Modelling sand-mud-bed interaction in the Scheldt estuary

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Front cover: Aerial view of Het Verdronken Land van Saeftinghe and the Western Scheldt
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Modelling sand-mud-bed interaction in the Scheldt estuary

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Preface

This thesis concludes the Master of Science programme at the faculty of Civil Engineering and Geosciences of Delft University of Technology. The research was conducted at Deltares in Delft.

I would like to thank all the members of my graduation committee for their feedback and guidance during my thesis work. Special thanks to my daily supervisor Jebbe van der Werf for the time invested in me, advice and discussions we had.

Furthermore, I would like to thank Gerard Dam, Thijs van Kessel and Mick van der Wegen for sharing their knowledge and providing useful feedback during the process.

Finally, special thanks to my family and Sophie for their encouragements, showing their interest and unconditional support.

Julien Groenenboom
Delft, August 2015
Summary

The tide-dominated Scheldt estuary is located in the southwest of the Netherlands. From the Dutch-Belgian border seawards, it consists of a system of channels and shoals and an ebb-tidal delta facing the North Sea. The behaviour of non-cohesive (sand) and cohesive (mud) sediment particles in the area are (until now) generally studied using separate numerical models. Better understanding of the physical processes in the area of interest can be obtained using process-based hydro-morphodynamic models that contain formulations for transport of both cohesive and non-cohesive sediment.

Based on a literature review, it is concluded that the mutual influence of sand-mud mixtures is of significant importance on the morphological development and should be accounted for when modelling multiple sediment fractions. Recently implemented modules in Delft3D can be used to improve the modelling of the cohesive fines and the interaction between the sand and mud fractions.

An existing Delft3D sand-model of the Scheldt estuary is extended with a mud fraction based on a mud model of the same area. The model simulates the morphological development of one year using a representative spring-neap tidal cycle and a morphological acceleration factor of 25. Initial conditions of the model are obtained from the results of previous model studies to avoid a large spin-up time. Time series are used to describe the boundary conditions regarding the tides, wind and waves. The bed is modelled using a fluff layer, transport layer and base layer. Furthermore, a critical mud content is used to distinguish between a non-cohesive and cohesive regime. In each regime, different formulations are used to calculate the erosion fluxes of sand and mud. A calibration on the mud parameters is performed to improve the behaviour of the mud particles in the model.

The performance of the model is assessed using a list of desiderata. The development in the model is subjected to a simulation loop in which the output is used as the input for the subsequent run. This ‘warming-up’ of the model is important to reduce the spin-up effects. The required period for the bed composition to develop into a state where it is in line with the boundary forcing is considered to be too long. Therefore, it is important that the model results are sufficiently stable so that the morphological development in the warmed-up model is better predictable.

The computed mud concentrations in the water column and their spatial distribution are in good agreement with the results of the mud model and with observations. However, the model calculates an export of mud at the mouth of the estuary whereas observations show an import of mud. Spin-up effects are responsible for this flaw of the model as the mud transports are still influenced by the initial bed composition. The computed mud export gradually decreases over time and is expected to change to import when a significantly longer simulation period is used.

Several model scenarios were set up to assess the importance of the hydrodynamic forcing mechanisms and sand-mud-bed interaction processes. By comparing the results of the model scenarios, the sensitivity of different components (tides, wind and waves) on the sediment transport and morphological development is investigated. In addition to the tidal forcing, the locally generated wind-waves have a significant impact on the morphological development of the Scheldt estuary.
Based on the results of this study, it is concluded that the effect of the mud fraction on the large-scale net sediment transport is of minor importance. Studies on the large-scale sand-transport patterns between macro cells in the Scheldt estuary can therefore be done using a model that only contains a sand fraction. However, the morphological development of the fringes of the intertidal areas is significantly affected by the presence of mud since it prevents erosion of these areas. It is therefore recommended to take this interaction into account in morphodynamic simulations of the Scheldt estuary. Furthermore, a wind-wave climate should be imposed because the locally-generated wind-waves are of significant importance on the morphological development of the fringes of the intertidal areas.
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1 Introduction

1.1 Background
Many studies have been conducted on the Scheldt estuary. This funnel shaped ebb-tidal estuary is located in the southwest of the Netherlands. There are several reasons for the need of understanding this system and they can be related to the functions of the Scheldt estuary, which are accessibility, ecology and safety. The first function refers to the use of the estuary as navigation route to the port of Antwerp, one of the largest ports in Europe, and other harbours. Maintaining this entrance, which is on Dutch territory, is of high economic value for Belgium. The unique landscape of the estuary with its channels, tidal flats and salt marshes provides a habitat for various types of ecological valuable flora and fauna. Unlike the other sea arms, the Western Scheldt is not closed as a part of the Delta Works. This makes safety another import issue, dikes around the estuary prevent cities like Middelburg, Vlissingen, Terneuzen and Antwerp from flooding.

Collaboration between the Netherlands and Belgium in order to maintain the functions and values of the Western Scheldt has resulted in several conventions and agreements. In 1998 the Dutch and Flemish governments decided to set up a Long Term Vision (LTV) for the Scheldt estuary. Studies into different aspects of the estuary, such as historical development and influence of human interventions, are done in the framework of LTV.

The Flemish government recently launched the Masterplan Flanders Bays\(^1\). This plan includes ideas on large-scale interventions in the mouth of the Scheldt estuary and along the Flemish North Sea coastline. The main goal is to improve protection of the coast against super-storms. Given the size of these interventions, it is expected that they will have a significant effect on the hydro- and morphodynamics of the entire estuary, both on the short and long term.

1.2 Problem definition
Deltaworks is currently setting up a Delft3D model to investigate the effects of large-scale interventions in the Scheldt estuary. It has to be decided which parameters and processes should be implemented in the model in order to represent reality while keeping the complexity and computational effort of the model to an acceptable level.

To simulate the sediment transports within the Scheldt estuary, currently only one characteristic grain size, with a median diameter \(D_{50}\) of 200 µm, is being used to mimic the sediment in the estuary. The relative fine sediments with cohesive properties (mud) are therefore not represented well in this simulation. Different studies (Mitchener & Torfs, 1996; Dam & Bliek, 2013; Dam & Cleveringa, 2013) have shown the potential importance of the interaction between sand and mud on the morphological development and the difference in behaviour to the hydrodynamic forcing. The presence of mud causes a more cohesive behaviour of the bed and thereby making it harder to erode. This raises the question if and how this cohesive mud fraction should be taken into account in simulations of the Scheldt estuary.

\(^1\) http://www.vlaamsebaaien.com
The focus of this thesis is on the sediment transport rates and morphological development of the Scheldt estuary and how these are affected by sand-mud-bed interaction processes. Next to this, wind and waves are considered to be important for the morphological development of (especially the mouth of) the Scheldt estuary. Therefore, the effects of these processes on the resulting sediment transports and bed composition will also be investigated.

In conclusion, the relevance of this study is twofold. Firstly, this study deals with the choices that have to be made and issues that arise when setting up a sand-mud model. Secondly, the model results can be used to gain better understanding of the physical aspects involved in sand-mud-bed interaction in the Scheldt estuary.

1.3 Objective and research questions
The objective of this study is to determine the importance of the hydrodynamic forcing (tides, wind and waves) and sand-mud-bed interaction on the sediment transport processes and morphological development in the Scheldt estuary on the timescale of a few years. To reach this objective, three research questions are formulated:

1. How can multiple sediment fractions and their interaction in the Scheldt estuary be modelled using a depth-averaged Delft3D model?
2. Can this model qualitatively reproduce the mud concentrations and large-scale sediment transport fluxes known from measurements and literature?
3. What is the importance of tides, wind and waves on the sediment-transport patterns and morphological development within the Scheldt estuary and how important are sand-mud-bed interaction processes?

1.4 Methodology
First, a literature study (Chapter 2) is performed on the relevant physical aspects in the Scheldt estuary, the study area itself and numerical modelling. Gathering this information is essential for understanding the physical processes in the area of interest and how to model them.

In this study the numerical process-based model Delft3D (Lesser et al., 2004) is used to simulate the morphodynamics in the Western Scheldt and the mouth of the estuary. Studies on the behaviour of sand and mud in the Scheldt estuary are carried out (until now) in separate models at Deltares. In this study the existing calibrated and validated Delft3D-NeVla model will be extended with a mud fraction (Chapter 3). The settings of this mud fraction are based on the mud model of the Scheldt estuary.

After the model is set up, the results are analysed to assess the performance of the model. The validation process focusses on the modelled mud concentrations in the water column, sediment transports and erosion/sedimentation patterns (Chapter 4). Furthermore, the stability of the modelled processes is checked by using a relatively long simulation period.

When the model is considered to be able to produce stable and reliable outcomes, it can be used to investigate the sensitivity of the hydrodynamic forcing and sand-mud interaction on the resulting sediment transports and morphological development (Chapter 5). Finally, the research questions are answered and recommendations for further research are provided (Chapter 6).
2 Literature review

2.1 Theoretical background

2.1.1 Estuaries

Pritchard (1967) defines an estuary as a semi-enclosed coastal body of water which has a free connection with the open sea and within which sea water is measurably diluted with fresh water derived from land drainage. Due to the connection with the sea, the water level in an estuary is affected by discharges from upstream rivers and tides. The fresh water from the upstream rivers and the salt water from the sea cause density differences in an estuary. The lighter fresh water is on top of the more dense salty sea water, which is known as stratification. The degree of stratification depends on the tidal prism of the estuary, river discharges and wave characteristics; more energy input leads to more mixing and consequently less stratification.

The density difference between fresh and salt water introduces additional flows and thus shear stresses at the bed which stir up sediment. When the dissolved fine sediments interact with the salt particles, flocculation might occur. This process leads to a higher local concentration of suspended particulate material. This region is called the estuarine turbidity maximum and its spatial-varying location is influenced by the tides and river discharges.

The sediment that can be found in an estuary can have a fluvial or marine origin. This depends, among others, on the tidal asymmetry - the situation in which the flood period is unequal to the ebb period. The sediments within an estuary can be spatially sorted due to the difference in behaviour to occurring bed shear stresses from tidal velocities and wave exposure. Another cause is the transport mode; relatively fine sediments are transported in suspension, while coarser sediments remain close to the bed. Mud that is transported in suspension is deposited in sheltered areas, while the channels that are being exposed to larger tidal velocities mainly consist of sand that is transported close to the bed.

Estuaries can be considered as dynamic areas as changes in morphology can be seen at different time and spatial scales. Variations in tidal prism, river discharges, relative sea level rise and the availability of sediment result in various characteristic types of estuaries.

2.1.2 Hydrodynamics

2.1.2.1 Tides

General

The tides arise from the combination of gravitational forces between the earth, moon and sun and the centrifugal forces as a result of the motion of the earth around the centre of gravity of the earth-moon and earth-sun system. The moon is closer to the earth, making its influence on the tides dominant compared to the sun. A tidal wave with a period of 12 hours and 25 minutes is caused by the moon component. When the sun and moon are aligned, they reinforce each other, which results in the highest high tides and the lowest low tides, also known as spring tides. Neap tides refer to the situation where the sun and moon are at right angles, resulting in the lowest high tides and the highest low tides. The duration of one spring-neap tidal cycle is approximately 14.8 days.

The tide is mostly represented by a combination of tidal constituents with their own frequency and amplitude. In most locations the largest contributor is the $M_2$ tidal constituent, where $M$
refers to the moon and 2 to semi-diurnal, which means that two high waters and two low waters occur during a lunar day. Because of the earth’s declination a daily inequality is introduced, resulting in the inequality of the two high waters on an arbitrary day.

The propagation of the tide is influenced by the depth of the oceans and seas, the Coriolis force and the land masses. The tide in the North Sea originates from the Atlantic Ocean that propagates to the north, while it is deflected to the right by the Coriolis force around Scotland. Travelling along the coastlines of the North Sea basin, the tide propagates as a Kelvin wave along the Dutch coast from south to north. The propagation speed of the tide reduces due to the decreasing water depths when it enters estuaries, rivers and tidal basins along the coast.

Tidal asymmetry
When describing a tidal wave, a distinction can be made between movements in horizontal and vertical direction. A horizontal tide refers to the tidal currents or discharges and a vertical tide to the rise and fall of the water level. The relationship between the horizontal and vertical tide depends on the shape of the cross-section (hypsometrical effect). In a rectangular cross-section, a two times larger vertical tide results in a two times larger horizontal tide. However, in an area with deep channels and large intertidal storage areas, the relationship between water level and flow velocity is not linear.

As a tidal wave propagates into an estuary, it is affected by the friction from the bed and the narrowing width. Due to the decreasing water depths and narrowing of the estuary, the tidal wave slows down and the amplitude increases. The friction of the bed causes a decrease in tidal amplitude. The net effect differs per situation.

Neglecting friction and assuming a prismatic channel, the propagation velocity of a tidal wave is given by $c = \sqrt{gh} = \sqrt{g(h_0 + \eta)}$. This means that the speed of the tidal wave is larger during high tides than during low tides. The tidal wave is deformed and differs from a sinusoidal curve. The resulting saw-tooth-shape profile can mathematically be described by the inclusion of higher harmonics or so-called overtides. The higher harmonics are generated by the interaction of basic tidal components causing non-linear effects. These effects grow in shallow water where the ratio amplitude over water depth increases.

Due to faster propagation of the tidal wave during high water with respect to the propagation during low water, the rising period is shorter than the falling period. In this case, larger flood velocities occur because the same amount of water is moved in and out of the system during a tidal cycle. This system, in which the period of the water level rise is shorter than the falling period, is called flood-dominant. For deep channels and large intertidal storage areas, the opposite occurs. Due to the low water depths in the intertidal areas, the propagation of the high tide is slowed down. The situation where the ebb velocities are larger than the flood velocities is referred to as an ebb-dominant system.

Special types of (tidal) waves are progressive waves or standing waves where the phase difference between the surface elevations and the velocity is 0° and 90° respectively. Because the tidal wave is affected by friction, a phase difference of approximately 45° (corresponding to approximately 3 hours) is mainly found in estuaries. This means that the mean water level during flood is higher than the mean water level during ebb.

Ebb and flood channels
Considering a straight channel connected to the sea, during each tidal cycle water flows in and out of the channel. A small deviation in a straight channel triggers a positive feedback mechanism called meandering. Due to curvature-induced secondary flow the outer bend will erode and deposition will occur at the inner bend. Especially the ebb channels are subjected
to this meandering process. During flood the water enters the channel and might overshoot the bend due to inertia (see Figure 2.1). The same phenomenon can occur during ebb. Due to the tidal flats that are above water during low tide, during ebb the water will flow particularly through the ebb channels. Because of this flow concentration, the ebb channels will be deeper and more curved than the flood channels (Van Veen, 1950). The resulting landscape of meandering channels and tidal flats is characteristic for an estuary basin.

![Figure 2.1 – Ebb (E) and flood (F) tidal channels. During flood the water might overshoot the bend leading to flood chutes, this process is schematized by the arrows (Van Veen, 1950).]

Different elements can be distinguished in an estuary by their elevation. Tidal flats (sand) and mud flats are around mean sea level and are regularly flooded by the tides. The tidal flats are surrounded by channels, the mud flats can be found at sheltered locations with calm hydrodynamic conditions. The high-lying salt marshes are only flooded during spring tides and are covered with salt-tolerant vegetation. Therefore, these areas have a high ecological value.

### 2.1.2.2 Waves

In order to describe the motion of a wave in a mathematical way, it is common use to simplify it into a sinusoidal wave. Linear wave theory (Airy, 1845) is, among others, based on the assumption that the surface displacement is relatively small and the wave is only affected by gravity. According to Airy, a wave can be described using a sinusoidal expression as in equation 2.1 and travels by the phase velocity $c$ (as indicated in equation 2.2). This propagation speed is defined as the ratio between wave length $L$ and wave period $T$. The instantaneous water level $\eta$ is a function of the amplitude $a = H/2$, the radian frequency $\omega = \frac{2\pi}{T}$ and wave number $k = \frac{2\pi}{L}$:

$$\eta(x,t) = a \sin(\omega t - kx)$$  \hfill (2.1)

$$c = \frac{L}{T} = \frac{\omega}{k} = \frac{g}{k} \tanh(kh)$$  \hfill (2.2)

Waves that are formed at the adjacent sea or ocean can affect the mouth of an estuary. Within the estuary short waves can be formed by wind forcing. Wave characteristics (wave height, period, propagation direction) are a function of the prevailing wind (speed, fetch) and water depth. At smaller water depths waves start to dissipate their energy, which results in the stirring up of sediments. This introduces the concept of waves stirring up the sediment and the current transporting it. An important parameter for describing waves is the significant wave height (see equation 2.3), which is defined as the average wave height of the highest one third of the waves. Another way to determine the significant wave height is using the wave spectrum.
Observations of the sea surfaces show that wind-waves are not regular sinusoidal waves. The surface elevation could be described as chaotic and irregular. Therefore, the waves are often described using statistics. For a period short enough to be stationary (not changing in time) and long enough to be reliable, the agreement between the theory and observations is reasonable. Assuming that the surface elevation can be seen as a stationary Gaussian process, a variance density spectrum gives a description of the surface elevation in a statistical way. This continuous variance density spectrum is given in equation 2.4 with amplitude $a$ being a random variable.

$$E(f) = \lim_{\Delta f \to 0} \frac{1}{\Delta f} \mathbb{E} \left[ \frac{1}{2} a^2 \right]$$

In deep water the trajectory of the water particles can be considered as closed circles from an Eulerian perspective (see Figure 2.2). At smaller water depths, the trajectory gets influenced by the bottom and develops into a horizontal oscillating flow. This enhances the sediment concentration in the water column and associated sediment transports.

For more information on waves, the linear wave theory and the derivations of the presented formulas, see Holthuijsen (2007).

2.1.2.3 Residual flows

Several processes within an estuary can cause a residual flow, each process on its own spatial scale. Residual flows are influenced by river discharges, tidal induced circulations, stratified flows and meteorological aspects.

At high water the propagation speed of the tide is larger than at low water. A larger water depth means a larger propagation speed and less bottom friction. The crest of the tidal wave travels faster than the wave through. This asymmetry of the tidal wave introduces a net mass transport into the propagation direction named Stokes drift. As the averaged tidal discharge should be zero an extra flow driven by a water level gradient arises to compensate this flow, the so-called rectification of the Stokes drift.

Due to the geometry of the cross-sectional area, a residual flow velocity can be found in ebb and flood channels. Consider an estuary with large intertidal areas and deep channels. On the intertidal areas the residual flow is directed in flood direction. During ebb, the flow is concentrated in the ebb channel leading to a residual ebb-directed current.
Due to the meandering system of ebb and flood channels a curvature-induced secondary flow is present. In an estuarine circulation, surface and bottom flows are oppositely directed due to the density differences. Another circulation cell can be generated by a wind-driven flow.

2.1.3 Sediment transport

2.1.3.1 General

Sediment particles can be discerned by their grain size, see Table 2.1. Non-cohesive sediment with a particle size between 63 μm and 2 mm are called sand. It is common use to describe the shape of a sediment particle as a sphere. However, the very fine clay particles resemble thin plates. Clay particles have a negative electrostatic charge and may adsorb positively charged organic matter. Mud can be considered as a combination of fine sediments (silt and clay), organic material and water.

<table>
<thead>
<tr>
<th>Grain size (μm)</th>
<th>Sediment type</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 63</td>
<td>Sand</td>
</tr>
<tr>
<td>2 - 63</td>
<td>Silt</td>
</tr>
<tr>
<td>&lt; 2</td>
<td>Clay</td>
</tr>
</tbody>
</table>

Table 2.1 – Grain size (Verruijt & Van Baars, 2001)

The definition used in this thesis allows for discriminating mud by grain size, but also the behaviour of mud and sand during erosion, transportation and settling differs significantly due to the cohesive properties of the mud fraction. The relatively fine sediments behave more cohesive compared to a sand layer. Therefore, a larger bed shear stress is needed to get these particles in suspension than one would infer from their grain size. Due to a smaller fall velocity, the mud remains longer in suspension.

Mud particles tend to accumulate and form flocs by their electrostatic forces. These flocs are much larger than the individual grains and settle at a faster rate. During the flocculation process, polymers from organic matter adhere to the clay particles and thus forming larger flocs with a high water content. The floc size depends on the amount of turbulence, sediment concentration, organic matter, salinity, residence time and differential settling (Van Kessel et al., 2006).

Bosboom and Stive (2011) define sediment transport as the movement of sediment particles through a well-defined plane over a certain period of time. The movement of these particles depends on the interaction between the hydrodynamic forcing and sediment properties like grain size and fall velocity. When the velocity induced bed shear stress exceeds a critical value, the so-called critical bed shear stress \( \tau_{b,crit} \), the sediment is entrained from the bed and can be transported.

Generally, three different transport modes are distinguished (Bagnold, 1956): bed load, suspended load and wash load. Bed load refers to the situation where particles roll, shift or make small jumps over the bed, but stay near the bed. In the suspended mode the flow velocities exceed a critical value and particles are lifted from the bed and transported by the moving water. Finally, the situation where the grains are very small and are kept constantly in suspension is called wash load. Because of the turbulence in the water column and their small settling velocity, these particles do not settle and therefore have none or little interaction with the bed.
Transport processes can be split into two categories: advection and diffusion. Advection is the transportation of sediment with the mean flow. Diffusion refers to the transport of sediment by random motions. This process decreases sharp gradients in sediment concentrations.

2.1.3.2 Sediment transport formulas

Shields

In general, sediment transport is proposed as a function of the velocity $u$ with a certain power and factor: $S \propto \alpha u^n$. The term $\alpha$ depends on the sediment and flow characteristics. For bed load transport $n$ differs mainly between 3 and 5, while for suspended load transport a value of $n = 1$ is most commonly used.

Shields (1936) studied the initiation of motion of a single grain by considering a spherical sediment particle on the threshold of motion. In that case the vertical forces, the gravity force and lift force, balance. Equilibrium of these forces results in the critical Shields parameter $\theta_{cr}$:

$$\theta_{cr} = \frac{\rho u^2_{cr}D}{(\rho_s - \rho)gD^3} = \frac{\tau_{b,cr}}{(\rho_s - \rho)gD}$$

Instead of a bed shear stress $\tau_b$, a shear velocity $u_*$ can be used, because they are related by $\tau_b = \rho u_* |u_*|$. The actual forcing can be described by a Shields parameter $\theta$ which depends on the bed shear stress $\tau_b$ or shear velocity $u_*$, the relative density $\Delta$ and the median grain size $D_{50}$:

$$\theta = \frac{\tau_b}{(\rho_s - \rho)gD_{50}} = \frac{\tau_b}{\Delta \rho g D_{50}} = \frac{\rho u_*^2}{\Delta \rho g D_{50}} = \frac{u_*^2}{\Delta D_{50}}$$

When the Shields parameter is smaller than the critical Shields parameter, no sediment transport takes place. When it is equal to or exceeds the critical Shields parameter, the sediment transport is a function of the difference between the two values. The Shields approach is only valid for uniform flow on a flat bed, as the gradation of the bed is not taken into account and the effect of cohesion is not represented (Bosboom & Stive, 2011). Nevertheless, it is used in many practical sediment transport formulations (e.g. Van Rijn, 1993). The curve in Figure 2.3 represents the initiation of motion based on experiments.
Van Rijn

Van Rijn et al. (2004) distinguishes between bed load and suspended load sediment transport by means of reference height \( \alpha \), this principle is schematised in Figure 2.4. Sediment transport below this value is treated as bed load, whereas sediment transport above this value is considered as suspended load. The expression for the reference height \( \alpha \) is:

\[
\alpha = \max(0.5k_{s,c,r}, 0.5k_{s,w,r}, 0.01)
\]

Where:
- \( \alpha \) = Van Rijn's reference height
- \( k_{s,c,r} \) = current-related bed roughness height due to small-scale ripples
- \( k_{s,w,r} \) = wave-related bed roughness height due to small-scale ripples

Figure 2.3 – Initiation of motion (Van Rijn, 1993)

Figure 2.4 – A distinction is made between suspended load and bed load transport by reference height \( z=\alpha \) (Van Rijn, 1993)
The bed load transport is calculated using the instantaneous bed shear stress. A distinction is made between the current and wave related transport. Besides the occurring bed shear stresses, instantaneous velocity and sediment characteristic, the formula uses a lot of coefficients. The exact expression used for calculating the bed load transport can be found in Van Rijn et al. (2004).

Above the reference height $a$ the suspended sediment transport is calculated. Sediment is entrained in the water column by imposing a reference concentration $c_a$ at reference height $a$. By using a Rouse distribution for the sediment concentration over depth, the sediment concentration in the water column can be calculated from this reference height and concentration. The reference concentration $c_a$ can be calculated using Van Rijn et al.’s (2000) formula:

$$c_a = 0.015 \rho_s \frac{D_{50} (T_a)^{1.5}}{a (D_s)^{0.3}}$$

Where:
- $\rho_s$ density of sand [kg/m$^3$]
- $D_{50}$ median diameter [m]
- $T_a$ non-dimensional bed-shear stress [-]
- $D_s$ non-dimensional particle diameter [-]

The settling velocity of the non-cohesive sediment fraction is described by Van Rijn (1993):

$$w_s = \begin{cases} \frac{(s - 1)gD^2}{18\nu} & 65 \mu m < D \leq 100 \mu m \\ \sqrt{1 + \frac{0.01(s - 1)gD^3}{\nu^2}} - 1 & 100 \mu m < D \leq 1000 \mu m \\ 1.1\sqrt{(s - 1)gD} & 1000 \mu m < D \end{cases}$$

Where:
- $s$ relative density $\rho_s/\rho_w$ of sediment fraction [-]
- $D$ representative diameter of sediment fraction [m]
- $\nu$ kinematic viscosity coefficient of water [m$^2$/s]

The settling velocity of a suspended particle is a function of its diameter. For relative coarse particles the fall velocity is proportional to the square root of the diameter: $w_s \propto \sqrt{D}$. In case of fine particles, the proportionality between fall velocity and diameter is given by $w_s \propto D^2$. For even finer particles the non-cohesive approach is not valid anymore and the sediment particles are treated as cohesive sediment.

The transport rate of suspended sediment in horizontal direction $q$ can be seen as the product of the sediment concentration $c$ and the flow velocity $u$ integrated over the water depth $h$:

$$q = \int_0^h c(z)u(z)dz$$

In general, the velocity profile is assumed to be logarithmic, with the lowest velocities near the bed and the highest velocities near the surface. For the sediment concentrations it is the other way around; the highest values can be found near the bed. Different approximations of the concentration distribution over the water column have been proposed (e.g. Rouse (1937))
and Van Rijn (1993)). In a depth-averaged approach, the total transport is estimated by the product of the depth-averaged sediment concentration $\bar{c}$, the depth-averaged flow velocity $\bar{u}$ and the water depth $h$:

$$q = \bar{c} \bar{u} h$$  \hspace{1cm} (2.11)

One should notice that the formulas above consider sediment transport by advection. Dispersion, the movement of particles from highly concentrated areas to less concentrated areas, is not included.

**Partheniades-Krone**

Influential research on the behaviour of fine cohesive sediments was done by Krone (1962), who focused on the deposition of the material and Partheniades (1965) who studied the erosion. The behaviour of cohesive sediments is modelled by suspended load transport only.

In these studies, a distinction is made between the erosion and deposition fluxes. The erosion flux is computed when the bed shear stress exceeds the critical shear stress for erosion and the deposition flux is computed when the bed shear stress is below the critical shear stress for sedimentation. The resulting fluxes of cohesive sediment between the water column and the bed are calculated with the Partheniades-Krone formulation (see equation 2.12 and 2.13). A Heaviside function $H$ is used to account for the threshold of erosion and sedimentation. As in the previous section, the sediment transport is calculated by the product of the flow velocity and concentration integrated over the water depth.

$$E_m = M \left( \frac{\tau_b}{\tau_{e,m}} - 1 \right) H \left( \frac{\tau_b}{\tau_{e,m}} - 1 \right)$$ \hspace{1cm} (2.12)

$$D_m = w_m c_m \left( 1 - \frac{\tau_b}{\tau_{d,m}} \right) H \left( 1 - \frac{\tau_b}{\tau_{d,m}} \right)$$ \hspace{1cm} (2.13)

Where:

- $E_m$: Erosion flux of mud
- $M$: Erosion parameter
- $\tau_b$: Bed shear stress
- $\tau_{e,m}$: Critical erosion shear stress for mud
- $H$: Heaviside function; 0 if argument < 0; 1 if argument $\geq$ 0
- $D_m$: Deposition flux of mud
- $w_m$: Fall velocity of mud
- $c_m$: Concentration of mud
- $\tau_{d,m}$: Critical deposition shear stress for mud

Winterwerp (2007) suggested that there is no threshold for deposition and the deposition flux can be determined using $D = w_m c_m$. In computational models this approach can be followed by using a very high value for the critical deposition shear stress for mud.

### 2.1.3.3 Residual sediment transports

As sediment transports are related to flow velocities, residual flows introduce residual sediment transports. Tidal asymmetry will lead to residual sediment transports because of the non-linear relation between velocity and sediment transport. Relatively fine sediments behave differently to identical hydrodynamic forcing compared to coarser sediments. Furthermore, the transport mode is important: bed load involves transportation close to the bed and is related to the instantaneous flow velocity, whereas suspended load also depends on past conditions.
due to relaxation effects. Therefore, the residual transport of sand and mud are discussed separately.

**Relatively coarse sediment (sand)**

Van de Kreeke and Robaczewska (1993) studied the effect of tidal asymmetry on the sediment transports. They assumed that the $M2$ component was dominant. Based on the sand transport formula $s(t) = f u^2(t)$ they found an expression for the long-term averaged sand transport:

$$\langle s \rangle = \frac{3}{2} \frac{u_0}{\bar{u}} + \frac{3}{4} \frac{u_{M4}}{\bar{u}} \cos \varphi_{M4} + \frac{3}{4} \frac{u_{M6}}{\bar{u}} \cos (\varphi_{M4} - \varphi_{M6})$$  \hspace{1cm} (2.14)

In this expression the phases are relative to the $M2$ phase and higher-order terms are neglected. This expression demonstrates that the averaged sand transport does not only depend of the main component of the tidal flow $M2$, but is also a function of the residual flow $u_0$ and the overtimes $M4$ and $M6$. The phase lags, relative to $\varphi_{M2}$, are also of importance. In expression 2.14 the sediment transport is directly related to the local and instantaneous flow velocity. This is valid for relative coarse sediment (sand) transported as bed load in general.

Another asymmetry in sediment transports can be explained by peak-flow velocities. When the peak flood velocities are larger than the peak ebb velocities a net flood-directed transport is found. This process is especially believed to be important for the coarser sediments, see for example Van de Kreeke and Robaczewska (1993).

**Relatively fine sediment (mud)**

The relationship between fine sediment transport and the occurring shear stresses is not linear. The energy required to mobilize fine cohesive sediments is much greater than the energy used to keep these particles in suspension. This difference is caused by the adhesion forces of the bed and is therefore more important for a cohesive bed. This phenomenon is called scour lag.

It takes some time for a suspended sediment particle to settle when the local flow velocity is below the threshold velocity. While it settles, the particle is still moving in the direction of the flow. When the flood velocities are larger than the ebb velocities, this settling lag leads to a landward transportation of suspended sediment. The smaller the particle, the greater is the settling lag.

Another residual transport of suspended sediment is caused by asymmetry in slack water periods. A residual transport of suspended sediment in flood direction is found when the high-water slack is longer than the low-water slack and vice versa. Particles that are transported as suspended load will settle during low hydrodynamic conditions like slack water. A larger high-water slack period means that more sediment particles can settle during that period than during the low-water slack period. A larger high-water slack period therefore results in an import of fines. Groen (1967) illustrated this lag effect in the depth-averaged sediment concentration $c$ with the following expression:

$$\frac{\partial c}{\partial t} = \frac{c_e - c}{T_a}$$  \hspace{1cm} (2.15)

An example of the solution of this equation is depicted in Figure 2.5. A velocity signal with equal ebb and flood velocities is used and it is assumed that an equilibrium concentration $c_e$ is reached under a constant flow and after a certain adaptation time $T_a$. 
Figure 2.5 – The effect of lag effects on the residual suspended sediment transport

The product of the velocity \( u \) (blue) and concentration \( c \) (red) results in suspended sediment transport \( uc \) (black). \( c_{eq} \) is proportional to \( u^2 \). Integrated over the tidal period, a net flood-directed transport of suspended sediment is found: \( \int_{t}^{t+T} uc \, dt > 0 \). The resulting residual transport is caused by the relaxation effect of the fines. Considering particles with a larger settling velocity and \( c = c_{eq} \) would in this theoretical example not result in residual transport, as \( \int_{t}^{t+T} uc_{eq} \, dt = 0 \).

2.1.3.4 Sand-mud mixtures

Sand and mud react differently to the same hydrodynamic forcing by currents and waves due to different critical shear stresses, fall velocities and transport modes. This may lead to sediment segregation as both fractions are transported to distinct areas. However, due to variations in the hydrodynamic forcing the bed will mostly consist of a mixture of sediments with different grain sizes and cohesiveness. Furthermore, human interventions such as dredging activities may also increase the mixing of sediments.

Experimental research by Torfs (1995) showed that the erosion resistance increases when the content of fine sediments increases. A mixture of sand and mud particles enhances the soil as the fine particles fill the pore spaces between the sand grains and smoothen the mixture. For example, Torfs’ experiments showed that the critical bed shear stress for erosion was 2 to 5 times higher when 10% mud was added to a sand bed.

Having a different shape and density, sand and mud particles settle and consolidate differently. Consolidation is the process where the sediment particles are getting packed more tightly due to the loads on it. This also affects the structure of the bed and therefore the erosion differs significantly between cohesive and non-cohesive sand-mud mixtures. Mitchener and Torfs (1996) suggested that this influence of mud content on the critical shear stresses for erosion should be accounted for when modelling erosion from a mixed bed. They showed that the erosion rate strongly decreased when mud content increased and suggested that the erosion formulations for pure sand and pure mud are not sufficient to describe the erosion behaviour of sand-mud mixtures.

Based on the experiments of Torfs, Van Ledden (2003) proposed new formulas for the critical bed shear stress as a function of the mud content. He distinguished between cohesive and
non-cohesive regimes by means of a critical mud content $p_{m,cr}$ of 30%. The expressions he proposed for the non-cohesive and cohesive regime are given in equations 2.16 and 2.17 respectively.

$$\frac{\tau_{e,nc}}{\tau_{cr}} = (1 + p_m)\beta \quad \text{for } p_m \leq p_{m,cr}$$  
(2.16)

$$\tau_{e,c} = \frac{\tau_{cr}(1 + p_{m,cr})\beta - \tau_{e,m}(1 - p_m)}{1 - p_{m,cr}} + \tau_{e,m} \quad \text{for } p_m \geq p_{m,cr}$$  
(2.17)

Where:
- $\tau_{e,nc}$ and $\tau_{e,c}$ critical bed shear stress for non-cohesive and cohesive sand and mud mixture respectively
- $\tau_{cr}$ and $\tau_{e,m}$ critical bed shear stress for pure sand and pure mud respectively
- $p_m$ and $p_{m,cr}$ percentage of mud and critical percentage of mud respectively
- $\beta$ empirical coefficient

The work of Jacobs (2011) follows up on Van Ledden (2003) and focuses on sand-mud erosion from a soil-mechanical perspective. Jacobs proposed a new surface erosion formula that is related to soil mechanical properties as granular porosity and undrained shear strength.

Ahmad et al. (2011) proposed a new formula based on the critical shear stress for pure sand and pure mud, as well as their fraction content. An important difference between the formulas of Van Ledden and Ahmad et al. is that the latter no longer needs a critical mud content. As a distinction is no longer made between the two regimes, one formula for the critical shear stress is sufficient for the whole range of mud content.

### 2.2 Study area

The Scheldt estuary is a funnel shaped estuary in the southwest of the Netherlands (see Figure 2.6). It is the transition from the North Sea to the Scheldt River and forms the access to the port of Antwerp in Belgium as well as to other harbours along the estuary like Vlissingen and Temseuzen. The influence of the tide reaches up to Ghent, located around 160 km upstream. The part of the estuary between Ghent and the Dutch-Belgian border is called Sea Scheldt. From this border seaward the estuary is a system of channels and banks entitled Western Scheldt. This part of the Scheldt estuary is approximately 60 km long and covers an area of roughly 370 km$^2$. The width at the mouth is almost 5 km and gradually decreases to 1 km near the Dutch-Belgian border. The mouth of the estuary, which connects the Western Scheldt with the North Sea, is an ebb-tidal delta.
2.2.1 Human interventions

The Scheldt estuary is a relatively young estuary which has been formed by sea level rise and storm surges. The Scheldt River used to end in the Eastern Scheldt, but over time this changed from a connection with both estuaries to the present situation where the Scheldt River is only connected to the Western Scheldt. During the last centuries the estuary has been subjected to embankments and losses due to flooding (Van der Spek, 1994). Human interventions as land reclamation, the building of defence works and river training has led to a less dynamic system.

Being the entrance to one of the largest ports in Europe, about 14,000 seagoing vessels used the Scheldt estuary to access the port of Antwerp in 2014 (Port of Antwerp, 2014). Dredging and dumping activities are carried out to maintain this navigation route to Antwerp. Dredged material is deposited inside the estuary at specific locations to preserve the natural system of channels and banks. Besides maintenance dredging, three large dredging operations have been performed in the estuary to lower the sills in the navigation route. The first deepening was in the 1970s, the second deepening in 1997/1998 and the third deepening was carried out in 2010.

In recent years, 13 million m$^3$ per year is dredged to ensure sufficient depth in the navigation channel for shipping (VNSC, 2014). By dumping these sediments at other locations in the estuary, in case they are not contaminated, the material is kept in the system. Besides the dumping and dredging activities, sediment is also taken out of the system by sand mining. The average value of the extracted sediments since 1955 is about 2-3 Mm$^3$ per year (Kuijper et al., 2006).

Human interventions are also found in the region of the ebb-tidal delta. This area is affected by the construction of the harbour of Zeebrugge around 1900, the extension of this port
around 1986 and the dredging operations to maintain a certain navigation depth (Van Oyen et al., 2015).

2.2.2 Hydrodynamic aspects
Deltas can be classified according to the influence of waves, rivers and tides. Because of the sheltered location, only the mouth of the Scheldt estuary is exposed to noteworthy waves. The river discharge, with a mean value of 120 m$^3$/s, is only 0.6% of the tidal prism at the mouth and is of minor importance (Van der Spek, 1997). The Scheldt estuary can therefore be classified as a tide-dominated estuary.

The spring-neap tidal difference at the mouth is around 3 to 4.5 m. The tidal wave propagates within the Western Scheldt in eastern direction. Due to the funnel shaped geometry of the inner estuary, there is an increase in tidal amplification. The tidal difference at Vlissingen is about 4 m and at Antwerp more than 5 m (VNSC, 2014). This amplification of tidal difference is mainly a function of the channel depths and water storage. Reduction of bottom friction due to dredging navigation channels caused an increase in tidal difference in the last decades (Kuijper, 2013). The tidal amplitude is reduced significantly after Antwerp due to rapidly decreasing water depths.

Wang et al. (1999) analysed field observations of the Scheldt estuary and found that the asymmetry of the horizontal and vertical tide during spring tide is stronger than during neap tide. In other words, the tidal asymmetry increases with the amplitude of the tide. Later, Wang et al. (2002) suggested that the changes in asymmetry of the vertical tide could be correlated with the ratio of tidal amplitude over mean channel depth $a/h$. This confirms the results of a previous study by Friedrichs and Aubrey (1988).

A study on the evolution of the tidal asymmetry in the Scheldt estuary for the period 1970 to 2002 was done by Bolle et al. (2010). Analysis of both the vertical and horizontal tides showed that deepening of the tidal channels resulted in a decrease of the amplitude ratios $M6/M2$ and $M4/M2$. This corresponds with a decrease of flood dominance.

The dominant wind direction is south to southwest with an average wind speed of 5 to 7 m/s. Waves mainly propagate from the north or southwest to the estuary and have a significant wave height of 1 to 2 m at the North Sea (Rijkswaterstaat, 2015a). Waves that are formed during severe storms at sea can reach wave heights of 2 to even larger than 3.5 m. Wave energy dissipates while entering the basin because of the decreasing depth. Within the basin, relative small wind-waves arise from friction between water and air. Due to wind set-up, water levels in the basin can raise another 3 m by a severe western/north-western storm (VNSC, 2014). The North Sea flood of 1953 was caused by such a heavy storm during spring tide.

Besides the tidal velocities, an additional flow is present as correction for the Stokes drift. Van der Werf and Briere (2013) calculated, using equation 2.18 and typical values for the parameters, that the return flow is in the order of 0.05 m/s. The upstream river discharge, with a typical value of 100 m$^3$/s, causes a flow of approximately 0.005 m/s. The return flow due to the Stokes drift is thus an order of magnitude larger than the residual flow due to river discharge.

$$\bar{u}_{\text{return}} = -\frac{\phi}{h_0} = 0.5 \frac{\eta}{h_0} \bar{u} \cos \varphi_1$$

2.2.3 Bathymetry
In Figure 2.7 the bathymetry for the year 2006 is shown, the different macro cells are separated by black lines. These schematised cells are based on morphological characteristics and numerically determined sand-transport patterns (Winterwerp et al., 2001).
The ebb and flood channels as well as the tidal flats can be recognized within the macro cells. In some macro cells, the ebb and flood channel are also linked by a shallow connecting channel. The dotted line represents the navigation channel to Antwerp, which coincides with the deeper (mainly ebb-) tidal channels.

The mouth of the estuary consists of a shallow ebb-tidal delta and two main channels. The large shallow area is named Vlakte van de Raan and is enclosed by the channels Wielingen (on the south) and Oostgat (on the north). Furthermore, some banks and shoals with a north-eastern orientation are present near Oostgat.

2.2.4 Sediment characteristics
The characteristic landscape of meandering channels, tidal flats and salt marshes is the result of different hydrodynamic conditions. However, these areas also influence the flow velocities and directions. Due to this coupled system, sediment segregation occurs. Characteristic values for the median grain size are given by Kuijper et al. (2006):

- Channels: $D_{50} > 150 \mu m$
- Shoals: $50 \mu m < D_{50} < 150 \mu m$
- Along the banks: $D_{50} < 125 \mu m$

Verlaan (2000) studied the marine mud in the Scheldt estuary. He found that the marine mud fraction is about 95% near Vlissingen and reduces to 75% near Saeftinghe. Further upstream a sharp decrease of the marine mud fraction is found. This significantly high marine mud content supports the indication of marine mud import. A yearly averaged value of approximately 0.5 million m$^3$ mud import is reported in these former studies. The mud transports differ significantly because of the uncertainties in composing a mud balance. The marine mud that is transported into the estuary is deposited at sheltered places, such as the Land van Saeftinghe and secondary channels Vaarwater langs Hoofdplaat and Middelgat.
McLaren (1994) measured the mud fraction (defined as the percentage of sediment particles smaller than 64 µm) within the Western Scheldt. His results, shown in Figure 2.8, are relatively high compared to other studies. A comparison between mud observation studies is discussed in Dam and Cleveringa (2013). This discrepancy is probably caused by the method of measuring the mud content and the definition of mud that was used. Because of the lack of data of more detailed area-wide information, the McLaren data is used in most studies on mud in the Scheldt estuary. Even though the results of the studies differ significantly, it can be argued that the amount of mud in the bottom of the Scheldt estuary cannot be neglected (Dam & Cleveringa, 2013).

An important feature of the Scheldt estuary is the presence of an estuarine turbidity maximum (ETM) near the port of Antwerp. Van Kessel et al. (2006) explain the existence of this ETM by the combination of a vertical estuarine circulation and tidal asymmetry. Due to the density differences of the sea water and river discharge, a seaward surface flow and landward bottom flow arises. The fluvial mud particles settle to the lower layer and are transported to the head of salt intrusion. As the velocities during flood are higher than the ebb velocities, more sediment is transported upstream up to the point where the river discharge becomes dominant. Furthermore, more sedimentation occurs due to the difference in slack water period. Within a tidal cycle the concentration in the ETM can vary with a factor of 2 to 10. Due to tidal mixing the floc sizes are minimal, around 50 µm, in the middle of the Scheldt estuary. The interaction between salt and fresh water further upstream results in an increase in floc size to approximately 100 µm.

Another ETM can be found in the region of Zeebrugge, this turbidity maximum is less affected by density differences and is influenced by wave exposure. In Figure 2.9 the depth-averaged sediment concentrations are shown during winter.
2.2.5 Sediment transports and morphological development

Studies on the sediment balances of the Scheldt estuary (Nederbragt & Liek, 2004; Haecon, 2006) show a change in net sediment transport from import to export at the mouth of the estuary in the 1990s. These sediment balances did not discriminate between the contribution of sand and mud.

Cleveringa (2013) provides an overview of the large-scale sediment balance of the Western Scheldt for the period 1994-2010, see Figure 2.10. During this period the sediment volume in the western part of the estuary increased (+1.5 Mm$^3$/year) whereas the eastern part shows a decrease of sediment volume (-4.1 Mm$^3$/year). Due to sand mining a volume of around 2 Mm$^3$ per year was removed from the estuary. A few million m$^3$ of sediment was transported from the eastern part towards the western part by dredging activities.

Figure 2.9 – Average sediment concentration in mg/l (vertically averaged) during winter in the southern North Sea, derived from satellite images (Fettweis et al., 2007).

Figure 2.10 – Large-scale sediment balance in Mm$^3$/year for the period 1994-2010 (Cleveringa, 2013). Blue arrows indicate sediment transports, red arrows indicate transportation due to dredging activities.
Dam and Cleveringa (2013) differentiated between the contribution of sand and mud on the sediment balance. The sediment transport rates between these cells are based on the observed volume changes over a certain time period. The resulting yearly sand and mud transport rates can be found in Figure 2.11. They found that an export of sand and a larger import of mud resulted in an overall sediment import in the period 1994-2010. The sand export was confirmed by various sand transport models (e.g. Van der Werf and Briere (2013)). In general, an overall import of marine mud is found in the Western Scheldt. At the seaside the estuary exports sand, while on the landside the transport is directed upstream. The turning point can be found approximately halfway the estuary. In this particular study, the transport of 0.615 Mm$^3$ of both fractions is the transport of sediment into the Scheldt River and to the Land van Saeftinghe combined.

![Figure 2.11 – Yearly sediment transport rates in Mm$^3$ for the period 1994-2010 (Dam & Cleveringa, 2013): sand (yellow) and mud (purple)](image)

A few assumptions were made in order to estimate these numbers. The volume percentage of mud in the bed was based on the mass ratio, ignoring the density differences between mud and sand. Assumptions were made regarding the amount and distribution of sediment transport over the Dutch-Belgian border and to Land van Saeftinghe. Furthermore, the mud fraction (based on the McLaren data) in the bed was assumed to be constant over time and the volume effects of mixing mud and sand were not taken into account. Even though a lot of assumptions were made, their study shows the importance of taking the mud fraction into account in the sediment balance.

The direction of the sand transports changes in the western part of the estuary. On the seaside of the tilting point, the transports are in seaward direction whereas the transports indicate import on the landward side. The existence of such a tilting point is also found in Van der Wegen and Roelvink (2008), in which a schematized estuary with the approximate dimensions of the Scheldt estuary was modelled. They started their simulation with a uniform flat bottom and found that after many (thousands of) years the bed slope reaches an equilibrium slope and has a tilting point as described above.

Considering the sediment transports in time, Van der Werf and Briere (2013) found that the net sand transport becomes more offshore-directed in the western part of the Scheldt estuary. This is caused by the decrease in flood asymmetry which decreases sand import. The reduction of sand export in the eastern part of the Western Scheldt is explained by a decrease in the offshore residual current that counteracts the Stokes drift.
2.2.6 Ecological aspects
The Western Scheldt estuary consists of large areas of tidal flats and salt marshes. A lot of valuable flora and fauna can be found in this area and several parties have acknowledged the ecological value of this area. For example, the Land van Saeftinghe is one of the largest salt marshes in Europe; the area is about 3500 ha (Sistermans & Nieuwenhuis, 2004).

2.3 Numerical modelling

2.3.1 Numerical models
A model can be seen as a simplified representation of a system in the real (i.e. complex) world. A numerical model is able to simulate both the hydrodynamics and morphodynamics of a coastal system. In Figure 2.12 a schematised diagram is given to clarify the mutual influence of different processes. The interaction between these processes can be switched on and off in a numerical model. By including more processes, the computation time will increase and non-linear effects are introduced in the model.

![Diagram of modelled processes and their interaction](image)

Based on the bathymetry and boundary conditions, the model computes the hydrodynamic properties of the current and waves (1). The two way wave-current interaction (2) accounts for, amongst others, wave-driven currents and enhanced turbulence. The combined wave-induced and flow-induced forcing as well as the sediment properties are used to calculate the sand and mud transports (3). The net flux of each sediment fraction causes a change in bed composition (4). Sediment transports can only take place when enough sediment is available in the bed and also the interaction between sand and mud is taken into account (5 and 6). Finally, the changes in available mass of sediment are linked to bed level changes and the bathymetry is updated (7). The described computations are executed at each time step according to the online approach.
Morphological development takes place on time scales longer than the hydrodynamic processes. The sediment fluxes to and from the bed and the associated bed level changes can therefore be enhanced by a user-defined morphological factor. As the changes in available mass in the bed are multiplied by this factor, the morphological development is accelerated. This approach is valid as long as the bed level change per time step does not disturb the flow significantly and does not exceed 5% of the water depth (Roelvink, 2006).

2.3.2 Spin-up time
At the beginning of a simulation, the initial values are usually inconsistent with the boundary conditions of the model. The spin-up or warm-up period of a model is the time required by a model to adjust itself to match the prescribed boundary and initial conditions. There are two different ways to start a model. A cold start refers to the situation where a model uses user-prescribed input fields as initial conditions. Another approach is to restart a model; the saved fields can be used to continue the simulation. This is called a warm start and leads to a reduction of the model spin-up time. The required spin-up time is different for each of the modelled processes. The hydrodynamic processes develop faster from initial values into more realistic values that are in line with the boundary forcing compared to the bed composition of a model.

According to Schoellhamer et al. (2008), more computational time should be devoted to model spin-up. Adequate spin-up time of the order of years is required to initialise models; otherwise the solution will contain bathymetric change that is not due to environmental forcings, but rather improper specification of initial conditions and model parameters (Schoellhamer et al., 2008). They used a warm-up period of 10 years for their cohesive transport model of San Francisco Bay.

Dam et al. (2013) describe a 110 year morphodynamic hindcast for the Western Scheldt using a process-based model. They stated that the short-term results should be interpreted carefully as they are the influenced by spin-up effects of the model. The performance of their model improved over time. After a warm-up period of a few decades, the model reproduced the morphological development reasonably well.

Processes in the water column reach a state of statistical equilibrium under the applied forcing much faster. For example, Van Kessel et al. (2006) expected the simulation time necessary to find a truly stable salinity distribution to be in the order of 3 months.

2.3.3 Previous model studies
Different numerical models are capable of modelling the hydrodynamics and morphodynamics in the Scheldt estuary, some relevant examples are given below.

2.3.3.1 Delft3D-NeVla
The precursor of the Delft3D-NeVla model is the NeVla-Simona model, which is a 2DH (depth-averaged) model calibrated on astronomical components and ebb/flood water levels for the year 2006 (Maximova et al., 2009abc). This model has been converted to Delft3D and morphological processes have been implemented (Grasmeijer, 2013). Only the sand fraction is taken into account in the model. After the conversion, the model has been validated based on water levels and discharges. The morphological processes have been validated for the period 1998-2002. Next to the two-dimensional version, also a three-dimensional version of the Delft3D-NeVla model is available (Verheyen et al., 2013).
The two-dimensional Delft3D-NeVla model was used by Van der Werf and Briere (2013) to study the influence of morphology on tidal dynamics and sand transport in the Scheldt estuary. The only difference between the different simulations they analysed is the imposed bathymetry. Observations from 2006 were used to create boundary conditions for the model.

2.3.3.2 Mud model of the Scheldt estuary
Van Kessel et al. (2006) describe the development of a 3D mud-transport model for the Scheldt estuary, hereinafter referred to as mud model, in the framework of LTV. They studied the behaviour of mud particles in the Scheldt estuary, sand transports were not computed in their model. Also in this study, the NeVla-grid is used as computational domain. In vertical direction the depth is discretised in five layers.

The hydrodynamics, computed with the 3D NeVla-Simona model, have been validated based on water levels and flow velocities. A first calibration of the sediment concentrations was done using a point model, further calibration was based on a comparison between model results and observations. Their model has been improved over the years and their simulations have been used to deal with managerial issues in the Scheldt estuary.

The model has been used to perform a mud-transport simulation for the year 2006 (Van Kessel et al., 2011). Two model scenarios were set up; one with summer and one with winter conditions. The seasonality was taken into account in the initial conditions for salinity, in the upstream discharges and the wind forcing. The mud concentrations in both models were based on observations during summer and winter.

2.3.3.3 FINEL2D model of the Western Scheldt
Another study on the Western Scheldt has been carried out by Dam and Bliek (2013). They used a two-dimensional horizontal (2DH) process-based morphological model called FINEL2D. The main difference between this model and aforementioned models is the computational grid; FINEL2D makes use of an unstructured triangular grid whereas the NeVla-grid is a structured curvilinear grid.

Using the sand-mud module of FINEL2D, a part of the Western Scheldt (Schaar van Waarde) in which both the sand and mud fraction play a role in morphological changes was modelled in detail. They focused on the morphological development of a tidal flat and adjacent channel after the construction of two cross-shore groynes. As cohesive behaviour of the bed makes it harder to erode, a critical mud content value was used to distinguish between a cohesive and non-cohesive regime. Sand-mud interaction was taken into account by using different sediment transport formulations for both regimes to model the sediment transports. The model appears to have significant skill in reproducing the erosion/sedimentation patterns. Comparing the modelled and observed mud fraction, it can be concluded that the mud content in the bed was reproduced reasonably well over a period of 5 years.

2.3.4 Delft3D

2.3.4.1 General
The computer software package Delft3D can be used to simulate two-dimensional and three-dimensional flow, waves, sediment transport and morphological development. It consists of various modules enabling the modelling of interaction between the hydrodynamic forcing, water properties and sediment. The program is mostly used to simulate coastal, river and estuarine areas.
The most important module is called Delft3D-FLOW, in which hydrodynamic conditions such as velocity, water level, density, salinity, viscosity and diffusivity are modelled. The influence of waves can be included by coupling the Delft3D-WAVE module. Delft3D-FLOW and Delft3D-WAVE are discussed in Appendix A.1.

2.3.4.2 Modelling multiple sediment fractions

This section is based on Van Kessel et al. (2012). For more information on (the implementation of) layered bed stratigraphy, the fluff layer and the two regimes, one is referred to their report.

Layered bed stratigraphy

Besides imposing a uniformly well-mixed bed, there is also the possibility of using a layered bed stratigraphy in a Delft3D model. The composition of this layered bed consists of three parts (see Figure 2.13): the transport layer, the underlayers and the base layer.

![Layered bed stratigraphy](image)

The transport layer has a distribution function; it imports sediment to the computational cell in case of deposition and it exports sediment in case of erosion. The thickness of this layer is user-defined and is kept constant. After sediment is eroded from the transport layer, it is replenished by the underlayer cell directly beneath it to maintain the user-defined thickness. In case of deposition, the excess in the transport layer is redistributed to the underlayers. The base layer stores all the information that does not fit in the underlayers. When the maximum number of underlayers is exceeded, the bottommost layer is merged with the base layer.

By default, a mixed Lagrangian-Eulerian frame is used to treat aggradation and degradation. The transport layer has a predefined thickness that does not change in height whereas the height of the underlayers changes corresponding to the occurring aggradation or degradation.

The following example will illustrate how a layered bed stratigraphy leads to more realistic behaviour of the bed during erosion. Consider a layered bed with a relatively coarse sediment fraction and a relatively fine sediment fraction and a bed shear stress that only exceeds the critical value for the relatively fine fraction. Erosion of the fines will occur and the transport layer is replenished by the underlayer directly beneath it. The percentage of the relatively fine sediment fraction in this topmost layer reduces during this process. As less fine sediment is available in the transport layer, the erosion flux of fines from this layer decreases. In case only one bed layer would be used, more erosion of the fine sediments is found as the bed layer is treated as well-mixed.
Fluff layer
The fluff layer is a thin layer that is used to simulate the dynamical layer between the bed and the water column. It does not contribute to the bed or water depth and only consist of mud particles. In case of relatively high bed shear stresses, e.g. during flood velocities, fine sediments are stirred up and become suspended. During slack water these particles will settle again. This timescale is much smaller than for the bed layer below. To capture this physical behaviour of the fine particles, the fluff layer is treated different than the bed layers and has its own critical shear stress and erosion parameters.

The mud content in the fast-responding fluff layer depends on the fluxes from the bed and the water column;

Erosion of mud from the fluff layer into the water column:

\[ E_f = \rho_m f M_f (\tau_b - \tau_{f,cr}) \]  

With

\[ M_f = \min(m M_1, M_0) \]

Deposition of mud from the water column into the fluff layer:

\[ D_f = e_d (1 - \alpha) w_m c_m \]

Erosion of mud from the bed layer into the water column:

\[ E_b = \rho_m M_b \left( \frac{\tau_b}{\tau_{b,cr}} - 1 \right) \]

Deposition of mud from the water column into the bed layer:

\[ D_b = e_d \alpha w_m c_m \]

Where:

- \( m \): Total mass of the fluff layer per unit area
- \( M_0 \): Erosion coefficient \( \text{ParFluff0} \)
- \( M_1 \): Erosion coefficient \( \text{ParFluff1} \)
- \( e_d \): Deposition efficiency
- \( \alpha \): Deposition factor to bed layer(s) \( 0 \leq \alpha \leq 1 \)

Two different methods can be distinguished by this \( \alpha \)-term, which are illustrated in Figure 2.14. When \( \alpha = 0 \), the mud will be deposited into the fluff layer and no direct deposition into the bed layer occurs since \( D_b = 0 \). In this case, the deposition from the fluff layer to the bed layer is given by a burial term. This expression can be found in equation 2.23, in which \( B_0 \) and \( B_1 \) are burial coefficients and \( m \) is the total mass of the fluff layer per unit area.

\[ B_f = p_{m,f} \min(m B_1, B_0) \]  

\( \alpha > 0 \) results in deposition directly to both the fluff layer and bed layer. The erosion flux is the same for both methods.
Figure 2.14 – Fluff layer. Two different methods are available; \( \alpha = 0 \) (method 1) and \( 0 < \alpha \leq 1 \) (method 2).

The fluff layer is recently implemented and studies using this fast-responding layer show promising results. Scheel (2012) successfully used this fluff layer in combination with the bed stratigraphy module to assess large-scale sand-mud segregation patterns in a schematized tidal basin. Another application can be found in De Lucas Pardo (2014), in which the fluff layer was used to model the fine sediment transport processes in Lake Markermeer.

**Cohesive and non-cohesive regime**

Depending on the mud content in the bed, the layer can be classified as a non-cohesive sand-mud mixture or a cohesive sand-mud mixture. A distinction between the non-cohesive and cohesive regime can be made by defining a critical mud content \( p_{m,cr} \), for which Van Ledden (2003) suggested a value of 30%.

Van Ledden suggested to interpolate the erosion parameter \( M_e \) for the cohesive regime between the erosion parameter \( M_{nc} \) for the non-cohesive regime and the erosion parameter \( M_{fm} \) for the full mud regime. Obtaining the critical bottom shear stress was done in a similar way.

Since the Delft3D model is able to simulate several sand and mud fractions, this approach is not valid as each mud and sand fraction can have its own erosion parameter for the cohesive and non-cohesive regime respectively. Therefore, not the erosion parameter and critical bottom shear stress but the erosion velocity is interpolated between the two regimes.

In the non-cohesive regime \( (p_m \leq p_{m,cr}) \), mud is proportionally eroded with sand. The erosion velocity of sand is influenced by the mud content due to a change in critical bottom shear stress. In the Van Rijn et al. (2004) erosion formula, the critical shear stress for erosion is calculated by:

\[
\tau_{e,cr} = \tau_{s,cr}(1 + p_m)^3
\]

2.24

When only mud is available in the bed \( (p_m = 1) \), the erosion flux is calculated using the standard Partheniades-Krone formulation. In the cohesive regime \( (p_m > p_{m,cr}) \), the erosion
fluxes of sand and mud are proportional to the sand and mud fraction respectively. The erosion velocity is interpolated between the erosion velocity in the fully mud regime $E_{fm}$ and the erosion velocity in the non-cohesive regime $E_{sm}$ using equation 2.25.

$$E_m = E_{fm} \left( \frac{E_{sm}}{E_{fm}} \right)^{1-p_m}$$  \hspace{1cm} (2.25)

The erosion flux $S$ is computed by multiplying the erosion velocity with the density $\rho$ and mass fraction $p$:

$$S = \rho p E_m$$  \hspace{1cm} (2.26)

### 2.4 Conclusion

The tide-dominated Scheldt estuary consists of a system of channels and banks (Western Scheldt) and ebb-tidal delta (mouth of the estuary). Human interventions, such as dredging activities and river training, has led to a less dynamic system in which the natural meandering of the channels is counteracted. The bed at the intertidal areas and near the more sheltered fringes of the estuary consists of a mixture of sand and mud. The sediment-transport patterns indicate an overall import of marine mud into the Western Scheldt. At the seaside the estuary exports sand to the North Sea, while on the landside the transport is directed upstream.

Different studies have shown the potential importance of the interaction between sand and mud on the morphological development and the difference in behaviour to the hydrodynamic forcing. As most of the studies on the behaviour of sand and mud in the Scheldt estuary are carried out in separate models, the mutual influence of sand-mud mixtures is neglected. The interaction between the two fractions can be modelled using the recently implemented bed module in Delft3D.
3 Model setup

3.1 General approach of the model

The model of Van der Werf and Briere (2013) representing the year 2006 is used as basis for the model study performed in this thesis. The model is extended with mud properties by using model settings and results of the mud model described by Van Kessel et al. (2011).

As both models were used to simulate the year 2006, the choice is made to make the model representative for this year. To reach the objective of this study hindcasting a certain period is not required and therefore another year could also have been simulated. However, since the availability of calibrated and validated models for simulating both the hydrodynamics and sediment dynamics, the model is attempted to be representative for the year 2006.

A representative period in the year 2006 is selected and the available data from observations and model results are used as initial and boundary conditions. The main reason of using this data instead of schematised conditions is the preservation of the natural variability of the forcing. Furthermore, imposing the resulting bed composition and initial mud concentration from the mud model can be considered a best guess since no other detailed information is available.

Wind and waves are included in the model to study the effects of these phenomena on the sediment-transport patterns and bed composition. To analyse the erosion/sedimentation patterns, the model is used to perform morphodynamic simulations. This means that the bed level is updated in time. Also the bed composition is calculated at every time step. Since the model is depth-averaged, vertical circulations are not included. This means that potential circulations due to density differences, wind forcing and curvature-induced flows are neglected.

3.2 Grid

The original NeVla grid covers the mouth of the estuary, the Western Scheldt and Belgian rivers until the upper point of tidal influence. The resolution of the computational grid varies between approximately 400 m on the North Sea and gradually decreases to around 30 m near Schelle (see Figure 3.1).
As this study focuses on the Western Scheldt and the outer delta, the grid upstream of Schelle is not used. By decreasing the amount of grid cells the calculation time is reduced. The new upstream boundary conditions are imposed at Schelle. The sea boundaries indicated in this figure are called north-eastern sea boundary (1), north-western sea boundary (2) and south-western sea boundary (3).

For the computation of wave propagation into the estuary, a wave grid is used that is twice as coarse as the regular computational grid. The grid covers the same area as the regular computational grid to study the effect of both waves formed at sea and locally generated wind-waves.

3.3 Simulation period
In order to save calculation time, one representative spring-neap tidal cycle is used as simulation period instead of simulating an entire year. The measured water levels at Vlissingen are used to discern 24 separate spring-neap cycles within the year 2006 that all start during neap tide. At the start of these cycles, the water levels are rising and are around 0 m NAP.

The aim is to find a period in which the hydrodynamic forcing is quite comparable to the annual characteristics. As the tidal variation, which is more or less a deterministic process, does not differ significantly between the different periods the focus is on wave and wind characteristics. The variation in these processes does vary significantly within the year 2006. The selection of a representative simulation period focusses especially on waves as their effect on the sediment transports is considered to be more important.
For each of the periods, the wave and wind roses are compared to roses for the year 2006. The wave data of location Europlatform is used and for the wind data an observation station in Vlissingen is used. These two locations are indicated in Figure 3.1. The selected spring-neap tidal cycle occurs between 07-Apr-2006 19:50:00 and 22-Apr-2006 06:00:00, a 14.4 day period. The wave and wind rose for this period as well as for the year 2006 are illustrated in Figure 3.2 and Figure 3.3 respectively.

![Wave rose year 2006](#) ![Wave rose simulation period](#)

*Figure 3.2 – Wave rose for the year 2006 (left) and wave rose for the simulation period (right) according to nautical convention*

![Wind rose year 2006](#) ![Wind rose simulation period](#)

*Figure 3.3 – Wind rose for the year 2006 (left) and wind rose for the simulation period (right) according to nautical convention*

By simulating this aforementioned period, not only the daily fluctuations can be found in the model but also the spring and neap tides are present. An even further shortening of the simulation period (e.g. only one tidal cycle) would lead to the lack of this variation, which is considered to be important for the behaviour of the sediment particles.

The model simulation starts at 05-Apr-2006 19:50:00 with a 2-day spin-up time. During this spin-up period the water levels and flow velocities develop from spatial uniform values (water level of 0 m NAP and no flow velocities) into more realistic values where the hydrodynamics
are in line with the boundary forcing. For more information on the selection of the representative simulation period, see Appendix B.1.

3.4 Boundary conditions

3.4.1 Boundary conditions at the North Sea

The north-eastern and south-western boundary conditions at the North Sea are given by velocities. The boundary parallel to the coast is described by Riemann invariants. These downstream boundaries were computed by another model containing the complete North Sea. As this North Sea model also simulates wind, potential wind set-up at the mouth of the estuary is included.

The mud concentrations that are used at the North Sea boundaries contain mean values of available summer and winter data. At the north-eastern sea boundary the mud concentration decreases from 47 mg/l a few kilometres from the coast to 7 mg/l at sea. The mud concentrations along the south-western sea boundary are higher because the boundary is located in a turbidity maximum, they vary from 182 mg/l near the coast to 15 mg/l at sea. The exact distribution along the boundaries can be found in Appendix B.2.1. For the north-western sea boundary a constant concentration of 11 mg/l is used. The Thatcher-Harleman time lag at the north-eastern boundary is set at 2 hours. As the residual current along the coast is directed from south to north, this is only applied to the northern boundary.

A Neumann boundary condition (a zero concentration gradient) is used for the sand concentrations. This implies that the concentrations at the boundary are equal to those just inside the model domain. Time series of salinity are imposed at the boundaries and the concentrations are around 32 ppt.

3.4.2 Boundary conditions at Schelle

To prevent ill-imposed boundary conditions at Schelle, a simulation was made with the original grid and the final settings as described in the following chapter in order to get time series of discharge, salinity and mud concentration at Schelle. The discharges and concentrations used for the upstream rivers are discussed in Appendix B.2.2.

An observation point and cross-section are used to monitor the discharge, salinity and mud concentration over time at Schelle. In the new grid, the boundary is located at the mentioned cross-section and the observed values are imposed as the new upstream boundary conditions.

3.4.3 Wind and waves

Adoption of both the initial values for the bed composition and the wind-wave climate should prevent a mismatch between the initial and boundary conditions as they would both be derived from the original mud model. However, different software was used and the implementation of wind and wave forcing is not perfectly transmissible. Therefore, new boundary conditions are created using data from Rijkswaterstaat (2015a). Time series from monitoring stations at sea are used as boundary conditions for the wave grid. Wind data of station Vlissingen is used to include wind in the model. The locations of these observation points are indicated in Figure 3.1.

During the simulation period there is no wave data available at Schouwenbank, located close to the boundary of the wave grid. Therefore the data of Europlatform is used as boundary condition for the computation of wave propagation. As the Europlatform is located further
offshore, the waves observed at this station are higher. The annual mean values for the year 2006 differ a factor of 1.34. The imposed significant wave heights $H_s$ are therefore divided by this factor while the used peak periods $T_p$ and wave directions are based on the measurements at Europlatform. The numerical settings for the wave computation are adopted from Van Rooijen (2015). The wind speed and direction are based on observations at Vlissingen. The wind and wave characteristics over time can be found in Figure 3.4.

Figure 3.4 – Imposed wind and wave characteristics based on measurements by Rijkswaterstaat (2015a)

### 3.5 Initial conditions

#### 3.5.1 Bathymetry

The bed of the Western Scheldt consists of several non-erodible layers, therefore not only the bathymetry for 2006 but also the corresponding erodible layer is used in the model. This layer, used to describe the availability of sediment, takes the observed non-erodible layers in the Scheldt estuary into account (Dam, 2013). The bathymetry and the erodible layer thickness are illustrated in Figure 3.5 and Figure 3.6 respectively. The third deepening, that took place in 2010, is not included in the bathymetry.

A Manning roughness field is applied with stepwise varying coefficients in the area of interest between 0.024 s/m$^{1/3}$ and 0.028 s/m$^{1/3}$. These values were used to calibrate the phase and magnitude of the most important harmonic tidal components (Maximova et al., 2009a).
3.5.2 Salinity

Horizontal gradients in salinity cause a density-driven current. The effect of salinity on the modelled flow velocities and bed shear stresses is not considered to be negligible. The initial salinity distribution is based on the output of another Delft3D-NeVIA model of the Scheldt estuary (Tonnon & Van der Werf, 2014). The salinity distribution, depicted in Figure 3.7, varies from 32 ppt at sea to less than 1 ppt at Schelle.
3.5.3 Mud concentration in the water column and mud fraction in the bed
As the original mud model is 3D, the initial spatial varying mud concentration in the water column is based on the annual mean of central layer. The initial mud concentration varies from 15 mg/l at sea, to 40 mg/l in the Western Scheldt to 150 mg/l near Schelle. A turbidity maximum can be found in the region of Zeebrugge (see Figure 3.8).

As much more mass of mud is kept in the bed compared to the part in suspension, the initial bed composition is more important than the initial mud concentration in the water column. The resulting equilibrium composition found in the original mud model is imposed as initial mud fraction. The yearly averaged values that were used as initial values are depicted in the top panel of Figure 3.9. On the intertidal areas and sheltered areas the mud fraction is 20-50%, at locations with higher hydrodynamic forcing a mud fraction of only a few percent can be found.
Figure 3.9 – Initial mud fraction in the bed and measurements by McLaren (1994). A comparison in the lower panel shows in red (blue) the locations where McLaren found a lower (higher) mud content.

Compared to the imposed mud fraction in the model, the McLaren (1994) data shows higher values near the fringes of the estuary and slightly lower values in the deeper channels (see Figure 3.9). The mud fraction of the mud model is used as initial bed composition since this model provides more spatially-detailed information and it covers the entire area of interest. Furthermore, it is consistent with the approach of using the mud model for mud related properties.

3.6 Sediment and morphology input
For a first simulation, the initial sediment parameters and morphological settings regarding the modelling of sand and mud are based on Van der Werf and Briere (2013) and Van Kessel et al. (2011) respectively. A critical mud content of 0.3, as proposed by Van Ledden (2003), is
used to distinguish between a cohesive and non-cohesive regime. The Van Rijn transport formula (Van Rijn et al., 2004) is used for the non-cohesive sand fraction and the transportation of cohesive particles are calculated with the Partheniades-Krone formulation (Partheniades, 1965; Krone, 1962).

A morphological factor \((\text{MorFac})\) of 25 is used to accelerate the morphological development in the model. The modelled changes in available height of sediment are thereby scaled up to yearly values. An example of the two-layered bed stratigraphy used within this model is given in Figure 3.10. The top layer is the transport layer and has a constant height of 10 cm. The total height of the two bed layers corresponds to the height of the erodible layer. In the lower panel, the two different layers can be distinguished. The fluff layer, located between the water column and the bed, is not shown in this figure.

![Mud fraction in cross section](image)

![Mud fraction in cross section - detail](image)

**Figure 3.10 – Bed stratigraphy along arbitrary cross-section. In the lower panel the transport layer and bed layer are illustrated.**

### 3.7 Synthesis

An existing model of the Scheldt estuary is extended with a mud fraction based on a mud model of the same area. The model is made representative for the year 2006 by using a representative spring-neap tidal cycle. The computational grid upstream of Schelle is not used and new boundary conditions are imposed at this location. Time series of the wind and wave data are used as boundary conditions. Initial conditions of the model are based on the results of previous model studies to avoid a large spin-up time. The sediment and morphology settings are based on the two original models of the Scheldt estuary. Two bed layers are described, a fluff layer is added and use of made of a critical mud content to improve the modelling of multiple sediment fractions.
4 Model assessment

4.1 Approach

4.1.1 General
The first model results are analysed to assess the performance of the model. Model output is generated at several conventional observation points and cross-sections, indicated in Figure 4.1. The observation points are used to monitor, amongst others, water levels, sediment concentrations and salinity. The cross-sections are used to calculate sediment transports between the different macro cells.

![Figure 4.1 – Observation points (indicated by dots) and the cross-sections between different macro cells](image)

A list of desiderata is used to evaluate the performance of several aspects of the model. After obtaining insight in the capability of the model, conclusions can be drawn about the validity of the model. A simulation period longer than 14.4 days (which corresponds to a morphological time of one year) is needed to determine whether the model results are still influenced by spin-up effects. By using a simulation loop, shown in Figure 4.2, the development in the model domain can be subjected to a longer simulation period. When a run is finished, the output is used as input for the subsequent run. As the morphological development is caused by the hydrodynamic forcing, it is hard to reach an equilibrium with changing hydrodynamics. The morphological development is therefore subjected to the same hydrodynamic forcing in every loop by using the same simulation period for several times. Following this approach a dynamic equilibrium can be reached.
As morphological developments on the large spatial-scale are linked to large time-scales, it might not be possible to reach a state of statistical equilibrium with this model in a reasonable period. The required warm-up period is expected to be in the order of decades (Schoellhamer et al., 2008; Dam et al., 2013). As the development of morphological processes takes much longer to develop into a fully stable distribution, the model results depend on the choice of initial conditions.

The aim of the simulation loop is to show that the largest redistribution, caused by a mismatch in initial and boundary conditions, takes place during the first loop(s). However, as each process needs a different spin-up period, a list of requirements is formulated for each process.

4.1.2 Desiderata

The model will be used to analyse relative differences between different scenario runs. Therefore, it is not necessary to exactly reproduce the results or observations of other model studies. However, as the model results depend on the choice of initial conditions, the goal is to start with a warmed-up model that will produce realistic outcomes. The model is considered to be warmed up enough when the desiderata, described below, are fulfilled.

1a) After decreasing the model domain by putting boundary conditions at Schelle, the modelled water levels in the estuary are still in good agreement with the observed ones.
1b) The modelled flow velocities, salinity and mud concentrations downstream of Antwerp are not influenced by the adjusting of the upstream boundary.
2a) The spatially-mean concentration of mud in the Western Scheldt is around 50 mg/l and the ETM’s near Zeebrugge and Antwerp are present.
2b) Fluctuations of the intra-tide mud concentration are factor of 2 to 5 and the fluctuations of spring-neap mud concentration are factor of 1.5 to 3.
3) The salinity distribution is significantly warmed-up and is mainly affected by the tidal variation.
4a) The computed mud transport in the final simulation is qualitatively comparable with those of the mud model.
4b) The computed cumulative total transport for both sand and mud are stable after the warm-up period.
5a) The modelled erosion/sedimentation patterns are comparable with the observed change in bathymetry.
5b) The bed levels show a more or less stable behaviour after the spin-up period.
6) The largest redistribution of sand and mud takes occurred in the warm-up period and do not change significantly in the final simulation.

4.2 Calibration

4.2.1 Calibration process

Some sediment parameters, which were used in different software, are adjusted to enhance the realism of computed mud concentrations in the water column. This is necessary as slightly different formulas for the erosion and sediment fluxes were used in the mud model of the Scheldt estuary (see Appendix C.1). Neglecting horizontal fluxes, the concentration in the water column is the result of the erosion and deposition of mud particles. However, due to the different erosion formulas, the relation between the parameters for these two fluxes is not retained.

The model parameters that are treated the same in the different software are directly adopted. The fall velocity of mud, the critical bed shear stresses (for both the bed layer and fluff layer) and the fraction of the sedimentation flux that is deposited directly to the bed layer (DepFac) are kept the same. The parameters that are changed during the calibration are the deposition efficiency (DepEff) and the erosion parameters (ParFluff0, ParFluff1 and EroPar). The ratio between the erosion parameters for the fluff layer ParFluff0 and ParFluff1 is retained.

The output of the original mud model at observation point ‘Hansweert’ is used to calibrate the parameters. The same simulation period is analysed in both models and the variations due to spring-neap tides should therefore match.

4.2.2 Calibration results

The modelled mud concentration with the final settings is shown in Figure 4.3. A perfect match between the two results could not be achieved. This can be explained by, amongst others, the difference in implementation of wind and wave forcing. In the original mud model a constant wave-induced bed shear stress was imposed whereas the sand-mud model uses a more realistic forcing. Furthermore, the mud model is a 3D model whereas the model used within this thesis is depth-averaged (2DH). With the resulting settings, the mean trend is considered to be sufficiently reproduced by the model.
The erosion parameter for the bed layer $EroPar$ is set at $1.0 \times 10^{-4}$ kg/m$^2$/s. The erosion parameters for the flux layer, $ParFluff0$ and $ParFluff1$, are $1.25 \times 10^{-4}$ s/m and $2.9 \times 10^{-5}$ ms/kg respectively. The deposition efficiency $DepEff$ is lowered to 0.4, which has the same effect as setting the fall velocity of the mud particles to 0.4 mm/s. The resulting parameters, see Table 4.1, are used in following simulations.

Table 4.1 – Sediment model parameters

<table>
<thead>
<tr>
<th>Sediment</th>
<th>SedTyp</th>
<th>SedDia</th>
<th>RhoSol</th>
<th>CDryB</th>
<th>200 μm</th>
<th>1600 kg/m$^3$</th>
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</tr>
<tr>
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<td></td>
</tr>
<tr>
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<td>$2.9 \times 10^{-5}$ ms/kg</td>
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</tr>
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</tbody>
</table>

4.3 Model validation
The model results are evaluated by the aforementioned desiderata to determine whether the model is sufficiently capable to use in this study. In this section the results of the final
calibrated simulation will be discussed. This simulation starts after being subjected to the simulation loop for three times.

4.3.1 Desiderata 1: Water levels and model results near Schelle
The impact of the relocation of the upstream boundary towards Schelle has been analysed, an elaboration can be found in Appendix C.2. The adjustment has no significant effect on the model results. The modelled water levels along the model domain are still in good agreement with the observed ones. At observation point ‘Antw Loodsgebouw’ the model gives approximately the same results for the water level, depth-averaged discharge, salinity and mud concentration.

4.3.2 Desiderata 2: Mud concentration in the water column
The desiderata concerning the mud concentrations are based on the performances and desiderata of the mud model of the Scheldt estuary (Van Kessel et al., 2006). The desired features of their model are based on data analysis.

In Figure 4.4 the mud distribution at an arbitrary time is depicted. The concentration of mud varies, due to the tides, between 20 and 60 mg/l in the middle part of the Western Scheldt. Locally higher concentrations can be found at the Scheldt River and along the Belgian coastline. These locations match with the observed ETM’s in the Scheldt estuary.

![Figure 4.4 – Mud concentration in the water column in mg/l](image)

In Figure 4.5 the concentration of mud in the water column is plotted for several observation points, the result of ‘Vlakte van de Raan’ is not included as the mud model does not have this monitoring station. The overall trend of the model results (blue) are in good agreement with the modelled concentrations in the mud model (red). The intra-tide fluctuations are around a factor of 2 and the spring-neap fluctuations are approximately a factor of 3. These fluctuations depend on the location within the estuary. Even though the mud parameters were only calibrated on the mud concentration at location ‘Hansweet’, the results show that the mud concentration at other observation points is reproduced reasonably well.
Figure 4.5 – Modelled mud concentration in the water column in mg/l (blue) and the results of the mud model (red)

Figure 4.6 shows the mud concentrations during the simulation loop. In each of the plots regarding the simulation loop, the average value $\bar{\mu}$ and standard deviation $\sigma$ are given to quantify the development of the discussed property. The standard deviation is an indication for the spread of the distribution. During the simulation loop, these parameters will develop towards a statistical equilibrium. The smaller the differences between the loops, the more stable are the model results.

The results of the simulation loop show that the concentrations need a relatively short time to develop into some kind of a dynamic equilibrium. The closer the observation point is to the North Sea, the longer it takes to reach a stable distribution.
4.3.3 Desiderata 3: Salinity distribution

As density differences introduce an extra flow and associated sediment transport, the salinity distribution in the model should be sufficiently stable. The model results in Figure 4.7 show that no significant changes occurred during the several simulation loops. The dynamic behaviour can be explained by the tidal variation.

Figure 4.6 – Mud concentration in the water column in mg/l during simulation loop
4.3.4 Desiderata 4: Sediment transports
The modelled mud transports, up-scaled to yearly values, are shown in Figure 4.8. The transport patterns show, in agreement with Cleveringa and Dam (2013), export of sand near the mouth of the estuary and a tilting point in the middle of the estuary.

The model results do not match the import of mud that was found in their study. According to the model, export of mud takes place at the seaside of the Western Scheldt and this export gradually decreases in upstream direction. From the Dutch-Belgian border seawards, the mud transports over the cross-sections are increasing. This is probably caused by an excess of imposed mud in the Western Scheldt.
In the first version of the mud model, a relatively large export of mud was found at the mouth of the estuary, whereas the mud at the Dutch-Belgian border was found to be transported further upstream (Van Kessel et al., 2006). Depending on the different model scenarios Van Kessel et al. used (representing winter, summer or a combination of both), the sediment transport differs. However, the general transport pattern of a large export at the mouth and smaller import near the Dutch-Belgian border remained the same. The overall trend found in the sand-mud model is in good agreement with the first mud model results.

Focussing on the mouth of the estuary, a transition of modelled export to import can be obtained by enhancing the trapping efficiency of mud in the Western Scheldt. Mud that is transported into the basin settles at locations with calm hydrodynamic conditions and could get trapped. After improving the performance of the mud model, Van Kessel et al. (2011) found a negligible net transport in the mouth of the estuary and a small import of mud further upstream.

The results of the simulation loop, see Figure 4.9 and Figure 4.10, show that the modelled morphological development is of minor importance on the mud transports. Since the availability of mud in the bed layers is not significantly affected (yet), the mud concentrations and thus transports are very similar during each loop. The morphological development due to gradients in sand transports is found more locally compared to mud. This explains the relatively large change in sand transports during the simulation loops. According to the results of the simulation loop, the largest redistribution of sand occurs in the first two loops. As the difference in overall trend of the cumulative sand transport in the last loops is relatively small, the sand transports are considered to be stable.
4.3.5 Desiderata 5: Erosion and sedimentation patterns

The modelled bed level change in Loop D are compared to the observed morphological change in Figure 4.11. The observed bed level change is acquired by comparing the bathymetries for the year 2005 and 2008 (Rijkswaterstaat, 2015b). This difference in bed level is divided by three to obtain an annual mean.

Figure 4.9 – Cumulative total transports of sand in m$^3$/year during simulation loop

Figure 4.10 – Cumulative total transports of mud in m$^3$/year during simulation loop
The largest bed level changes can be found in the Western Scheldt, the bed level in the mouth of the estuary is more stable. The alternating areas of erosion and sedimentation indicate migrating channels and tidal shoals. At some locations, the modelled erosion/sedimentation pattern is comparable to the observed ones. However, the model is not able to correctly reproduce the observed morphological development over the last years. One of the reasons for this shortcoming might be spin-up effects. As the required warm-up period is expected to be in the order of decades, the currently used simulation period is too short. Furthermore, there are no dumping and dredging activities included in the model. When these processes are included in the model, certain bed levels are maintained and sediment is redistributed to a user-defined location. As dredging activities take place at location where a lot of sediment is deposited, it counteracts the natural morphological changes.

Figure 4.12 shows the bed levels at the end of each simulation in the simulation loop (left panel) and the cumulative erosion/sedimentation during that simulation (right panel). The morphological development shows that the largest redistribution of sediment takes place in the first loops. The erosion/sedimentation pattern for Loop C and Loop D are already more alike. The model results are still dependent on the initial conditions, but the development is now better predictable.
4.3.6 Desiderata 6: Availability of sand and mud

The morphological development discussed in the previous section can be linked to changes in the availability of sand and mud. By dividing the sediment mass by its dry bed density, the changes in sediment mass are also expressed in units of length. In Figure 4.13 and Figure 4.14 the loop results are shown for the sand and mud fraction respectively. The panels on the left-hand side illustrate the change in available height of sediment during the simulation loop. The difference between these changes is shown at the right-hand side.

The modelled bed level change is mainly caused by the transportation of sand; the contribution of mud is significantly smaller. The imposed boundary conditions are not in line with the initial mud fraction in the bottom. During Loop A, erosion of mud is found in the entire domain. This is also caused by the lack of sediment in the fluff layer in this first simulation. The simulation loop results illustrate how the mud distribution in the model domain develops over time. Mud is transported from the Western Scheldt to the mouth of the estuary.

Figure 4.12 – Left: Bed levels at the end of each simulation.
Right: erosion (blue) and sedimentation (red) at the end of each simulation.
Despite the acceleration of morphological development by the *MorFac*, the relative changes in available height of sediment are small. According to the simulation loop results, the largest redistribution takes place during the first loop and the changes between subsequent runs are more alike. From the right-hand side panels it can be concluded that the bed level changes are sufficiently stable.

Figure 4.13 – Left: change in available height of sand in m at the end of each simulation. Right: development of available height of sand in m during the simulation loop.
4.3.7 Longer simulation period

The spin-up effect of the model is responsible for the discrepancy between the modelled export of mud and observed import of mud. The used warm-up period of three years is too short to fully develop the bed composition and bed levels into a state where they are in line with the boundary conditions. It is expected that when a much longer warm-up period is used, the modelled export of mud will turn into import. According to model results in Table 4.2, the modelled export gradually decreases when a simulation period of 8 loops is used. Including dredging activities in the model should also increase the mud import. The cohesive sediment deposits in sheltered areas, but as no maintenance dredging is modelled siltation of the harbours stops once they are filled.
Table 4.2 – Mean value $\mu$ and standard deviation $\sigma$ of mud transport in simulation loop

<table>
<thead>
<tr>
<th>In 10$^5$ m$^3$/year</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crs #1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\mu$</td>
<td>-0.68</td>
<td>-1.17</td>
<td>-1.43</td>
<td>-1.38</td>
<td>-1.19</td>
<td>-0.98</td>
<td>-0.82</td>
<td>-0.69</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>0.88</td>
<td>1.55</td>
<td>1.86</td>
<td>1.94</td>
<td>1.95</td>
<td>1.94</td>
<td>1.94</td>
<td>1.93</td>
</tr>
<tr>
<td>Crs #2</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\mu$</td>
<td>-0.93</td>
<td>-1.26</td>
<td>-1.38</td>
<td>-1.36</td>
<td>-1.29</td>
<td>-1.21</td>
<td>-1.15</td>
<td>-1.10</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>0.92</td>
<td>1.36</td>
<td>1.52</td>
<td>1.54</td>
<td>1.51</td>
<td>1.46</td>
<td>1.42</td>
<td>1.39</td>
</tr>
<tr>
<td>Crs #3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\mu$</td>
<td>-0.78</td>
<td>-0.90</td>
<td>-0.83</td>
<td>-0.74</td>
<td>-0.67</td>
<td>-0.63</td>
<td>-0.60</td>
<td>-0.58</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>0.65</td>
<td>0.84</td>
<td>0.82</td>
<td>0.76</td>
<td>0.72</td>
<td>0.68</td>
<td>0.66</td>
<td>0.64</td>
</tr>
</tbody>
</table>

4.4 Discussion

Some numerical instability occurred during the calibration process which resulted in chessboard patterns in plots of the bed level changes. This is a known problem in modelling with Delft3D and it also appeared in the sand-mud model of Scheel (2012). To ensure numerically stable model results, the erosion/deposition fluxes of the mud fraction should not be too large. As the net flux is the sum of the gross erosion and sedimentation fluxes, the erosion parameters and deposition efficiency is lowered to achieve a more stable concentration of mud in the water column.

The mud concentrations are calibrated and validated based on the sediment concentrations in the top layer of the mud model. The mud model is a three-dimensional model and the erosion and sedimentation fluxes in the bottommost layer are therefore influenced by the bed layer beneath it and the water layer directly above it. The modelled concentrations are underestimated since the mud concentrations near the bottom are higher.

As the model is used to investigate the relative effects of different forcing components, the validation process focusses on the stability of the model outcomes. The spin-up period of the model is too short to let the available mass of the sediments develop into a state where they are in line with the boundary conditions. The result is that the calculated sediment transports are still affected by the initial bed composition. The modelled export of mud, which is considered to be an important flaw of the model, is caused by the dependency of the mud transports on the initial conditions. Forced by imposed mud concentrations at the North Sea boundaries, the modelled export of mud will probably eventually change into import at the mouth of the estuary. This assumption is supported by the gradually decreasing export found in the simulation loop.

The erodible layer was used in the morphological-validated sand model which is the basis for the model study performed in this thesis. The initial mass of mud available in the bed is derived from the combination of the height of the erodible layer and the mud fraction in the original mud model. This influences the sediment transports as (almost) no sediment is available at some locations.

The desideratum regarding the modelled morphological development is not satisfied. The model is not able to reproduce the bed level changes over the last years. The first cause for this shortcoming of the model is the discussed spin-up effect. Morphological changes are still caused by the adaption of the model to the imposed boundary forcing and are not solely due to the modelled physics. Secondly, dredging and dumping activities were not modelled. Maintenance dredging does not only prevent the siltation of harbours and navigational channels, this human intervention also causes a net transport of sediment from the eastern to the western side of the estuary.
4.5 Conclusion

4.5.1 Evaluation

The relocated upstream boundary has no noticeable effect on the model results in the area of interest. The model proves to have sufficient skill producing realistic mud concentrations in the water column as the formulated requirements regarding this aspect are fulfilled. Also the salinity desideratum is satisfied since the simulation loop results indicate a statistical equilibrium is reached.

The erosion/sedimentation patterns are mainly caused by the sand fraction. The simulation loop results indicate that the morphological development due to the transportation of mud is more subtle. The effect of the mud redistribution is spread over the domain and thereby has hardly any effect on the computed mud transports. The effects of sand transport on the morphology are found more locally compared to the impact of mud fraction. This also results in the changing cumulative sand transports in the simulation loop. In the last loop, the transports can be considered sufficiently stable.

The desiderata regarding the hydrodynamic properties, mud concentrations and salinity are satisfied. The model is not able to correctly reproduce the observed morphological development over the last years. However, the used warm-up period was sufficient to ensure stable results regarding the morphological development. As the model will be used to analyse relative differences and not to reproduce exact findings, the warmed up model is considered to be capable for analysing the model scenarios in the next chapter.

4.5.2 Final model settings

The initial conditions for the bathymetry, salinity distribution, mud concentration in the water column, initial height of available sand and mud and corresponding mud fraction in the bed are given in Figure 4.15 – Figure 4.20 respectively. These conditions will be imposed as initial values in the scenario runs described in Chapter 5. The most important settings of the sediment characteristics and morphological processes are given in Table 4.3 and Table 4.4 respectively.

Compared to the initial settings (Loop A) discussed in Chapter 3, the imposed bathymetry and salinity field are not significantly changed. The mud concentration is lower as not a time-averaged distribution is used but the results at the end of the simulation during neap tides. The available height of sand and mud is still largely determined by the initial erodible layer. The inclusion of wind and waves in the model has led to a significant reduction of the mud fraction over the entire domain. Mud is transported from the Western Scheldt towards the North Sea.
Figure 4.15 – Bathymetry in m NAP

Figure 4.16 – Initial salinity distribution in ppt

Figure 4.17 – Initial mud concentration in the water column in mg/l
Figure 4.18 – Initial height of available sand in the bed in m

Figure 4.19 – Initial height of available mud in the bed in m

Figure 4.20 – Initial mud fraction in the bed
Table 4.3 – Sediment model parameters

<table>
<thead>
<tr>
<th>SedTyp</th>
<th>SedDia</th>
<th>RhoSol</th>
<th>CDryB</th>
<th>EroPar</th>
<th>WS0</th>
<th>TcrSed</th>
<th>TcrEro</th>
<th>DepEff</th>
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<tbody>
<tr>
<td>Sand</td>
<td>200 μm</td>
<td>2650 kg/m³</td>
<td>1600 kg/m³</td>
<td>1.0⋅10⁻⁴ kg/m²/s</td>
<td>1 mm/s</td>
<td>1000 Pa</td>
<td>0.5 Pa</td>
<td>0.4</td>
</tr>
</tbody>
</table>

Table 4.4 – Morphology model parameters

<table>
<thead>
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<th>MorFac</th>
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<th>NeuBcSand</th>
<th>true</th>
</tr>
</thead>
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<tr>
<td>BedUpd</td>
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<td>NeuBcMud</td>
<td>false</td>
</tr>
<tr>
<td>CmpUpd</td>
<td>true</td>
<td></td>
<td></td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Type</th>
<th>DepFac</th>
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</thead>
<tbody>
<tr>
<td>2</td>
<td>0.1</td>
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</tbody>
</table>
5 Scenario testing

5.1 Relative influence of the hydrodynamic forcing

5.1.1 Description of the model scenarios
Several model scenarios are designed to determine the importance of tides, wind, sea-waves and wind-waves on the sediment transports and morphological development of the Scheldt estuary. The first model scenario uses the input as described in section 4.5.2 and includes the forcing of tides, wind and waves (A1). To assess the net effect of the tidal movement a simulation is made with solely the tides as forcing mechanism (A2). Simulations are performed with tides and waves (A3) as well as with tides and wind (A4) as forcing components to investigate the impact of wind and sea-waves separately. Wave growth due to wind is not simulated in A3 as no wind is included. Furthermore, no wind-waves are formed in A4 because wave properties are not computed in that simulation. An overview of the model scenarios and included forcing is given in Table 5.1.

Table 5.1 – Overview of model simulations regarding tides, wind and waves

<table>
<thead>
<tr>
<th>Simulations</th>
<th>Description</th>
<th>Tides</th>
<th>Wind</th>
<th>Waves</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>Reference run, input as described in section 4.5.2</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>A2</td>
<td>As A1, but waves and wind are not included</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A3</td>
<td>As A1, but wind is not included</td>
<td>✓</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>A4</td>
<td>As A1, but waves are not included</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
</tbody>
</table>

By subtracting the results of the model scenarios, the tide effect (A2), wind effect (A4 - A2), sea-wave effect (A3 - A2) and wind-wave effect (A1-tide-wind-waves) can be analysed. The sea-wave effect refers to the influence of waves that are formed at sea and propagate into the model domain. The impact of locally generated waves that are formed due to the friction at the interface between air and water is included in the wind-wave effect. The wind-wave effect also accounts for the growth of sea-waves due to wind stress. For all components it holds that interaction between the component itself and tides is included. The following hypotheses are based on the literature review in Chapter 2:

Hypothesis 1
Compared to the other physical processes, the tides are the main contributor to the sediment transports and morphological development of the Scheldt estuary.

Hypothesis 2
The role of wind is especially important for the morphological development of the intertidal areas of the estuary. Due to the wind-induced shear stress, mud particles are entrained from the bed and exported from these areas.

Hypothesis 3
The effect of sea-waves on the sediment transport and morphological development is mainly found at the mouth of the estuary. These waves stir up the sediment in shallow areas which results in extra net sediment import.

5.1.2 Results
An overview of the cross-sections used to calculate sediment transports is shown again in Figure 5.1.
In Figure 5.2 the contribution of the individual components (tides, wind, sea-waves and wind-waves) on the total net sediment transports is illustrated. The numbers on the y-axis correspond to the seven cross-sections. The summation of the different components results in the total transport. The transport diagrams of sand, mud and total transports are shown in separate panels.

Figure 5.2 – Contributions of the different components on the net sediment transport rates in Mm$^3$/year

As the morphological development is caused by spatial gradients in sediment transport, the changes in available mass of sediment are simultaneously analysed. The bed level changes are discerned between the different forcing mechanisms. The computed changes for sand and mud, expressed as available height in meter, are depicted in Figure 5.3 and Figure 5.4 respectively.
The **tides** are the most important component on the total transport since the difference between the transport fluxes caused by the tides and the sum of the components is small (see Figure 5.2). Sand exports at the seaside of the estuary, whereas a small import is found at the eastern side of the estuary. Throughout the domain, the model calculates an export of mud. This modelled export is considered to be a flaw of the model and is discussed in section 4.4. Related to the gradients in sediment transport, the morphological development is also mainly influenced by tidal forcing. The tides are responsible for the natural migration of channels and shoals.

In the model scenario where only tides are used as forcing component, sedimentation of mud at the intertidal areas is found (see Figure 5.4). This is caused by the relatively calm hydrodynamic conditions. During a higher energetic climate, when wind and wave processes are included in the simulation, mud is exported from these locations. In reality, seasonality provides the natural variation between this modelled erosion and deposition.

**Sea-waves** are responsible for an import of sand and mud at the seaside of the estuary (see Figure 5.2), although the net transport remains offshore-directed due to the tides. The transportation of mud is affected by wave forcing. This can be explained by the higher

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**Figure 5.3** – Change in available height of sand in m caused by tides, wind, sea-waves and wind-waves. The lower plot shows the total change in available height of sand. For clarity reasons the scale of the colour bar for tides and total is a factor of 10 larger.
concentrations of sediment at the shallow parts near the mouth of the estuary due to wave-induced bed shear stresses. The tides transport these higher concentrations into the estuary while during ebb lower sediment concentrations are transported seawards. The effect of sea-waves mainly influences the morphological development in the mouth of the estuary and is not relevant in the Western Scheldt (see Figure 5.5).

Figure 5.4 – Change in available height of mud in m caused by tides, wind, sea-waves and wind-waves. The lower plot shows the total change in available height of mud.

The influence of wind is only noteworthy on the change of available height of sand. The model results indicate that these transports mainly affect the fringes of the intertidal areas and deeper parts of the channels. However, the waves that are formed due to the interaction with wind (wind-waves) do have a relatively large impact on the sediment transports and morphological development. This interaction leads to the growth of waves that propagate from the seaside into the estuary and consequently the effect of these sea-waves. However, due to energy dissipation these waves, which are formed at sea, have lost their influence when reaching the Western Scheldt. Inside the estuary, wind-waves do have effect on the sediment transports within the basin. Sand and mud are transported from the intertidal areas by these locally generated waves.
In Figure 5.5 the bed level changes for the combination of the sand and mud fraction are shown. The largest cumulative erosion and sedimentation are caused by the changes in available height of sand. Because the morphological developments due to the mud fraction are found on a larger spatial-scale, their impact is more subtle.

This can be explained by the following: when the bed shear stress exceeds the critical bed shear stress for mud, the fines are entrained from the bed and are transported in suspension. These particles will be transported over a longer distance compared to coarse sediment particles due to lag effects. The sand grains need a higher bed shear stress to erode and they exhibit a higher fall velocity. This difference in transport behaviour also marks a clear distinction between the erosion and deposition areas in the plots of the mud fraction.

Focussing on the bed level changes due to sand transports, a different result is found. The morphological development at the high-lying areas, caused by gradients in sand transport, is negligible. The impact of transportation of sand is mainly found at the fringes of the intertidal areas and deeper parts of the tidal channels. The alternating areas of erosion and sedimentation indicate migrating channels and tidal shoals.
Next, a more quantitative analysis of the effect of tides, wind, sea-waves and wind-waves on the morphological development is performed. The volume change in a computational cell is calculated by the product of the absolute value of the bed level change and the area of the grid cell. Summation of these volume changes gives the total volume change. In a more mathematical notation:

$$\Delta V_{\text{total}} = \sum_{m,n} |\text{Bedlevel}_{\text{end}}(m,n) - \text{Bedlevel}_0(m,n)| \cdot \text{Area}(m,n)$$

This analysis focusses only on the grid cells in the area of interest and not on the entire model domain. Using this approach, the contribution of the different components on the morphological development can be determined for the sand and mud fraction. In Table 5.2, the relative influence of tides, wind, sea-waves and wind-waves is shown. More than 80% of the volume changes are caused by the transportation of sand. The tides are the main contributor to the modelled volume changes. The effect of wind on the volume changes due to transportation of mud is negligible.

<table>
<thead>
<tr>
<th>Component</th>
<th>Sand</th>
<th>Mud</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tides</td>
<td>58.9</td>
<td>7.8</td>
<td>66.7</td>
</tr>
<tr>
<td>Wind</td>
<td>5.0</td>
<td>0.6</td>
<td>5.6</td>
</tr>
<tr>
<td>Sea-waves</td>
<td>5.9</td>
<td>4.7</td>
<td>10.6</td>
</tr>
<tr>
<td>Wind-waves</td>
<td>13.3</td>
<td>3.8</td>
<td>17.1</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>83.1</strong></td>
<td><strong>16.9</strong></td>
<td><strong>100.0</strong></td>
</tr>
</tbody>
</table>

An analysis is made of the contribution of the different components in separate areas. A bed level of –2 m NAP is used as critical value to distinguish between the area covering the tidal channels and the intertidal areas. Another distinction is made between the mouth of the estuary and the Western Scheldt using cross-section 1 'Vlissingen-Breskens'. The four areas are illustrated in Figure 5.6.
Figure 5.6 – Overview of the areas defined as ‘Tidal channels’, ‘Intertidal areas’, ‘Mouth of the estuary’ and ‘Western Scheldt’. The bathymetry in m NAP is plotted.
The total volume change in the intertidal area is much smaller compared to the impact in the tidal channels, see Table 5.3. This is mainly due to the fact that the intertidal area covers a significantly smaller area. The locally generated wind-waves have a large impact on the intertidal areas. The wave-induced bed shear stress enhances the erosion of the shallow areas. The model results indicate that the effect of wind-waves on the morphological development of the intertidal areas is larger compared to the impact of the tides. Due to the wind set-up additional shoals are submerged during flood which leads to an increase of submerged areas that are affected by the wind-waves.

Table 5.3 – Contributions of the different components on the morphological development of the tidal channels and intertidal areas in percentages

<table>
<thead>
<tr>
<th>Component</th>
<th>Sand</th>
<th>Mud</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tidal channels</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Tides</td>
<td>57.6</td>
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<td>64.7</td>
</tr>
<tr>
<td>Wind</td>
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<td>5.3</td>
</tr>
<tr>
<td>Sea-waves</td>
<td>5.5</td>
<td>4.6</td>
<td>10.1</td>
</tr>
<tr>
<td>Wind-waves</td>
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<td>2.7</td>
<td>13.1</td>
</tr>
<tr>
<td>Intertidal areas</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tides</td>
<td>1.3</td>
<td>0.6</td>
<td>1.9</td>
</tr>
<tr>
<td>Wind</td>
<td>0.2</td>
<td>0.1</td>
<td>0.3</td>
</tr>
<tr>
<td>Sea-waves</td>
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<td>0.1</td>
<td>0.5</td>
</tr>
<tr>
<td>Wind-waves</td>
<td>3.0</td>
<td>1.1</td>
<td>4.1</td>
</tr>
<tr>
<td>Total</td>
<td>83.1</td>
<td>16.9</td>
<td>100.0</td>
</tr>
</tbody>
</table>

Table 5.4 gives an overview of the effect of the components regarding the area covering the mouth of the estuary and the Western Scheldt. Next to the tides, the sea-waves are the second most important component for the mouth of the estuary. These waves stir up the sediment at the shallow ebb-tidal mouth of the estuary and the banks along e.g. tidal channel Oostgat. Within the more sheltered Western Scheldt, the influence of sea-waves is negligible. Besides the tides, the wind-waves play an important role within the estuary.

The volume changes in mud at the mouth of the estuary are relatively high compared to the total volume changes. This is probably caused by the redistribution of mud in this area as the sharp gradient in initially imposed mud fraction is still present.

Table 5.4 – Contributions of the different components on the morphological development of the mouth of the estuary and the Western Scheldt in percentages

<table>
<thead>
<tr>
<th>Component</th>
<th>Sand</th>
<th>Mud</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mouth of the estuary</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tides</td>
<td>13.5</td>
<td>4.3</td>
<td>17.8</td>
</tr>
<tr>
<td>Wind</td>
<td>2.0</td>
<td>0.4</td>
<td>2.4</td>
</tr>
<tr>
<td>Sea-waves</td>
<td>5.1</td>
<td>4.5</td>
<td>9.6</td>
</tr>
<tr>
<td>Wind-waves</td>
<td>4.6</td>
<td>2.1</td>
<td>6.7</td>
</tr>
<tr>
<td>Western Scheldt</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tides</td>
<td>45.4</td>
<td>3.5</td>
<td>48.9</td>
</tr>
<tr>
<td>Wind</td>
<td>3.0</td>
<td>0.2</td>
<td>3.2</td>
</tr>
<tr>
<td>Sea-waves</td>
<td>0.7</td>
<td>0.2</td>
<td>0.9</td>
</tr>
<tr>
<td>Wind-waves</td>
<td>8.8</td>
<td>1.7</td>
<td>10.5</td>
</tr>
<tr>
<td>Total</td>
<td>83.1</td>
<td>16.9</td>
<td>100.0</td>
</tr>
</tbody>
</table>
5.2 Relative influence of the sand-mud-bed interaction

5.2.1 Description of the model scenarios

To analyse the effects of the mud fraction on the sand transports and morphological development, a simulation is executed that only contains a sand fraction (B2). The available mass of sand is kept the same to make a fair comparison with the reference run in which both fractions are simulated (B1).

In this study the mud content is based on the outcomes of the original mud model. As discussed in section 3.5.3, the McLaren (1994) data indicates that the distribution of the mud fractions is more bimodal compared to the results of the mud model. Roughly speaking, his observations show that the mud content is either relatively high or low. To determine the importance of mud content in the bed on the sand transports, a model scenario is made with adapted mud content (B3).

![Figure 5.7 – Curve used to convert the old mud fraction to the new mud fraction](image)

Following the curve depicted in Figure 5.7, the available mass of mud in each computational cell is adjusted to get the new mud fraction while keeping the height of available sand constant. The critical mud content between the non-cohesive and cohesive regime remains 0.3. Mud fractions in the cohesive regime are enhanced whereas the lower mud fractions are decreased. The corresponding equations used for this conversion are given in equation 5.2 and 5.3.

The old and new mud fraction are depicted in Figure 5.8. As discussed in the previous chapter, the mud fraction is mainly reduced during the spin-up period. This has resulted in a mud distribution where the mud fraction scarcely exceeds the critical mud content of 0.3. The harbours of Zeebrugge and Vlissingen, where a lot of mud is deposited due to the exclusion...
of dredging activities in the model, are locations with high mud content. Neglecting the few locations where the mud content is enhanced, the mud fraction in simulation B3 can be seen as a transition between simulation B1 (reference run) and simulation B2 (no mud at all).

![Mud fraction B3](image1)

![Mud fraction B1](image2)

![Difference (B3 - B1)](image3)

**Figure 5.8 – The mud fraction used in simulation B3, simulation B1 and the difference between these two mud fractions.**

In Table 5.5 the different model scenarios are summarised.

<table>
<thead>
<tr>
<th>Simulations</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1 (= A1)</td>
<td>Reference run, input as described in section 4.5.2</td>
</tr>
<tr>
<td>B2</td>
<td>As B1, but only a sand fraction is used</td>
</tr>
<tr>
<td>B3</td>
<td>As B1, but with a more bimodal mud content in the bed</td>
</tr>
</tbody>
</table>

**Table 5.5 – Overview of model simulations regarding sand-mud-bed interaction**
The hypotheses regarding the influence of sand-mud-bed interaction are:

**Hypothesis 4**
The mud fraction enhances the soil structure and consequently reduces the sand transports. This process is especially relevant in muddy areas with low hydrodynamic forcing.

**Hypothesis 5**
The sand transports are strongly dependent on the mud fraction in the bed. When the spatially-averaged mud fraction is significantly lowered, the gross sand-transport rates are still affected by the cohesive fraction.

5.2.2 Results

Figure 5.9 shows the sand transport between the macro cells in the simulation including only the sand fraction (B2) and the reference situation (B1). The effect of neglecting the mud fraction on sand transport is illustrated in the lowest subplot.

The exclusion of the mud fraction decreases the critical bed shear stress for sand and thereby it enhances the sand transports. This effect is reproduced in the model as the absolute values of the sand transport increase. There is no significant difference between the influence of mud on the gross import and gross export. Therefore, the overall trend of net sand transport remains the same.
To analyse the spatial effects of the mud fraction on the change in available height of sand, the bed level changes in the reference simulation are subtracted from the bed level changes in the simulation including only the sand fraction. The result is shown in Figure 5.10. Additional erosion is found on the fringes of the intertidal areas and this sediment is deposited in the channels.

![Simulation B2](image)

![Simulation B1](image)

![Effect of neglecting the mud fraction (B2 - B1)](image)

Figure 5.10 – Impact of neglecting the mud fraction on the changes in available height of sand. Red (blue) indicates areas where relatively a lot of sand is deposited (eroded).

The effect of neglecting the mud has a high correlation with the mud fraction in the model. Due to the less cohesive behaviour of the bed, the critical bed shear stress decreases. This results in more local erosion, as a lower bed shear stress is needed to transport the sand compared to the situation where both fractions where modelled. However, some regions of low mud content are also affected by the mud fraction. As more sand is transported from muddy areas to adjacent areas of low mud content, the gradients in sand transport at these locations are also affected. The net result is that at these sandy areas more deposition
occurs, because the gross transport to these locations increases while the gross transport flux from these locations is approximately the same.

Figure 5.11 gives an overview of the cumulative sand-transports in simulation B2 and simulation B1. The difference between these two simulations, depicted in the third panel, shows the net effect of neglecting the mud fraction. The bottom panel shows the percentage increase and decrease of sand transports for each computational cell.

The sand-transport vectors of the net effect (panel 3) indicate that the largest net transportation takes place in the ebb-tidal channels. However, the largest relative impact (panel 4) is found at the fringes of the intertidal areas where the cohesive fraction enhances the soil structure. Removal of the mud in the harbours results in a change of cohesive regime to non-cohesive regime and therefore the sand transport at these locations reduces.
The effect of the adapted mud fraction on the gross import, gross export and net transport is illustrated in Figure 5.12. The qualitative effect is the same as the previous discussed model scenario, but the impact of the mud fraction on the sand transports is decreased.
Figure 5.12 – Sand transports in case a more bimodal mud distribution is imposed (B3), the transport rates in the reference situation (B1) and the effect of this new distribution on the sand transport rates in Mm$^3$/year. Note that the lower panel has a different y-axis scale.

The percentage increase of the sand transports for simulation B2 and B3 are plotted in Figure 5.13 to analyse the relation between the imposed mud fraction and the impact on the sand transports. The mud content used in model scenario B2 leads to an overestimation of the gross sand-transport of approximately 10-30%.
The spatially-averaged mud fraction in the area of interest is 3.3% in simulation B2. As most of the computational cells had a mud content smaller than the critical value of 30%, the mud fraction in simulation B3 was significantly lowered. The spatially-averaged mud content in simulation B3 is 1.2%. This means that the total mud content has decreased by a factor of 2.75. The factor between the percentage increase/decrease in Figure 5.13 depends on the amount of mud within a macro cell, but the factor between the magenta and cyan bar is in the same order of magnitude.

The results of simulation B3 show that even when a very low mud content is present, with a spatially-averaged value of 1.2%, the gross sand-transport between the macro cells are overestimated with 5-10% in case the mud fraction is neglected.

5.3 Discussion
The initial height of available sediment was limited in some areas to account for non-erodible layers in the Scheldt estuary. In the resulting morphology of the warmed-up model there is almost no mud available for erosion at e.g. the Vlakte van de Raan. It could be questioned how realistic the modelled cumulative sedimentation of mud in this area is since erosion in this area was not possible.

The model calculates an erosion of mud from the intertidal areas due to the wind-waves. In reality, a more complex behaviour is found. Severe hydrodynamic conditions are responsible for the export of mud from these areas. During calm conditions, mud is transported as suspended load to the relatively shallow regions where it settles. This variation is included in the model by simulating an entire spring-neap tidal cycle and imposing a representative wind-wave climate. However, only the model results at the end of the simulation are analysed and not the development during the simulation. The calculated erosion indicates that the imposed boundary conditions for wind and waves might be too severe. On the other hand, it could also be argued that the imposed mud fraction in these areas is too high.

Even though some of the model results still depend on the initially imposed values and are influenced by spin-up effects, using the model to analyse relative effects is considered to be
valid. The modelled mud-transport after an even longer simulation period, discussed in section 4.3.7, indicates that the model results are slowly developing into a state of statistical equilibrium. The model scenarios were also started after this warm-up period of 8 loops. However, the difference between the outcomes was insignificant and the conclusions regarding the hypotheses would not have been different.

The more quantitative analysis of the several forcing components on the morphological development is influenced by the spin-up effects. For example, the sharp gradient in the initially imposed mud fraction at the mouth of the estuary causes volume changes in this area due to the redistribution of mud.

5.4 Conclusions

After analysing the model results, a concise conclusion is drawn for each of the hypotheses.

**Hypothesis 1:** Compared to the other physical processes, the tides are the main contributor to the sediment transports and morphological development of the Scheldt estuary.

Analysis of the contribution of the several forcing components on the sediment transports budgets indicates that the total transport is indeed mainly determined by the tidal forcing. As the morphological development is linked to spatial transport gradients, most of the bed level changes are caused by the tidal forcing. Focussing on the intertidal areas, the impact of the wind-waves on the morphological development are more important compared to the influence of the tides.

**Hypothesis 2:** The role of wind is especially important for the morphological development of the intertidal areas of the estuary. Due to the wind-induced shear stress, mud particles are entrained from the bed and exported from these areas.

According to the model results, this hypothesis is only partially true. Only the transition between tidal channels and intertidal areas is significantly affected by the wind. The quantitative analysis indicates that wind is only of minor importance on the volume changes. Wind-waves are particularly responsible for the erosion of mud from intertidal areas.

**Hypothesis 3:** The effect of sea-waves on the sediment transport and morphological development is mainly found at the mouth of the estuary. These waves stir up the sediment in shallow areas which results in extra net sediment import.

Compared to the reference situation, higher sediment concentrations are transported into the estuary. This results in an import of both sand and mud as contribution of the sea-wave component. Regarding the waves formed at the North Sea, this hypothesis is valid. However, the locally generated wind-waves have shown to be of importance for the morphological development of the intertidal areas within the estuary.

**Hypothesis 4:** The mud fraction enhances the soil structure and consequently reduces the sand transports. This process is especially relevant in muddy areas with low hydrodynamic forcing.

This hypothesis appears to be correct, because decreasing sand transport from muddy areas leads to sedimentation at these locations. As less sand is transported from the areas with a
high mud fraction, a positive transport gradient is found in adjacent areas with low mud content, resulting in erosion of these sandy areas.

**Hypothesis 5**: The sediment transports are strongly dependent on the mud fraction in the bed. When the spatially-averaged mud fraction is significantly lowered, the gross sand-transportsp are still affected by the cohesive fraction.

A decrease in mud content resulted in a decrease of gross sand-transport by approximately the same factor. Even with a spatially-averaged mud content of 1.2%, the gross sand-transport between the macro cells are overestimated with 5-10% in case the mud fraction is neglected. Even though no extensive analysis with different mud contents is performed, the dependency of the calculated sand transports on the mud content is evident.
6 Conclusions and recommendations

6.1 Conclusions
The objective of this study is to determine the importance of the hydrodynamic forcing (tides, wind and waves) and sand-mud-bed interaction on the sediment transport processes and morphological development in the Scheldt estuary on the timescale of a few years. The research questions (RQ) formulated in the first chapter, are answered in this section.

RQ 1: How can multiple sediment fractions and their interaction in the Scheldt estuary be modelled using a depth-averaged Delft3D model?

An existing model of the Scheldt estuary is used as basis for the performed model study. The most important change is the addition of a mud fraction to this model. Instead of starting with uniform conditions and having a relatively long spin-up time, the model settings and results of a mud model of the Scheldt estuary are used as initial and boundary conditions. The model is made representative for the year 2006 and available data is imposed as boundary conditions. The depth-averaged model is used to perform morphodynamic simulations. Vertical circulations are excluded but salinity is modelled to include density-driven flows.

Observations showed that the mutual influence of sand-mud mixtures should be accounted for when modelling multiple sediment fractions. A layered bed stratigraphy is used with a base layer, a transport layer and a fluff layer. The transport layer has a distribution function and has a user-defined thickness. The fluff layer is a thin layer between the bed and water column that improves the modelling of easily erodible fines. All the other information is stored in the base layer. To model the interaction between the sand and mud fraction, a critical mud content is used to distinguish between a non-cohesive and cohesive regime. For each regime, different erosion formulas are used to calculate the vertical fluxes for sand and mud.

RQ 2: Can this model qualitatively reproduce the mud concentrations and large-scale sediment transport fluxes known from measurements and literature?

Calibration of the mud parameters has been done to improve the behaviour of mud to the hydrodynamic forcing in the model. The values of the deposition efficiency and erosion parameters for both the fluff layer and bed layer are adjusted during this process. The model has sufficient capacity reproducing the overall trend of the mud concentration in the water column as both the spatial distribution and variation due to the tidal variations are in good agreement with the results of the mud model and observations.

Considering the sand transports, export is found near the mouth of the estuary and a transition to import is found halfway the estuary. This result corresponds with the findings in previous studies. However, as the sand fraction was validated in an earlier study, more attention is required on the behaviour of mud.

The modelled export of mud at the seaside of the estuary is considered to be a flaw of the model since observations and the latest version of the mud model show an import of mud at the mouth of the estuary. The warm-up period is not sufficient for the bed composition to develop into a state where it is in line with the boundary forcing. From the Dutch-Belgian border seawards, the mud transports over the cross-sections are increasing. Using a
simulation period representing the morphological development of 8 years, it is shown that this spin-up effect gradually decreases over time.

The largest redistribution of sand and mud, caused by the mismatch between initial and boundary conditions, takes place during the first two simulation periods. The model results are stable after a warm-up period of 3 loops. Even though the model results are still dependent on the initial conditions, the development in the warmed-up model is better predictable and is therefore sufficiently capable for the purpose of this study.

RQ 3: What is the importance of tides, wind and waves on the sediment-transport patterns and morphological development within the Scheldt estuary and how important are sand-mud-bed interaction processes?

The appearance of the funnel-shaped Scheldt estuary with its system of channels and shoals reveals that the morphological development is mainly tide-dominated. The model results confirm that the tides are the most important contributor to the sediment transports in the Scheldt estuary. Alternating erosion and sedimentation is found along the estuary corresponding to the natural migration of the channels and shoals.

Sea-waves introduce additional bed shear stresses in the mouth of the estuary, which in turn result in higher sediment concentrations. The wave-induced import of sand and mud is explained by the transportation of these relatively high concentrations into the estuary by flood velocities. The model results show that wind is only of importance for the transportation of sand.

The effect of wind-waves is found to be of significant importance on the morphological development of the estuary. Near the mouth of the estuary, the effect of waves is enhanced as wind stress increases the wave heights. Within the estuary, the locally generated wind-waves affect the intertidal areas. The effect of these wind-waves on the morphological development in the intertidal areas is larger than the impact of the tides.

The difference in transport mode and behaviour of sand and mud to hydrodynamic forcing is responsible for the morphological development found on different spatial scales. Once entrained from the bed, mud particles are transported over a longer distance compared to the sand fraction. The eroded fines are distributed more smoothly along the estuary due to the lower fall velocity. This explains the more local impact of gradients in the transport of sand whereas changes in the available height of mud are more spread.

The strength of the bed is increased by including the mud fraction. The enhanced critical bed shear stress resulted in smaller net sand transports. This locally leads to less erosion of the sand. The effect of the mud fraction preventing erosion is especially found at the fringes of the intertidal areas. However, not only the muddy areas are affected. As less sand is transported from these locations, it also influences the nearby sandy beds. These adjacent areas encounter a positive transport gradient leading to erosion. By imposing a different bed composition it is demonstrated that the net sand transport is strongly dependent on the mud fraction. As the effect on the gross transports counteracts each other, the impact on the net transports is more subtle.
6.2 Recommendations

This study analysed the importance of sand-mud-bed interaction processes on the large-scale sediment dynamics in the Scheldt estuary. As the effect of the mud fraction on the large-scale net sediment transports is of minor importance, studies on the sand transport between macro cells in the Scheldt estuary can be performed with a sand-model. However, the mutual influence of the sand and mud fraction is considered to be important for the morphological development of the intertidal areas.

The calibration performed in this study was solely based on the results of one monitoring station of the mud model. In future models of the Scheldt estuary including both fractions, a better calibration of the erosion parameters should be performed. Data from observations should be used and more attention should be paid to the response to tidal variations. Furthermore, it is important to gain better understanding of the numerical instabilities that occurred in calculating the bed level changes.

The mud content of the Scheldt estuary has been analysed in different studies. However, a large discrepancy can be found between these studies. As the effect of mud on the morphological development of the Scheldt estuary is considered to be important, it is recommended to collect more data regarding the mud distribution by doing field measurements. This information can be used to calibrate and validate models which in turn can provide detailed information on the mud content of the entire area.

The area of the wave grid that is used in the model was initially created to compute wave propagation at the North Sea. The wind-waves have a substantial effect on the sediment transports and morphological development within the Western Scheldt. It is therefore recommended to use a computational wave grid that covers the entire Western Scheldt in future models of this area to include the effect of the locally generated wind-waves on the morphological development.

In addition, it is advised to investigate the option of setting up a 3D model of the Scheldt estuary to enhance the performance of the sand-mud model on simulating mud characteristics. Three dimensional effects were not included in this study, but they might show a contribution to the import of mud. Extra processes, such as an estuarine circulation where surface and bottom flows are oppositely directed, can be modelled using an extra dimension. Furthermore, the distribution for the sediment concentration over depth and the associated vertical fluxes between the bed and water layers can be modelled using more layers in vertical direction.
7 References


August 2015


Appendices
A Appendix to Chapter 2 – Literature review

A.1 Delft3D

The most important features of Delft3D-FLOW and Delft3D-WAVE are given below. For more information, see the Delft3D User Manuals (Deltares, 2015ab).

A.1.1 Delft3D-FLOW

The FLOW module of Delft3D calculates the basic hydrodynamics by solving the shallow water equations in two or three dimensions. The shallow water equations are derived from the Navier-Stokes equations for incompressible free surface flow under the shallow water and Boussinesq assumptions. Vertical accelerations are neglected in the vertical momentum equation, which leads to the hydrostatic pressure equation.

To solve the shallow water equations a set of initial and boundary conditions need to be specified. These conditions are also needed for solving other equations like for suspended sediment concentrations. The required water levels and velocities, to discretise the equations, are not considered in the same grid points, but in a so-called staggered grid. The water levels are calculated in the middle of the computational cell and the velocities are determined in the middle of a grid cell face.

When solving the equations a certain condition regarding the spatial and time steps must be fulfilled. An important parameter for the accuracy of the model is the Courant-Friedrichs-Lewy number (CFL), which is given by:

\[
CFL = \frac{\Delta t \sqrt{gH}}{\Delta x, \Delta y}
\]

where \(\Delta t\) is the time step [s], \(g\) the acceleration of gravity [m/s\(^2\)], \(H\) the total water depth and \((\Delta x, \Delta y)\) the minimum value of the grid spacing in \(x\)- and \(y\)-direction [m]. It is recommended to keep the CFL number below a value of ten for general cases.

The calculation of sediment transports is also done in the FLOW module. Within the sediment transport feature it is possible to use different sediment transport formulas, include different sediment fractions and differentiate between cohesive and non-cohesive sediments.

Bed level changes are caused by horizontal gradients in bed load transports and the net fluxes of both sand and mud in vertical direction. In this thesis only bed level changes due to exchange of sediments are considered. An expression for this relation is given by the Exner-equation, which is based on the continuity equation and corrected for porosity of the bed:

\[
\frac{(1 - \varepsilon_p)}{correction\ for\ porosity} \frac{\partial z_b}{\partial t} = \frac{- \partial q_b}{\partial x} \frac{\partial q_b}{\partial y} + \frac{D_s - E_s}{vertical\ sand\ fluxes} + \frac{D_m - E_m}{vertical\ mud\ fluxes}
\]

where \(z_b\) is the bed level [m], \(q_b\) the bed load transport [m/s], \(\varepsilon_p\) the porosity [-], \(D_s\) and \(D_m\) the sediment deposition [m/s], and \(E_s\) and \(E_m\) the sediment erosion [m/s].
A.1.2 Delft3D-WAVE

The WAVE module uses the numerical Simulating Waves Nearshore (SWAN) model, which is a third generation phase-averaged wave model (Ris, 1997). SWAN computes the evolution of random short-crested wind-generated waves in coastal areas.

When currents are present, wave energy is no longer conserved as energy can be transferred between the waves and the current. SWAN therefore uses the action density spectrum \( N(\sigma, \theta) \), see equation A.3, instead of the energy density spectrum \( E(\sigma, \theta) \). The action density spectrum is a function of the relative frequency \( \sigma \) and wave direction \( \theta \). The wave computation is based on the spectral action balance equation given in equation A.4.

\[
N(\sigma, \theta) = \frac{E(\sigma, \theta)}{\sigma} \quad \text{A.3}
\]

The source term in the equation above represents physical processes as generation by wind, dissipation (due to whitecapping, bottom friction and depth-induced breaking) and non-linear wave-wave interaction (quadruplets and triads).

\[
\frac{\partial N}{\partial t} + \frac{\partial c_x N}{\partial x} + \frac{\partial c_y N}{\partial y} + \frac{\partial c_\sigma N}{\partial \sigma} + \frac{\partial c_\theta N}{\partial \theta} = \frac{S}{\sigma} \quad \text{A.4}
\]

where:
- \( \frac{\partial N}{\partial t} \) is the local rate of change of \( N \)
- \( \frac{\partial c_x N}{\partial x} \) is the propagation of \( N \) in the \( x \)-direction with \( c_x \)
- \( \frac{\partial c_y N}{\partial y} \) is the propagation of \( N \) in the \( y \)-direction with \( c_y \)
- \( \frac{\partial c_\sigma N}{\partial \sigma} \) is the shifting of \( N \) with \( c_\sigma \)
- \( \frac{\partial c_\theta N}{\partial \theta} \) is the refraction of \( N \)
- \( S \) is the source term
B Appendix to Chapter 3 – Model setup

B.1 Representative simulation period
An analysis of the measured water levels at Vlissingen is performed to discern spring-neap tidal cycles. The aim is to find a representative spring-neap cycle that can be used as simulation period. With the frequencies of the $S2$ and $M2$ components, the duration of one spring-neap cycle is calculated by:

$$T_{springneap} = \frac{1}{f_{S2} - f_{M2}} \approx 14.8 \text{ days}$$

During neap tide the flow velocities and sediment transports are smaller compared to the values during spring tide. Therefore, the start of every spring-neap tidal cycle is chosen at neap tide and zero up-crossing water level. Following this approach, 24 cycles can be distinguished in the year 2006 (see Figure B.1).

Spring-neap cycle number 7 turned out to be the most representative simulation period. The water levels during the chosen period, 07-Apr-2006 19:50:00 until 22-Apr-2006 06:00:00, are shown in Figure B.2.
Figure B.2 – Water levels at Vlissingen during the selected spring-neap cycle
B.2 Boundary conditions

B.2.1 Mud concentrations at sea boundaries

Figure B.3 – Mud concentration in mg/l at the north-eastern sea boundary

Figure B.4 – Mud concentration in mg/l at the south-western sea boundary
B.2.2 Discharges

The upstream rivers (Zenne, Dijle, Grote Nete, Kleine Nete, Schelde and Dender) and the sluices at Bath and Terneuzen are simulated by discharge points in the model. The time series for discharge, illustrated in Figure B.5, are based on observations. For the mud concentration an annual mean value is used and the salinity concentration is set at a constant value of 0.3 ppt.

Figure B.5 – Discharges in the model in m$^3$/s
C Appendix to Chapter 4 – Model assessment

C.1 Erosion formulas in Delft3D and DELWAQ

The formulas used to calculate the erosion flux in the described sand-mud model and original mud model are slightly different. Delft3D is used for the model used within this thesis whereas the mud model is a DELWAQ model.

Table C.1 – Erosion of mud from the fluff layer into the water column

<table>
<thead>
<tr>
<th>Delft3D</th>
<th>DELWAQ</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_f = \rho_{m,f} M_{f,D3D} (\tau_b - \tau_{f,cr})$</td>
<td>$E_f = \rho_{m,f} M_{f,DW} \left( \frac{\tau_b}{\tau_{f,cr}} - 1 \right)$</td>
</tr>
<tr>
<td>$M_f = \min(M_{b,D3D}, m M_{l,D3D})$</td>
<td>$M_f = \min(M_{b,DW}, m M_{l,DW})$</td>
</tr>
</tbody>
</table>

Where:
- $E_f$ Erosion flux of mud from fluff layer [kg/m$^2$/s]
- $\rho_{m,f}$ Mud fraction in the fluff layer [-]
- $\tau_b$ Bed shear stress [N/m$^2$]
- $\tau_{f,cr}$ Critical shear stress for fluff layer [N/m$^2$]
- $m$ Total mass of the fluff layer per unit area [kg/m$^2$]
- $M_{f,D3D}$ Erosion parameter for fluff layer in Delft3D [s/m]
- $M_{b,D3D}$ Erosion coefficient (ParFluff0) in Delft3D [s/m]
- $M_{l,D3D}$ Erosion coefficient (ParFluff1) in Delft3D [ms/kg]
- $M_{f,DW}$ Erosion parameter for fluff layer in DELWAQ [kg/m$^2$/s]
- $M_{b,DW}$ Erosion coefficient in DELWAQ [kg/m$^2$/s]
- $M_{l,DW}$ Erosion coefficient in DELWAQ [1/s]

The most important difference between the Delft3D and DELWAQ approach is the treatment of the (critical) shear stress, see Table C.1. In Delft3D, $\tau_b - \tau_{f,cr}$ leads to the difference between the critical and occurring bed shear stress in the same units (N/m$^2$). In DELWAQ, this difference is divided by the critical bed shear stress to obtain a non-dimensional factor. Consequently, the erosion parameters are different for both models.

In Table C.2, a comparison is made between the formulas describing the erosion flux from the bed layer. The only difference is that DELWAQ uses a power of 1.5 for the non-dimensional shear-stress factor.

Table C.2 – Erosion of mud from the bed layer into the water column

<table>
<thead>
<tr>
<th>Delft3D</th>
<th>DELWAQ</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_b = \rho_{m,b} M_b \left( \frac{\tau_b}{\tau_{b,cr}} - 1 \right)$</td>
<td>$E_b = \rho_{m,b} M_b \left( \frac{\tau_b}{\tau_{b,cr}} - 1 \right)^{1.5}$</td>
</tr>
</tbody>
</table>

Where:
- $E_b$ Erosion flux of mud from bed layer [kg/m$^2$/s]
- $\rho_{m,b}$ Mud fraction in the bed layer [-]
- $M_b$ Erosion coefficient (EroPar) [kg/m$^2$/s]
C.2 Effect of adjusted upstream boundary

The modelled and observed water levels at several observations points along the estuary are depicted in Figure C.6. The overall trend is reproduced reasonably well. In Figure C.7 the differences between the modelled and observed water levels are plotted (blue). The red line in this figure shows the difference between the modelled water levels with the original NeVla-grid and the grid used within this thesis where the upstream boundary is relocated. The adjusted upstream boundary has no significant impact on the modelled water levels.

The water level, flow velocity, salinity and mud concentration at observation point ‘Antwerp Loodsgebouw’ are plotted for a simulation with the original grid and adjusted grid in Figure C.8. The difference between these plots is shown in Figure C.9 to assess the impact of the relocated boundary. The deviations are insignificant and are in the order of only a few percent.
Figure C.6 – Modelled water levels (blue) and observed (Rijkswaterstaat, 2015a) water levels (red) at different observation stations

Figure C.7 – Difference between modelled and observed water levels (blue) and difference between the water levels with the NeVla-grid and the adjusted grid (red)
Figure C.8 – Model results at ‘Antw Loodsgebouw’ with grid used within the model (blue) and original NeVla-grid (red)

Figure C.9 – Difference between the model results with the grid used within the model and original NeVla-grid