan et al. (1997)

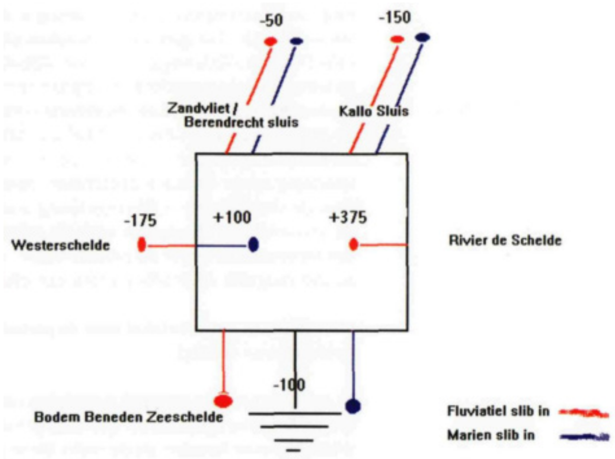


Figure 66 – Mud balance of the Lower Sea Scheldt for 1964-1986 after Verlaan et al. (1997), reported by Salden (1998). [103 ton/y]

The balance is representative for the period 1964-1986. The fluvial input is high (375.000 ton/y), sedimentation is based on the difference between the measurements of Bastin in 1964 and 1986. During this time interval the mud content increased by 2.2 million ton or about 100.000 ton/y. More correct is in fact a sedimentation of 250.000 ton/y of which 150.000 ton/ y is dredged and permanently removed. About 150.000 ton of mud flows into the harbours each year, however 100.000 ton is pumped back into the river. Given a fluvial mud concentration in the water column of 2/3, the transport over the border with the Netherlands is calculated at -175.000 ton/y fluvial mud and +100.000 ton/y marine mud.

10.10 Salden (1998) based on Claessens (1993-1994) and Taverniers (1995-1997)

During the period 1992-1996 large amounts of mud were removed from the estuarine system due to the WVO-permit with the Dutch authorities. Salden (1998) developed a mass balance based on the data given in the yearly reports on the Mud balance of the Lower Sea Scheldt by Claessens and Taverniers. In this mud balance the transport of fluvial mud towards the Western Scheldt is chosen as one third of the fluvial input (73.000 ton/y), the part of the mud that can barely deposit (van Maldegem, 1993). Based on carbon isotope measurements at the Zandvlier-Berendrecht and Kallo lock the fluvial ratio is determined at respectively 67 and 80%. The abstraction of bottom mud, due to the intensive dredging, is in this case the closing term of the mud balance.

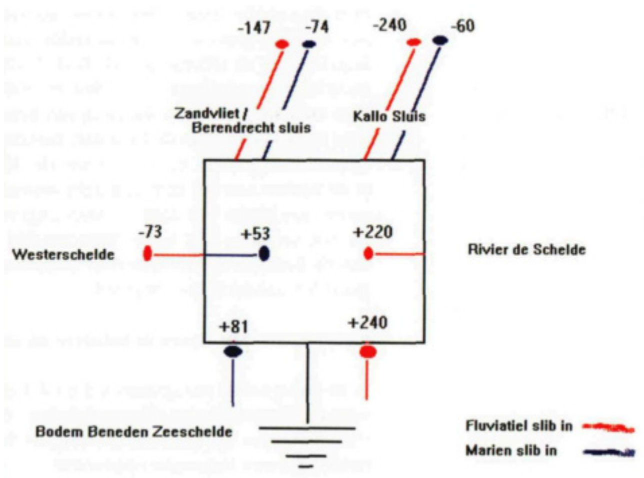


Figure 67 – Mud balance of the Lower Sea Scheldt for 1992-1996 based on fluvial mud input and dredging data of Claessens (1993 & 1994) & Taverniers (1995-1997). [103 ton/y]

10.11 Salden (1998)

Field observation around 1992-1998 showed a decrease of the fraction marine mud in the suspended matter near the Dutch-Belgian border. Salden therefore proposed an increase of fluvial mud transported to the Western Scheldt from 73.000 to 100.000 ton/y. To respect the fluvial-marine ratio also the marine import to the Lower Sea Scheldt is increased. Assuming the fluvial-marine ratio did not change at the Kallo lock to unknowns remain: the marine-fluvial ratio at the Zandvliet/Berendrecht lock and in the bottom of the Lower Sea Scheldt. A linear relation exist between the fluvial-marine ration at the Zandvliet/Berendrecht lock and in the bottom. For the lock the ratio was chosen at 60% resulting in a bottom ratio of 78%.

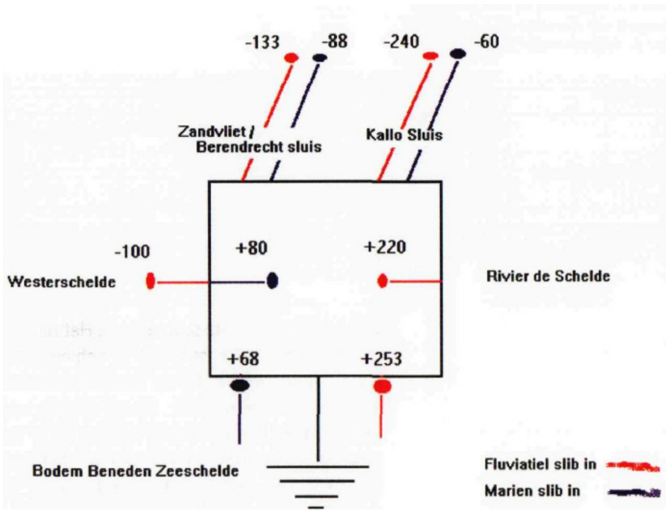


Figure 68 – Mud balance of the Lower Sea Scheldt around 1998 based on the mud balance presented in Figure 67 but updated using new field measurements. [103 ton/y]

10.12 Baeyens et al. (1998)

The mud balance presented in Figure 69 is based on the balances of van Eck (1991) and Baeyens *et al.* 1998). The balance is updated and refined for the downstream part of the estuary. The balance assumes the sediment mass balance estimates did not change substantially over a period of ten years. For zones I and II a distinction is made between the fluvial and marine mud.

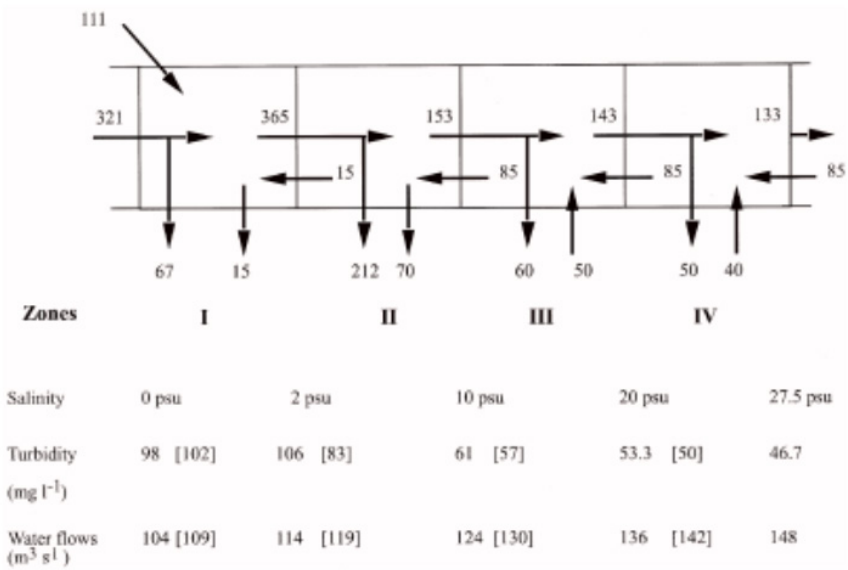


Figure 69 – Particulate matter flows for the Scheldt estuary [103 ton/y]. Zone I ranges from Rupelmonde to Antwerp, Zone II from Antwerp to the Belgian-Dutch border, Zone III from the border to 40 km from the mouth and Zone IV from 40 km to the mouth to the mouth. (Source: Baeyens et al., 1997)

10.13 Van Maldegem et al. (1999)

The mud balance of van Maldegem *et al*. (1999) describes the situation in 1998-1999, the period before the construction of the Western Scheldt tunnel (Terneuzen-Borssele). The exchange of mud with the Sea Scheldt is obtained from Salden (1998) (paragraph 10.10). The exchange of mud with the North sea is based on a mud balance developed by van Maldegem for 1995 (Van Maldegem, 1997). Van Maldegem et al. (1999) propose a sedimentation of 100.000 ton/y, however to correctly close the balance 140.000 ton/y is presented below.

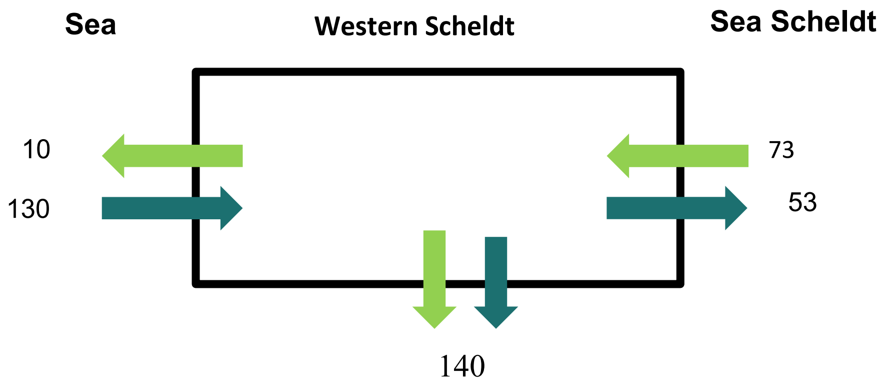


Figure 70 – Mud balance 1998-199 for the Western Scheldt as proposed by van Maldegem et al. (1999) [103 ton/y]. Blue arrows represent marine mud, green arrows fluvial mud.

10.14 Lefèvre (2000)

The mud transport model of Lefèvre (2000) is described in §3.5 . Calculations are based on an average tide condition. Despite efforts, the SLIB3D model is not able to calculate correctly the erosion of the bottom. This mechanism is however responsible for the largest part of the sedimentation in the area around the harbour docks around the Zandvliet- and Berendrechtlocks and the access channel of the Kallolock. Because these model limitations, scenarios are simulated without including the mud removal in the Kallolock and mud flow into the harbours. After comparing these scenarios the mud removal is incorporated based on expert-judgment.

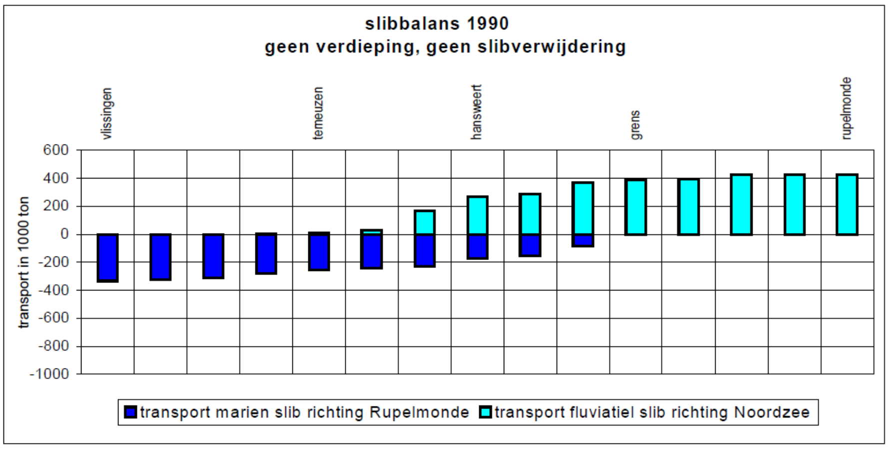


Figure 71 – Mud balance for 1990, assuming no deepening and no mud removal (Source: Lefèvre, 2000)

The mud balance of 1990, before the deepening and assuming no mud removal, is presented in Figure 71. Figure 72 shows the model results after deepening of the Western Scheldt (1997-2001). Results show a strong increase in the marine mud import from the North Sea.

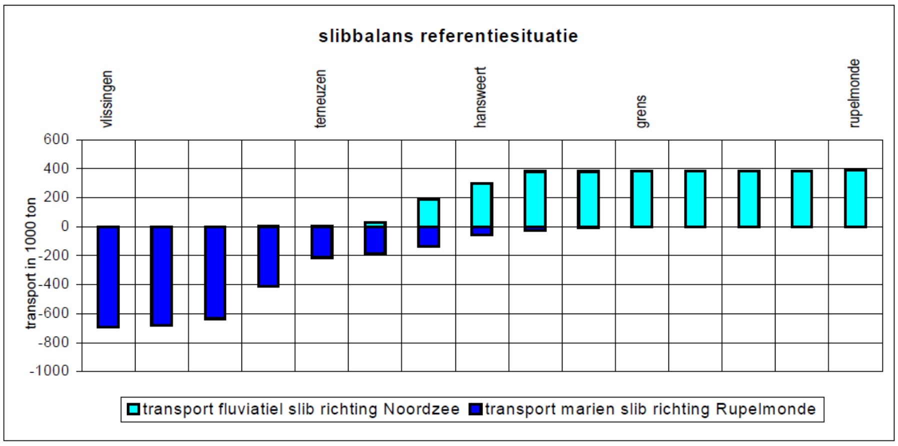


Figure 72 – Mud balance for the reference situation after completion of the second deepening (Source: Lefèvre, 2000)

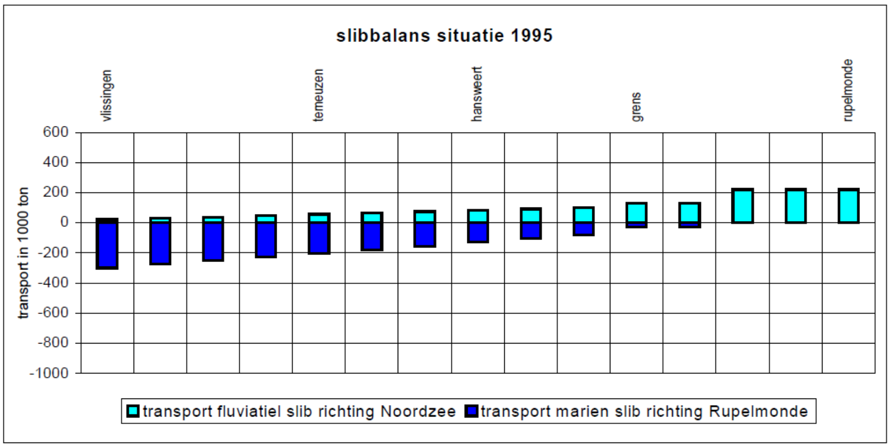


Figure 73 – Mud transport for 1995, including the mud removal in the access channel of the Kallolock but not the second deepening of the Scheldt. (Source: Lefèvre, 2000)

10.15 Wartel et al. (2007) for 1964-1986

Based on the bottom maps of Bastin 1964 and 1986 and the fluvial input, Wartel *et al.* (2007) calculated transport and accumulation of fluvial mud through the Middle estuary (Lower Sea Scheldt). The results are presented in Figure 74. For the salt marshes an average sedimentation of 500 g/m² per neap-spring cycle on the 24 km² tidal salt marsh area is assumed. Transport towards the harbours is not accounted for due to a lack of data.

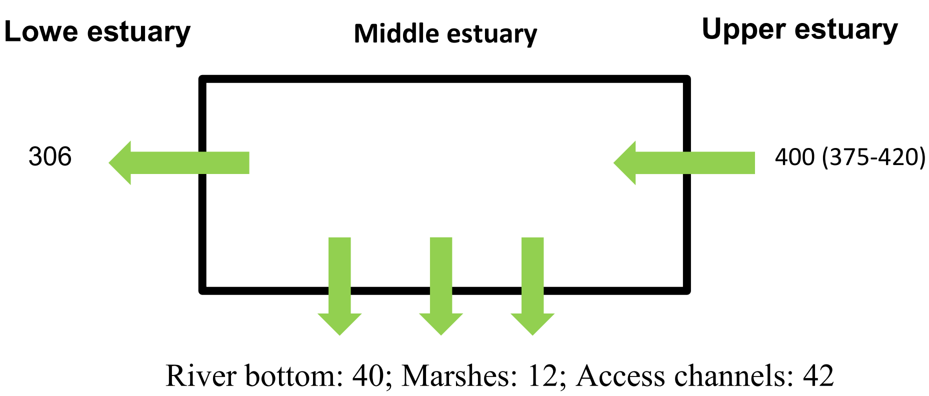


Figure 74 – Fluvial mud balance for 1964-1986 [10^3 ton/y] (after Wartel et al. 2007)

10.16 Wartel et al. (2007) for 1986-1999

The mud balance for 1986-1999 is based on the bottom maps of Bastin (1988) and Wartel *et al.* (2000). Results are illustrated in Figure 75. The value for the mass deposited on the river bottom and in the access channels include the fraction that is removed by dredging.

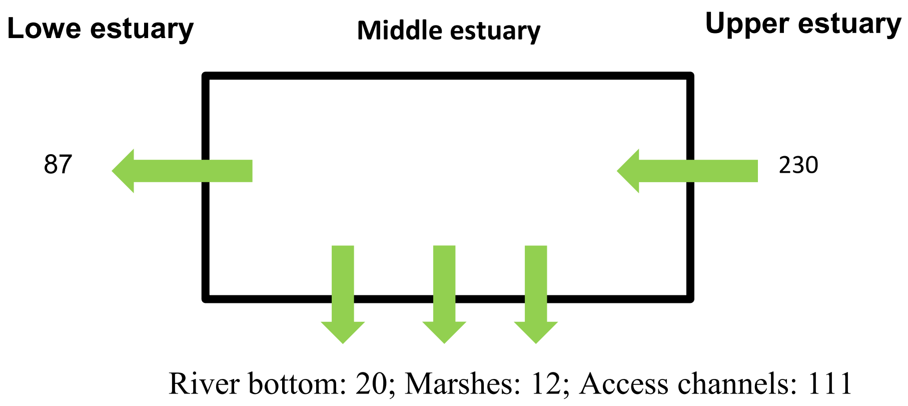


Figure 75 – Fluvial mud balance for 1986-1999 [10^3 ton/y] (after Wartel et al. 2007)

10.17 Dam & Cleveringa (2013) & Cleveringa & Dam (2013)

Cleveringa & Dam (2013) and Dam & Cleveringa (2013) applied a different approach than the other authors discussed in this literature review. The result is the yearly net transport of sand and mud along the Western Scheldt presented in Figure 76. Values in Figure 76 are given in million m³ of material. For the fine particles such as the mud the volume can be converted to mass using a dry density of 0.45 ton/m³. The latter implies an net input of mud into the Scheldt Estuary of about 333.000 ton/y between 1994 and 2010. About one third is deposited at the western side of the Western Scheldt (±108.000 ton/y), in the eastern side of the Western Scheldt the mud stock is eroded (±-50.000 ton/y).

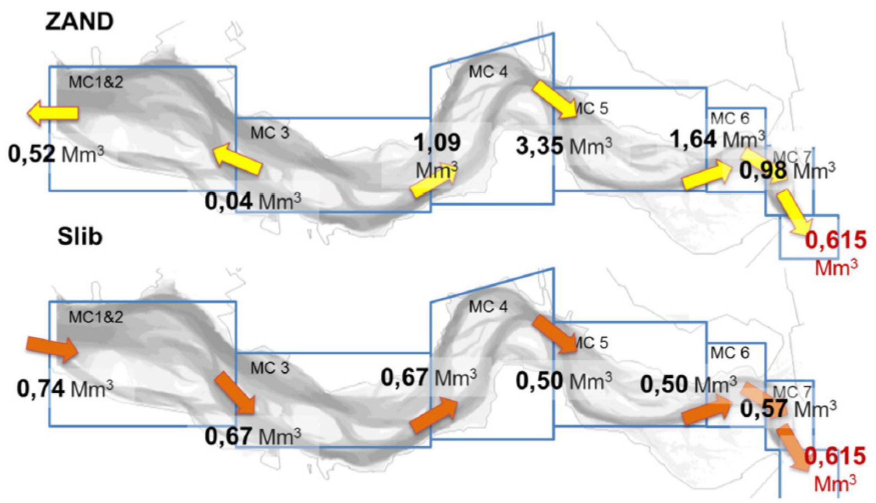


Figure 76 – Calculated yearly transport of sand (upper) and mud (lower) based on the net volume trend 1994-2010. [Mm³/y] (Source: Dam & Cleveringa (2013) & Cleveringa & Dam (2013))

The salt marsh of Saeftinghe is not included in the study area and incorporated in the transport term towards the Sea Scheldt. The transport to the Lower Sea Scheldt and the "Verdronken Land van Saeftinghe", assumed 615.000 m³ of mud per year, is chosen as the boundary condition. Using a dry density of 0.45 ton/m³ this volume corresponds with approximately 280.000 ton/y.

Based on the transport of fluvial and marine mud across the Dutch-Belgian border reported in literature (Table 18) and the estimated sedimentation on "Verdronken land van Saeftinghe" (§9.4.1) the assumed boundary condition of 615.000 m³ of mud per year to the Lower Sea Scheldt and the "Verdronken Land van Saeftinghe" is evaluated. Table 37 gives an overview of the net transport from the Sea Scheldt and "Verdronken land van Saeftinghe" towards the Western Scheldt. Calculations are made in ton/y based on data of the presented authors and converted to volumes.

As discussed in §9.4.1 the sediment accumulation on the "Verdronken land van Saeftinghe" is between 1 and 2 cm/y. Given the marsh has an area of 2730 ha and assuming a mud percentage of 50% and a dry density of 0.75 ton/m³ (Ten Brinke, 1992a) the mud accumulation is roughly between 100.000 and 200.000 ton/y. We will assume a mud sedimentation on the "Verdronken land van Saeftinghe" of 150.000 ton/y.

Dam & Cleveringa (2013) use a dry density of fine material of 0,45 ton/m³. Brinke (1992) and Vereeke (1994) suggest a dry density of 0,75 ton/m³ for the mud deposited on the "Verdronken land van Saeftinghe". For the simplicity of the calculation we will use an dry density of 0,6 ton/m³, the average of 0,45 and 0,75.

Based on the calculations shown in Table 37, the mud transported from the Western Scheldt to the Sea Scheldt and "Verdronken land van Saeftinghe" was roughly around 100.000 m³/y before 1987. In this period fluvial input was high, mud removal in the Lower Sea Scheldt was low. In the period 1988-1997, when large amounts of mud were removed in the Lower Sea Scheldt, the net transport of mud to the Lower Sea Scheldt and "Verdronken land van Saeftinghe" was around 200.000 m³/y.

These results indicate that the mud volume transported from the Western Scheldt to the Sea Scheldt and "Verdronken land van Saeftinghe" suggested by Dam & Cleveringa (2013): 615.000 m³/y is likely to be an overestimation.

Table 37 – Calculation of the mud volume transported from the Sea Scheldt to the Western Scheldt after deposition on "Verdronken land van Saeftinghe". Negative total values indicate a net transport towards the Sea Scheldt and "Verdronken land van Saeftinghe". *assuming a density of 0.6 ton/m³

Source	**time**	**Fluvial mud**	**Marine mud**	**Saeftinghe**	**Totaal**	
		[ton/y]	[ton/y]	[ton/y]	[ton/y]	[m³/y]*
van Maldegem, 1993	1975-1985	140.000 - 460.000	30.000 - 130.000	150.000	-140.000 - 280.000	-233.000 - 466.667
Verlaan et al., 1997	1973-1986	175.000	100.000	150.000	-75.000	-125.000
Baeyens et al., 1998	1980-1985	153.000	85.000	150.000	-82.000	-136.667
IMDC, 1993	1989	0 - 190.000	9.000 - 20.000	150.000	-170.000 - 31.000	-283.333 - 51.667
Vereeke, 1994	1992-1994	121.000	130.000	150.000	-159.000	-265.000
Salden, 1998 A	1992-1996	73.000	53.000	150.000	-130.000	-216.667
Salden, 1998 B	1992-1997	100.000	80.000	150.000	-130.000	-216.667
Average	< 1987				-99.000 - 41.000	-165.000 - 68.333
	> 1988				-153.000 - -86.000	-255.000 - -143.333

10.18 Final Overview

Toevoegen figuur met verschillende onderdelen en de range van transporten zoals beschreven in de verschillende rapporten. Dit geeft dan een bandbreedte van alle beschikbare historische studies.

11 REFERENCES

Baeyens, W., Adam, Y., Mommaerts, J. P., & Pichot, G. (1981). Numerical simulations of salinity, turbidity and sediment accumulation in the Scheldt estuary. Elsevier Oceanography Series, 32, 319-332.

Baeyens, W.; Eck, B. Van; Lambert, C. (1998). General description of the Scheldt estuary. *Hydrobiologia* (366): 1–14. Retrieved from http://link.springer.com/article/10.1023/A:1003164009031

Baeyens, W.; Monteny, F.; Ryssen, R. Van; Leermakers, M. (1997). A box-model of metal flows through the Scheldt estuary (1981–1983 and 1992–1995). *Hydrobiologia* 366(1-3): 109–128. Retrieved from http://link.springer.com/article/10.1023/A:1003180428595

Bakker, W.T. (1975). Het huidige slibgehalte en slibtransport in het oostelijk deel van de Westerschelde

Bastin, A. (1988). Schelde, Lithologische kaart 1986-1987

Bastin, A. (1993). Evaluatie van de hoeveelheid slib in de Beneden Zeeschelde. Evolutie tussen 1964 en 1986. Ministerie van de Vlaamse Gemeenschap. Departement Leefmilieu en Infrastructuur. Administratie Waterinfrastructuur en Zeewezen, Antwerpse Zeehavendienst. 23 pp.

Berger, G.W.; Eisma, D. (1988). Datering van sedimenten in de Westerschelde met behulp van de isotopen 134Cs, 137Cs en 210Pb.: Texel, The Netherlands. 11 pp.

Bouve, J.; Caluwe, J.; Claessens, J.; Debaene, L.; Al., E. (1995). Beleidsplan sanering waterbodem Beneden-Zeeschelde

Cancino, L., & Neves, R. (1994). 3D-Numerical modelling of cohesive suspended sediment in the Western Scheldt estuary (the Netherlands). Netherlands Journal of Aquatic Ecology, 28, 337–345.

Cauwenberghs, K. (1998). Waterbodem: beter voorkomen dan genezen. Eerste rapport van de Werkgroep “Duurzame ontwikkeling” in het kader van het beleidsplan “Sanering van de waterbodem Beneden-Zeeschelde”.: Brussel

Chen, M.; Wartel, S.; De Smedt, F. (2007). Water en sediment in het estuarium van de Schelde. *Tijdschrift Water* (Congres Watersysteemkennis 2006-2007, Water en Sediment)

Chen, M.; Wartel, S.; Eck, B. Van; Maldegem, D. Van. (2005). Suspended matter in the Scheldt estuary. *Hydrobiologia* 540(1-3): 79–104. doi:10.1007/s10750-004-7122-y

Claessens, J. (1993). Beneden Zeeschelde: slibbalans 1992

Claessens, J. (1993). Beneden Zeeschelde Berekeningen op basis van het rapport “Evaluatie van de hoeveelheid slib in de Beneden Zeeschelde” van Bastin (1993)

Claessens, J. (1994). Beneden Zeeschelde: slibbalans 1993

Claus, J.; Ides, S.; De Mulder, T.; Mostaert, F. (2009). Baggeren en storten in de Schelde - Onderzoek naar de slibhuishouding in de Zeeschelde: Antwerpen, België. 91 pp.

Cleveringa, J.; Dam, G. (2013) Instandhouding vaarpassen Schelde Milieuvergunningen terugstorten baggerspecie. Grootschalige sedimentbalans van de Westerschelde. Consortium Deltares, IMDC, Svašek, Arcadis, report G-02

Dam, G.; Cleveringa, J. (2013). De rol van slib in de Westerschelde. Consortium Deltares, IMDC, Svašek, Arcadis, report G-2A

Coen. (1988). Ontstaan en ontwikkeling van de Westerschelde. *Water* 43: 156–162

De Looff, D. (1978). Kaartering van de bodemsamenstelling van het oostelijk gedeelte van de Westerschelde. Methode en Resultaten

De Looff, D. (1980). Kaartering van de bodemsamenstelling van het westelijk gedeelte van de Westerschelde. Methode en Resultaten

D'Hondt, P.; Jacques, T.G. (Beheerseenheid van het M.M. van de N. en het S. (1982). Gesuspendeerde materie in de Schelde. Evaluatie van een onderzoek van de ULB voor het Ministerie van Volkgsgezondheid. *Water* 133–135

Fettweis, M. (1995). Modelling currents and sediment sediment transport phenomena in shelf seas and estuaries. Katholic University of Leuven. 253 pp.

Francken, F.; Wartel, S.; Parker, R. (2000). Bepaling van de hoeveelheid slib in de Beneden-Zeeschelde

Gourgue, O.; Baeyens, W.; Chen, M.S.; De Brauwere, A.; De Brye, B.; Deleersnijder, E.; Elskens, M.; Legat, V. (2013). A depth-averaged two-dimensional sediment transport model for environmental studies in the Scheldt Estuary and tidal river network. *Journal of Marine Systems* null(null). Retrieved from http://dx.doi.org/10.1016/j.jmarsys.2013.03.014

Haecon. (2006). Actualisatie van de zandbalans van de Zee-en Westerschelde: Bergen op Zoom. 90 pp.

Heylen, A. (2013). Dredging in the Port of Antwerp: challenges and best practice. Retrieved from www.seinemaritime.net/suports/uploads/files/workshop Heylen.pdf

Holland, A.; Bitter, G.; Van Eck, B.; Van de Kamer, S.; Lefèvre, F.; Schouwenaar, A.; Wulffraat, K. (1991). De belasting van het Schelde-estuarium (1980-1988) SAWES nota 91.07. 80 pp.

IMDC. (1989). Tunnel Liefkenshoek, onderzoek betreffende de morfologische factoren (2D). Langdurige stroom- en sedimentmeting

IMDC. (1993). Gedrag van particulair materiaal in het Schelde-estuarium: Antwerp

IMDC. (2004). Optimalisatie van de onderhoudsbaggerwerken Deurganckdok. Hoofdrapport: Onderzoek naar de effecten op het milieu van het terugstorten van baggerspecie in de Beneden Zeeschelde.

IMDC; VUB. (2010). Lithologische en geomorfologische kaart van de Beneden- Zeeschelde Analyserapport : Opmaak en Interpretatie

IMDC (2013). Monitoringprogramma Flexibel Storten - Fase 2. Deelopdracht 1 - Analyse slibconcentratiemetingen in de Zeeschelde

IMDC; INBO (2015) Duurzaam Beheerplan Boven-Zeeschelde Klasse IV. Post 1 - Inventarisatie bestaande gegevens:

IMDC; INBO (2015b) Duurzaam beheerplan Boven-Zeeschelde. Duurzame bathymetrie.I/RA/11448/14.240/JFA/ v1.0

inventarisatie**Jeuken, M.-C.J.L.; Wang, Z.B.; Van der Kaaij, T.; Van Helvert, M.; Van Ormondt, M.; Bruinsma, R.; Tanczos, I.** (2004). Morfologische ontwikkelingen in het Schelde estuarium bij voortzetting van het huidige beleid en effecten van een verdere verdieping van de vaargeul en uitpoldering langs de Westerschelde. Deelovereenkomst 2 en 3. Morfologie

Kuijper, C.; Steijn, R.; Roelvink, D.; Van der Kaaij, T.; Olijslagers, P. (2004). Morphological modelling of the Western Scheldt

Kuijper, C. (2013) Instandhouding vaarpassen Schelde. LTV V&T rapport G-8. Aanvullend onderzoek historische ontwikkeling getij.

Lamalle, C.; Petit, F.; Koch, G.; Hurtgen, C.; Pissart, A. (1989). Les Transports en suspension et en solution dans la Burdinale, affluent principal de la Méhaigne. *Bulletin de Société Géographique de Liège* 25(39-51)

Lefèvre, F. (2000). Effecten van systeemingrepen op de water- en bodemkwaliteit van de Westerschelde. 42 pp.

Levy, Y.; Vereecken, H.; Deschamps, M.; Verwaest, T.; Mostaert, F. (2014). MONEOS 2012 - 13 uursmetingen: Factual data rapport: Stromingen, debiet en sediment concentratie. Versie 3.0. WL Rapporten, 13_086. Waterbouwkundig Laboratorium: Antwerpen, België.

Levy, Y.; Meire, D.; Vereecken, H.; Deschamps, M.; Verwaest, T.; Mostaert, F. (2015). MONEOS, Metingen halftijeb in de Beneden-Zeeschelde: factual data rapport 2007-2013. Versie 4.0. WL Rapporten, 13_084. Waterbouwkundig Laboratorium: Antwerpen. XXII, 303 + 13 p. appendices pp.

Manni, R.J. (Geografisch I.R.U. (1986). Slibtransport en slibbalans in de Westerschelde: Utrecht. 107 pp.

Merckelbach, L. M. (2006). A model for high frequency acoustic Doppler current profiler backscatter from suspended sediments in strong currents. Continental Shelf Research, 26, 1316–1335.

McLaren, P. (1994). Sediment transport in the Westerschelde between Baarland and Rupelmonde: Cambridge UK

Migniot, C. (1989). Tassement et rheologie des vases. *La Houille Blanche* 1/2: 11–30

Ministerie van de Vlaamse Gemeenschap (1991)**.** De baggerwerken in de Schelde en de kwaliteit van water en bodem: stand van zaken. Ministerie van de Vlaamse Gemeenschap. Departement Leefmilieu en Infrastructuur: Brussel. 67 + appendices pp.

Ministerie van de Vlaamse Gemeenschap. (2000). Ontwikkelingen I.V.M. slibberging en slibhuishouding in de Beneden-Zeeschelde in de periode 1991-2000. Bijlage 13: Antwerpen, België

Mwanuzi, F., & De Smedt, F. (1997). A suspended sediment transport model applied to the Scheldt estuary. In Zeszyty Naukowe Akademii Rolniczej we Wroclawiu. Konferencje (Poland).

Nihoul, J.C.J.; Wollast, R. (1976). Project Zee Eindverslag. L’estuaire de l'Escaut

Nolte, A.J. (2012). Vervolgonderzoek drie buitendijkse maatregelen voor natuurherstel in de Westerschelde

Peeters, B. (2010). Milieurapport Vlaanderen MIRA. Achtergronddocument. Thema Kwaliteit oppervlaktewater

Peeters, P., Claeys, S., Michielsen, S., De Schutter, J., Temmerman, S., Meire, Vandenbruwaene, W.; Maris, T.; P., Chen M.; Wartel, S. (2009). Sediment behaviour within a flood control area with a controlled reduced tide - pilot project Lippenbroek. In: 31eme journees de l’hydrauilique de la SHF.

Peters, B.G.T.M.; Liek, G.A.; Wijsman, J.W.M.; Kuijper, M.W.M.; Van Eck, G.T. (2003). Monitoring van de effecten van de verruiming 48’/ 43’. Een verruimde blik op waargenomen ontwikkelingen. MOVE Evaluatierapport 2003. MOVE-rapport 8. Deel B : Hoofdrapport: Middelburg. 60 pp.

Pieters, T.; Dillingh, D.; Graveland, J. (2005). “Het Scheldegetij” (rapport BGW-0102) met oplegnotitie.

Plancke, Y.; Maximova, T.; Ides, S.; Peeters, P.; Taverniers, E.; Mostaert, F. (2012). Werkgroep O&M - Projectgroep Veiligheid: Sub project 1: Data analysis and hypothesis - Lower Sea Scheldt. Version 4.0.

WL Rapporten, 756/05. Flanders Hydraulics Research: Antwerp, Belgium

Bi, Q., & Toorman, E. A. (2014). Mixed-Sediment Transport Modelling in the Scheldt Estuary with a Physics Based Bottom Friction Law. Ocean Dynamics SI, 65(4), 555–587.

Salden, R.M. (1998). Het effect van slibverwijdering in de Beneden Zeeschelde op de waterkwaliteiten slibhuishouding in de Westerschelde

Salomons, W.; Eysink, W.D.; Kerdijk, N.H. (1981). inventarisatie en geochemisch gedrag van zware metalen in de Schelde en Westerschelde. 61 pp.

Santermans, J. (IMDC). (2013). Instandhouding Vaarpassen Schelde Milieuvergunningen terugstorten baggerspecie. LTV - Veiligheid en Toegankelijkheid. Baggeren en storten Achtergrondrapport A-31

Sas, M.; Van Holland, G.; Toro, F. (2007). Milieueffectrapport Verruiming vaargeul Beneden-Zeeschelde en Westerschelde. Basisrapport Slibdynamiek. 205 pp.

Spronk, G.C. (1994). Invloed slib onttrekking Beneden-Zeeschelde op waterkwaliteit op Belgisch-Nederlandse grens. 33 pp.

Swart, J.P. (1982). Onderzoek oppervlaktebemonstering slib in de Westerschelde, periode 69-82

Swart, J.P. (1983). Slibtransportberekening in een dwarsraai in de Westerschelde periode ’69 - '80

Swart, J.P. (1987). Onderzoek verhouding mariene-fluviatielslib in de Westerschelde. 21 pp.

Taverniers, E. (1995). Beneden Zeeschelde Slibbalans 1994

Taverniers, E. (1996). Beneden Zeeschelde Slibbalans 1995

Taverniers, E. (1997). Beneden Zeeschelde Slibbalans 1996. Ministerie van de Vlaamse Gemeenschap, Departement Leefmilieu en infrastructuur, Administratie waterwegen en zeewezen, Afdeling Maritieme Schelde

Taverniers, E. (1998). Beneden Zeeschelde Slibbalans 1997. Ministerie van de Vlaamse Gemeenschap, Departement Leefmilieu en infrastructuur, Administratie waterwegen en zeewezen, Afdeling Maritieme Schelde

Taverniers, E. (1998). Evolutie van het getij in het Zeescheldebekken. *Water* 102: 304–308

Taverniers, E. (1999). Beneden ZeescheldeSlibbalans 1998

Taverniers, E. (2000). Beneden Zeeschelde Slibbalans 1999

Taverniers, E. (2001). Beneden Zeeschelde Slibbalans 2000

Temmerman, S.; Govers, G.; Bouma, T.; Vries, M. De; Wartel, S.; Antwerpen, U.; Ecologie, O.P.; Leuven, K.U.; Geografie, R.; Ecologie, M.; Brussel, V.U. (2006). Opslibbing van schorren en over- stromingsgebieden langs de Schelde : een onvermijdelijk natuurlijk proces. *Water* 26(1): 1–9

Temmerman, S.; Govers, G.; Meire, P.; Wartel, S. (2003). Modelling long-term tidal marsh growth under changing tidal conditions and suspended sediment concentrations, Scheldt estuary, Belgium. *Marine Geology* 193(1-2): 151–169. doi:10.1016/S0025-3227(02)00642-4

Temmerman, S.; Govers, G.; Wartel, S.; Meire, P. (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(7): 739–755. doi:10.1002/esp.495

Temmerman, S.; Govers, G.; Wartel, S.; Meire, P. (2004). Modelling estuarine variations in tidal marsh sedimentation: response to changing sea level and suspended sediment concentrations. *Marine Geology* 212(1-4): 1–19. doi:10.1016/j.margeo.2004.10.021

Ten Brinke, W.B.M. (1992). Slib in het estuarium van de Schelde: paden en lotgevallen deel 1. De grootschalige (semi-)natuurlijke slibbeweging. Nr. 9

Ten Brinke, W.B.M. (1992). Slib in het estuarium van de Schelde: paden en lotgevallen deel 2. Rapport R 92-10. 51 pp.

Terwindt, J.H.J. (1967). MUD TRANSPORT IN THE DUTCH DELTA AREA and along the adjacent coastline. *Netherlands Journal of Sea Research* 3(4): 505–531

Van Alphen, J.S.L.J. (1990). A mud balance for the Belgian Dutch coastal waters between 1969 and 1986. *Netherlands Journal of Sea Research* 25(1/2): 19–30

Van Braeckel, A.; Plesschaert, G.; Van den Bergh, E. (2006). Historische analyse van de Zeeschelde en haar getijgebonden zijrivieren. 19e eeuw tot heden.

Van Braeckel A.; Coen L.; Peeters P.; Plancke Y.; Mikkelsen J.; Van den Bergh E. (2012) Historische evolutie van Zeescheldehabitats. Kwantitatieve en kwalitatieve analyse van invloedsfactoren. Rapporten van het Instituut voor Natuur- en Bosonderzoek 2012 (59). Instituut voor Natuur- en Bosonderzoek, Brussel.

Van Daele, T.; Van den Bergh, E.; Maris, T.; Schneiders, A.; Breine, J.; Van Braeckel, A. (2007). Focus Zeeschelde, ***in***: Natuurrapport 2007. Toestand van de natuur in Vlaanderen: cijfers voor het beleid (M. Dumortier, L. De Bruyn, M. Hens, J. Peymen, A. Schneiders, T. Van Daele & W. Van Reeth, eds.). Mededelingen van het Instituut voor Natuur- en Bosonderzoek: Brussel

Van Damme, S.; Struyf, E.; Maris, T.; Ysebaert, T.; Dehairs, F.; Tackx, M.; Heip, C.; Meire, P. (2005). Spatial and temporal patterns of water quality along the estuarine salinity gradient of the Scheldt estuary (Belgium and The Netherlands): results of an integrated monitoring approach. *Hydrobiologia* 540(1-3): 29–45. doi:10.1007/s10750-004-7102-2

Van der Spek, A.J.F. (1994). Large-scale evolution of Holocene tidal basins in the Netherlands. Universiteit van Utrecht

Van Eck, B. (1999). De Scheldeatlas : een beeld van een estuarium: Middelburg

Van Eck, B.; Van Maldegem, D. (1990). Datering schorren Westerschelde

Van Eck, G. T. M.; De Pauw, N.; Van Den Langenbergh, M.; Verreet, G. (1991). Emissies, gehalten, gedrag en effecten van (micro)verontreinigingen in het stroomgebied van de Schelde en Schelde-estuarium. *Water* 10(60): 164–181

Van Eck, G.T.M. (1991). De ontwikkeling van een waterkwaliteitsmodel voor het Schelde-estuarium. *Water* 61(november/december): 215–218

Van Hoestenberghe, T.; Ferket, B.; De Boeck, K.; Vanlierde, E.; Vanlede, J. (2013). Slibbalans Zeeschelde: Deelrapport 2 – Sediment load for the river Scheldt and its main tributaries (1972 – 2009). Versie 1_1. WL Rapporten, 12_029.: Antwerpen, België

Van Kessel, T; Vanlede, J.; Bruens, A. (2006). Development of a mud transport model for the Scheldt estuary in the framework of LTV. Phases 1 and 2

Van Kessel, Thijs; Vanlede, J.; De Kok, J. (2011). Development of a mud transport model for the Scheldt estuary. *Continental Shelf Research* 31(10): S165–S181. Retrieved from http://dx.doi.org/10.1016/j.csr.2010.12.006

Van Ledden, M. (2003). Sand-mud segregation in estuaries and tidal basins. Delft University of Technology

Van Maldegem, D. (1987). 1e Benadering Slibbalans Westerschelde: Middelburg

Van Maldegem, D. (1993). De slibbalans van het Schelde-estuarium

Van Maldegem, D. (1997). Slibbalans Schelde-estuarium 1995

Van Maldegem, D.; Mulder, H.P.J.; Langerak, A. (1993). A cohesive sediment balance for the Scheldt Estuary. *Netherlands Journal of Aquatic ecology* 27(2-4): 247–256

Van Maldegem, D.; Wattel, G.; De Winder, B.; Arends, A.; Stikvoort, E. (1999). Slib in de Westerschelde. Een beschrijving van de troebelheid en slibverspreiding in de Westerschelde voor de periode december 1998 tot juli 1999: Middelburg

Vandenbruwaene, W.; Wildemeersch, K.; Plancke, Y.; Vanlede, J. (2015) On the short- and long-term SPM variations in the Scheldt estuary, in: (2015). Scheldt Estuary: physics and integrated management - Special Session on of the 36th IAHR WORLD CONGRESS, 28 June – 3 July, 2015, The Hague, the Netherlands. pp. 57-60

Vanlierde, E.; Vereecken, H., Plancke, Y., Taverniers, E., Mostaert, F. (2013). MONEOS - jaarboek monitoring WL 2012: Factual data rapportage van monitoring hydrodynamiek en fysische parameters zoals gemeten door WL in het Zeescheldebekken in 2012. Versie 2_0. WL Rapporten, 12_070_1. Waterbouwkundig Laboratorium: Antwerpen, België.

Verbeek, H. (1998). Adaptation of 2D sediment transport patterns using 3D hydrodynamic modelling. OCEANS'98 Conference, 444–448.

Verbessem, I.; Ysebaert, T.; Bergh, E. Van Den; Regge, N. De; Soors, J.; Kuijken, E. (2010). 10 Jaar m onitoring op het Groot Buitenschoor: Brussels

Vereeke, S.J.P. (1994). Geactualiseerde slibbalans Schelde-estuarium (2e concept): Middelburg. 10 pp.

Vanlierde, E.; Wouters, M.; Vereecken, H.; Mostaert, F. (2010) Jaarlijks waterbodemonderzoek in de Westerschelde: monsternamecampagne 2010. Versie 2.0. WL Rapporten, 708_08a. Waterbouwkundig Laboratorium: Antwerpen. II, 6 + 17 p. appendices, 1 map pp.

Vanlierde, E.; Van Eerdenbrugh, K.; Vereecken, H.; Mostaert, F. (2011) Jaarlijks waterbodemonderzoek in de Westerschelde: monsternamecampagne 2011. . versie 2.0. WL Rapporten, 708_08a. Waterbouwkundig Laboratorium: Antwerpen. II, 19 + 21 p. Appendices, 1 map pp.

Vanlierde, E.; Vereecken, H.; Boeckx, L.; Mostaert, F. (2013) Jaarlijks waterbodemonderzoek in de Westerschelde: monsternamecampagne 2012. versie 2.0. WL Rapporten, 708_08a. Waterbouwkundig Laboratorium: Antwerpen. II, 19 + 18 p. appendices pp.

Vereecken, H.; De Backer, E.; Vanlierde, E.; Mostaert, F. (2013) Jaarlijks waterbodemonderzoek in de Westerschelde: monsternamecampagne 2013. . Versie 4.0. WL Rapporten, 13_023. Waterbouwkundig Laboratorium: Antwerpen. II, 19 + 26 p. appendices pp.

Vereecken, H.; De Backer, E.; Vanlierde, E.; Deschamps, M.; Verwaest, T.; Mostaert, F. (2014) Jaarlijks waterbodemonderzoek in de Westerschelde: monsternamecampagne 2014. . Versie 4.0. WL Rapporten, 14_032. Waterbouwkundig Laboratorium: Antwerpen. II, 19 + 39 p. appendices pp.

Verlaan, P. (1998). Mixing of marine and fluvial particels in the Scheldt estuary. Technische Universiteit Delft. 218 pp.

Verlaan, P. a. J. (2000). Marine vs Fluvial Bottom Mud in the Scheldt Estuary. *Estuarine, Coastal and Shelf Science* 50(5): 627–638. doi:10.1006/ecss.1999.0599

Verlaan, P.A.J.; Donze, M.; Kuik, P. (1998). Marine vs Fluvial Suspended Matter in the Scheldt Estuary 873–883

Verlaan, P.A.J.; Meijerink, S. V; Maartense, V.J.; Donze, M. (1997). Slibtransport in de Schelde over de Belgisch-Nederlandse grens. *H2O* 8

Verliefde, G.; Nielandt, W.; Vanthienen, W. (1994). Haven van Antwerpen, slibbalans 1989-1993: Antwerp

VMM (2009), Chemische kwaliteit van baggerspecie in de Beneden-Zeeschelde. Campagne 2009

VMM (2010), Jaarlijks waterbodemonderzoek in de Westerschelde: chemische kwaliteit van baggerspecie in de Westerschelde, campagne 2010

VMM (2011), Jaarlijks waterbodemonderzoek in de Westerschelde: chemische kwaliteit van baggerspecie in de Westerschelde, campagne 2011

VMM (2012), Jaarlijks waterbodemonderzoek in de Westerschelde: chemische kwaliteit van baggerspecie in de Westerschelde, campagne 2012

VMM (2013), Jaarlijks waterbodemonderzoek in de Westerschelde: chemische kwaliteit van baggerspecie in de Westerschelde, campagne 2013

VMM (2014), Jaarlijks waterbodemonderzoek in de Westerschelde: chemische kwaliteit van baggerspecie in de Westerschelde, campagne 2014

Vos, G.; Bastiaensen, E.; De Bruyn, L.; De Schutter, J.; Plancke, Y.; Mostaert, F. (2011). Lithologische kaart Beneden Zeeschelde: Resultaten korrelanalyse sedimentstalen. Versie 2_0. WL Rapporten, 736_56. Waterbouwkundig Laboratorium: Antwerpen, België

Vroon, J.; Storm, C.; Coosen, J. (1997). Westerschelde, stram of struis? Eindrapport van het project Oostwest, een studie naar de beïnvloeding van fysische en verwante biologische patronen in een estuarium.: Middelburg

Wartel, S.; Chen, M.; Van Eck, G.T.M.; Van Maldegem, D. (2007). Influence of harbour construction on mud accumulation in the Scheldt estuary. *Aquatic Ecosystem Health & Management* 10(1): 107–115. doi:10.1080/14634980701194001

Wartel, S.; Chen, M.S.; Baeyens, W.; Dehairs, F. (2004). Bepaling van de verhouding marien - fluviatiel slib in de beneden Zeeschelde in het voorjaar van 2004: Brussel

Wartel, S.; Francken, F. (1998). Sedimenttransport en sedimentatie-processen in de Schelde tussen Zandvliet en Gent. Suspensiemateriaal in de Schelde. Nr. III: Brussel

Wartel, S.; Parker, R.; Francken, F. (2000). Bepaling van de sedimenttypes en opstelling van een lithologische kaart van de Beneden-Zeeschelde.: Antwerpen

Wartel, S.; Van Eck, G.T.M. (2000). Slibhuishouding van het SCHELDE ESTUARIUM

Winterwerp, J.C. (1997). Slibtransport via zeesluizen; Zandvlietsluis en Berendrechtsluis

Wollast, R.; Marijns, A. (1981). Evaluation des contributions des différents sources de matière en suspension à l'envasement de l'Escaut. Rapport Final au Ministère de la Santé Publiqure. 152 pp.

Wollast, R.; Peters, J.J. (1979). Biogeochemical properties of an estuarine system: the River Scheldt

Zeehavendienst, A. (1993). Zeeschelde: temperatuur en zoutgehalte 1986-1990 Verslag. 11 pp.

APPENDIX A: FORMULAS FOR DREDGING AMOUNTS

In literature different units are being used to report dredging amounts. Some texts mention formulas to convert in between units. Because of differences in notation, these formulas are sometimes difficult to compare.

This appendix contributes to that discussion by deriving conversion formulas from known basic definitions, and by making all assumptions explicit.

Notation

Symbol	Description	Unit
m_g	Mass of dry fraction, mass of grains	kg, TDS
m_b	Mass of mixture; bulk mass	kg
V_b	Volume of Mixture water sediment (Bulk Volume)	m³
V_g	Volume of dry fraction; volume of grains	m³
ρ_b	Bulk density	kg/m³
ρ_w	Density of water	kg/m³
ρ_g	Grain density	kg/m³
C	Volume concentration	-

Volume concentration

Volume concentration is a powerful concept for conversions. It is defined as the ratio [-] of volume of grains to the volume of the mixture.

$$C = \frac{V_g}{V_b}$$

One can link this to densities as:

$$C = \frac{\rho_b - \rho_w}{\rho_g - \rho_w}$$

Reduced Volume V'

[definition in Dutch, taken from Ministerie van de Vlaamse Gemeenschap (1991)]

> "Onderhoudsbaggerwerken op de drempels in de vaargeul
>
> Er werd onderscheid gemaakt tussen specie met een densiteit groter of gelijk aan 1,6 en specie met een lagere densiteit.[…]
>
> In de tabel wordt bij een densiteit groter of gelijk aan 1,6 het volume aangegeven dat rechtstreeks in de baggerschepen werd opgemeten. **Bij een densiteit kleiner dan 1,6, dit is het geval van slibhoudende specie of zelfs zuiver slib, wordt het volume aangegeven dat eenzelfde hoeveelheid vaste specie zal aannemen bij een densiteit gelijk aan 2.**
>
> Dit komt er in feite op neer dat het volume slibhoudende specie **herleid wordt naar het volume dat eenzelfde gewichtshoeveelheid met water verzadigd zand zou innemen**."

This is the definition of the reduced volume V'. For reasons of consistency, V' is noted in full as V'_b in the formulas below.

The formula for V' is derived based on the assumption of invariance of m_g and V_g. m_g is invariant because of the last paragraph in the definition from Ministerie van de Vlaamse Gemeenschap (1991). Invariance of V_g follows, because of the fact that ρ_g doesn't change. Based on the invariance of V_g under the conversion from V_b to V'_b, one can work out the conversion relation.

<table>
<tr><th>Normal</th><th>Reduced (for ρ_b<1.6)</th></tr>
<tr><td>$V_g = C \cdot V_b$
$C = \frac{\rho_b - \rho_w}{\rho_g - \rho_w}$</td><td>$V_g = C' \cdot V'_b$
$C' = \frac{\rho'_b - \rho_w}{\rho_g - \rho_w}$
$\rho'_b = 2$ kg/m³ (definition)</td></tr>
<tr><td colspan="2">$C \cdot V_b = C' \cdot V'_b$
$V'_b = V_b \frac{\rho_b - \rho_w}{2 - \rho_w}$</td></tr>
</table>

In case we assume $\rho_w = 1$, the conversion formula above to calculate V'_b from V_b simplifies to:

$$V'_b = m_b - V_b$$

Both m_b and V_b are readily available from automatic measurements on a dredging vessel. $V_b$is derived from the level the dredged material in the hull, combined with the geometry of the hull. m_b is derived from the sinking-in (immersion) of the dredging vessel.

Conversion of $\boldsymbol{V'_b}$ [m³] to $\boldsymbol{m_g}$ [TDS]

Combining the basic relation $m_g = V_g \cdot \rho_g$ with the relation under reduced volume $V_g = C' \cdot V'_b$ (derived above), one can easily work out that

$$m_g = \rho_g \cdot C' \cdot V'_b$$

The table below gives this conversion factor under typical values:

ρ_g	ρ_w	Conversion factor $\rho_g \cdot C'$
2,65	1	1,606
2,65	1,025	1,59

Note that because the assumption $\rho_w = 1$ is typically used in the derivation of V'_b from m_b and V_b (derivation above), it is recommended to use the conversion factor 1.606 to convert reduced volume to mass.

DEPARTEMENT **MOBILITY AND PUBLIC WORKS**

Flanders Hydraulics Research

Berchemlei 115, 2140 Antwerpen
T +32 (0)3 224 60 35
F +32 (0)3 224 60 36
waterbouwkundiglabo@vlaanderen.be
mow.vlaanderen.be
waterbouwkundiglaboratorium.be

//

Vlaamse
overheid

DEPARTMENT **MOBILITY & PUBLIC WORKS**
Flanders hydraulics Research

Berchemlei 115, 2140 Antwerp
T +32 (0)3 224 60 35
F +32 (0)3 224 60 36
waterbouwkundiglabo@vlaanderen.be
www.flandershydraulicsresearch.be