Deltares

A conceptual framework for fine sediment dynamics in the Scheldt estuary

Providing a framework for data and model analyses and impact assessments

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Summary

In the Scheldt estuary, located in the Netherlands and Flanders (Belgium), authorities cope with several problems and challenges associated to fine sediment dynamics. These are related to dredging, turbidity, and development of intertidal areas and salt marshes. These issues are typical for other estuaries with large ports around the world, in densely populated areas.

Sustainable management of the estuary means that interventions are within the limits of resilience of morphology and ecology, and/or safe operating space. This requires system understanding, which can be brought together into a conceptual model. The presentation, discussion and application of such conceptual model for fine sediment dynamics in the Scheldt estuary is the objective of this report. It is based on a decade-long experience from monitoring, modelling and analysis of fine sediment dynamics in the Scheldt (in the framework of VNSC studies) and beyond.

Using the framework that this conceptual model provides, the impact of several human interventions on fine sediment dynamics are assessed, such as maintenance dredging and disposal of harbor mud, channel deepening and the removal or addition of intertidal areas. Based on this impact analysis, remaining data and knowledge gaps are identified and how the reduction of these gaps can reduce the uncertainty of future impact assessments. This provides guidance on future monitoring, modelling and analysis efforts.

The system understanding on long time scales, when a combination of changes in hydrodynamic forcing, mud availability and mud properties play a role, should be improved. In order to do so, existing observations on SPM dynamics at tidal, seasonal and long-term scale should be accompanied by more long-term observations on mud accretion, mud properties and vertical profiles of bed composition.

Contents

1 Introduction

In the Scheldt estuary, located in the Netherlands and Flanders (Belgium), authorities cope with several problems and challenges related to fine sediment dynamics. These are related to dredging, turbidity and development of intertidal areas and salt marshes. These issues are also typical for other estuaries around the world in densely populated areas with large ports.

Sustainable management of the estuary means that interventions are within the limits of resilience and/or safe operating space. This requires system understanding which can be brought together into a conceptual model to link system knowledge to policy and management (Figure 1.1). This is the objective of this report.

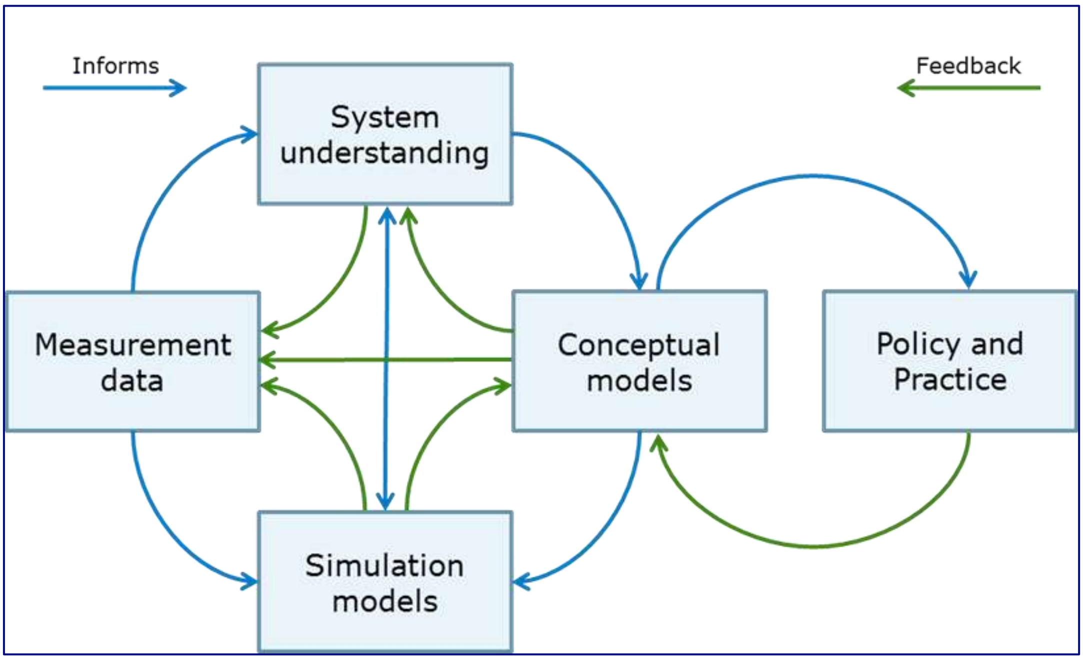


Figure 1.1 Illustration of the role of a conceptual mode in developing knowledge for policy and management (based on Lodder et al., 2023)

A useful conceptual model can link the most important processes to each other and shows how variables of interest (for the context of this report e.g. suspended sediment concentrations, sedimentation rates and bed composition) are influenced. A good conceptual model helps to reveal processes or relationships that are still under discussion or unknown. Analysis of data, literature, models and expert judgement all contribute to developing the conceptual model. New knowledge may change or confirm and strengthen our understanding the system. It also helps to focus new research, to build numerical models and to investigate management questions. With it we can prioritize which processes and interactions we need to consider, given the questions from policy and management. For example, if a question belongs to a short time scale (1-5 years) it makes less sense to include the effect of sea level rise, as this is a driving force that is only dominant on longer time scales.

Implicitly everybody uses conceptual models when taking decisions and/or explaining behavior. By materializing the concepts on which experts agree, into a report or scientific paper, these are explicitly available and can become part of the shared understanding of the functioning of the estuary. In this way it supports discussions between scientists, policy, management and stakeholder, as well within their groups as across them.

In Chapter 2, a generic conceptual model of fine sediment dynamics is presented. It elaborates how suspended sediment concentrations and (residual) transport are steered by hydrodynamic forcing, sediment supply and sediment properties. In Chapter 3, the present state of knowledge on fine sediment dynamics in the estuary embedded in the conceptual model is applied to the Scheldt estuary. This framework is applied in Chapter 4 to evaluate the effect of human interventions (channel deepening, removal or addition of intertidal area and maintenance dredging and disposal) on fine sediment dynamics. Chapter 5 discusses data and knowledge gaps and how the reduction of these gaps can reduce the uncertainty of future impact assessments.

2 A conceptual model of fine sediment dynamics: the framework

2.1 Fine sediment dynamics and user functions

This report focuses on fine sediments (typically below < 63 μm, although flocculated fines may exceed this limit) and not on sand. Sand is dominant in the large-scale morphological evolution of channels in the Western Scheldt. Several publications are available contributing to conceptual models on that subject. Examples are Röbke et al. (2020), describing a model study on sea level rise and sediment strategies and Van der Wegen and Taal (2022, in prep.) give an overview of the knowledge on the response to sea level rise.

The management of estuaries requires understanding of the fine sediment dynamics. The dynamics of fine sediments result in quantities that influence user functions (safety, ecology and accessibility are the three main ones of the Scheldt estuary). SPM (suspended particulate matter, i.e. the amount of inorganic sediment and organic particles in the water column) e.g. determines the light penetration in the water column and the growth of algae, which are the basis of the food web. Fine sediment depositing in harbors and fairways require dredging for navigation purposes. Another example is the amount of fines on top of or in the bed, influencing habitat quality, e.g. for benthic organisms.

Fine sediments also influence safety against flooding. Muddy beds are hydraulically smoother and can enhance tidal amplification in estuaries, leading to higher maximum water levels. However, fine sediments have also positive effects on safety, on a longer time scale. Sedimentation at intertidal flats and vegetated foreshores leads to higher beds in front of the embankments and reduces the hydrodynamic energy during storm conditions. Where hydrodynamic conditions and availability of sediments are suitable, the bed may, (partially) grow with sea level rise. Sedimentation in flood control areas reduces their storage volume and hence their buffer capacity to reduce storm surges. Sedimentation with fine sediments that lead to high soil fertility has been a driving force for ages to converse floodplains into agricultural land.

2.2 Overall model for forces driving SPM and bed composition

Many interactions and different timescales
The dynamics of fine sediments, both suspended (SPM) and in the bed (Figure 2.1) are controlled by the hydrodynamic forcing, itself influenced by the large-scale planform and bathymetry of an estuary, i.e. the morphology.

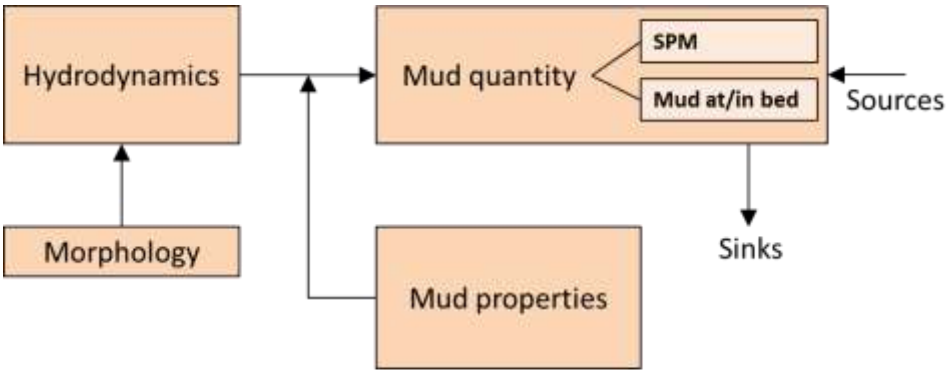


Figure 2.1 Driving forces of SPM and bed composition (mud on/in bed) dynamics, i.e. the conceptual model.

The hydrodynamic forcing influences the mud (quantity) in the bed and hence redistributes mud between bed and water column. Currents exert a force on the bed (bed shear stresses) and erode mud from the bed and transport it. How much mud is eroded also depends on the available mud and the mud properties. Stiff, consolidated old deposits will erode more slowly than freshly deposited mud. Mud properties also have effect on the time it takes for mud particles to settle on the bed again (deposition).

Interactions play at different time scales. **On the short term**, mud availability, mud properties and morphology are fairly constant, and both can be directly linked to the hydrodynamics. On the **medium term**, mud availability and mud properties may change significantly, thereby complicating the link between hydrodynamics and SPM dynamics. To put it simply: the same hydrodynamic forcing results in different SPM dynamics if mud properties and mud availability are different. This explains why the correlation between hydrodynamic forcing and SPM dynamics, which is strong at short time scale, becomes weaker at longer time scale (e.g. Blaas and Van den Boogaard, 2006). **On the long term**, also the morphology may change significantly, resulting in a feedback loop changing the hydrodynamic forcing. Another example at a longer time scale is when a change in mud quantity in the bed results in a change in hydraulic roughness.

The importance of net transports

Short term fluctuations in SPM and fluctuations in currents result in daily transport of sediment with the ebb and flood phases. The net result, for example a little bit more sediment that is transported during the flood than during the ebb, adds up over longer time scales. Therefore, net sediment transports are important. These net transports are usually much smaller than gross sediment transports. They are not only induced by tidal currents, but also by salinity gradients and the presence of sinks and sources.

Because of mass conservation, gradients in sediment transport are directly linked to sedimentation and erosion (or the anthropogenic variants hereof dredging and dispersion, all combined into the more generic terms ‘sinks and sources’, see textbox). The question is what is causing what, i.e. do gradients in sediment transport cause sinks and sources or do sinks and sources cause gradients in sediment transport? This depends on whether conditions are ‘supply limited’ or ‘transport capacity limited’.

Fine sediment transport is often ‘supply-limited’. In these cases, sinks and sources (see textbox) steer residual transport. Supply-limitation may be caused by the absence of mud altogether (i.e. a purely sandy bed) or by the presence of mud in a form that is difficult to resuspend (i.e. mixed with sand or well-consolidated). More mud means more mud transport, and if a local sink (e.g. sedimentation pit) or source (e.g. dispersion location for dredged mud) is added, residual transport will change in response to this perturbation.

In case of abundant presence of soft mud and/or limited hydrodynamic forcing, transport capacity can also become the limiting factor, i.e. the maximal suspended load that can be carried by the flow. In such cases gradients in transport capacity steer sinks and sources (i.e. erosion and deposition). In this case adding more mud doesn’t mean more transport, but just a local accumulation where it is placed. So depending on the transport conditions, the system response to changes in hydrodynamics or sediment supply may be quite different. Also for the interpretation of concentration and transport measurements this distinction is important.

A change between transport and supply limitation may occur within a tidal cycle, as during maximal ebb and flood velocity fine sediment transport is typically supply-limited but around slack transport-limited. But as mud settles slowly, the concentration will become over-saturated until tidal currents increase again after slack (settling lag effect).

Sinks and sources
A sink can be a sheltered location which is not in equilibrium that ‘catches sediment’ and reduces the amount of mud that is available for the rest of an estuary (or study-area). Examples are an abandoned channel, a harbor basin and a salt marsh with low hydrodynamic energy increasing in height over time. A source is e.g. a consolidated mud deposit that becomes exposed as result of higher shear stress (changing hydrodynamics) or erosion of (sandy) top layers. Another example of a source is dredging disposals.

Mud balance
The mud balance of an estuary (or a part hereof) is the result of the time integral of the residual transport over a certain period, typically a year or multiple years. This is an important element in the system understanding / the conceptual model. Residual transport at short timescales (e.g. tidal or seasonal) may not at all be representative for the long-term average, as stochastic factors such as setup, wind and wave-induced resuspension and freshwater discharge influence residual transport. Studying the mud balance at these shorter time scales fits other purposes.

2.3 The conceptual model refined

2.3.1 Mud quantity and appearances

Figure 2.2 shows that the total amount of mud in a system is partly in suspension and partly in the bed. Typically, the amount of mud in the bed is much larger than the amount of mud in suspension. Small changes in the amount of mud in the bed result hence in very large changes in SPM. For example, erosion of 1 cm of fresh deposited mud (dry density 500 kg/m^3) from the bed in a water depth of 5 m can increase the SPM by 1 g/l[1].
The transition between water column and bed can even become gradual, when very high concentration ‘fluid mud’ layers are present. Fluid mud is a transient state between a dilute mud suspension and a consolidated mud bed, still demonstrating fluid-like behavior (notwithstanding enhanced viscosity), which may persist for a substantial time but eventually turns into a sediment bed by consolidation, or suspended state by mixing. Freshly deposited mud can be fluffy, and especially in low energy locations such as harbors or access channels may have a substantial thickness affecting ship navigability if not dredged. Fluffy layers contain a large amount of water, have a low dry density. Through consolidation they gradually gain density and strength. In the bed, mud can be present as old, stiff deposits or be buffered in a sandy substrate. When buffered in sand the erosion of mud is affected by the erosion of sand. The bed can also be stratified (with vertical alterations of mud and sand-dominated deposits).

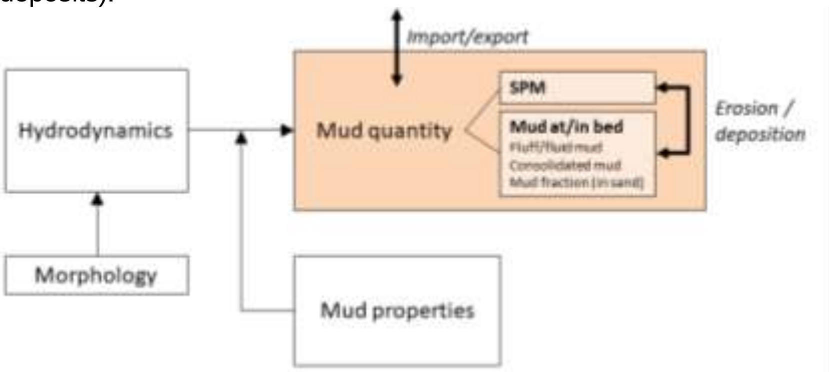


Figure 2.2 Mud quantity, defined as the sum of SPM and different appearances of mud in and on the bed. Mud quantity changes by import / export of mud, but not by exchange between SPM and mud on/in the bed due to erosion and deposition.

[1] 0.01 m x 500 kg/m^3 (density freshly deposited mud) = 5 kg/m^2 / a water depth of 5 m = 1 kg/m^3 = 1 g/l.

Vertical exchange of mud between the water column and the bed will change SPM, but not the mud quantity within a given area (see Figure 2.2). Only if there is a net transport over the boundaries of the area, its mud quantity changes. The area that is studied can be as large as an estuary, as small as a harbor or even smaller.

2.3.2 Hydrodynamic factors controlling transport and hence mud quantities

Waves, currents and inundation periods

Figure 2.3 zooms in on hydrodynamic factors. The fluctuations in hydrodynamics determine the SPM levels and its fluctuations on the short timescale. The combination of currents and the orbital motion of waves determines the bed shear stress, usually referred to with Greek letter τ. The higher this stress, the more sediment can be eroded from the bed (if available). Sediment can settle to the bed when the bed shear stress is low, for example during slack water periods.

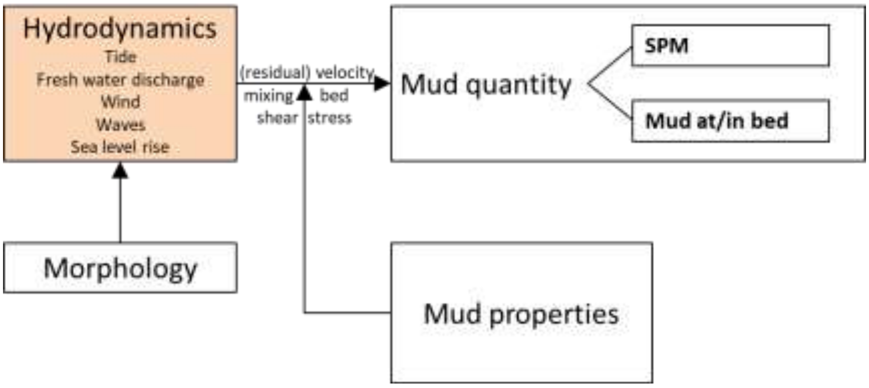


Figure 2.3 Hydrodynamics

The tidal motion controls, besides the flow, the water depth. This is the main factor controlling the emergence time of intertidal areas. The slack water duration in subtidal areas and the air exposure duration in intertidal areas determine the duration for consolidation and possibly drying of fresh sediment deposits. The longer this period, the more strength against subsequent erosion may develop, thus enhancing local accretion.

Once in suspension, the mud transport is steered by advection and diffusion, i.e. currents and turbulent mixing. The magnitude and direction of these currents and turbulent mixing are controlled by tidal dynamics, wind, waves and freshwater discharges (also interacting with each other). Residual currents (i.e. averaged over the tide) steer residual sediment transport, but this relation is not straightforward. Depth-averaged residual currents and residual sediment transport may even be in opposite direction caused by vertical gradients in residual currents and sediment concentration, as explained below.

Fresh water discharge and density currents

Fresh water discharges introduce a seaward residual flow but may also increase the water depth (reducing the flow velocity at the same tidal prism) and create salinity-driven density currents. In an estuary fresh river runoff meets salty seawater. The density difference between the more buoyant fresh river discharge and the denser salt water from the sea drives a net circulation with landward flow near the bed and a seaward flow near the surface. As the SPM concentrations are higher near the bed, this so-called gravitational circulation drives net landward sediment transport (Figure 2.4). This is a strong mechanism driving fine sediment import in estuaries, notably in stratified estuaries. The strength of gravitational circulation increases quadratically with the water depth, introducing an important sensitivity to deepening of tidal channels (Winterwerp et al., 2021).

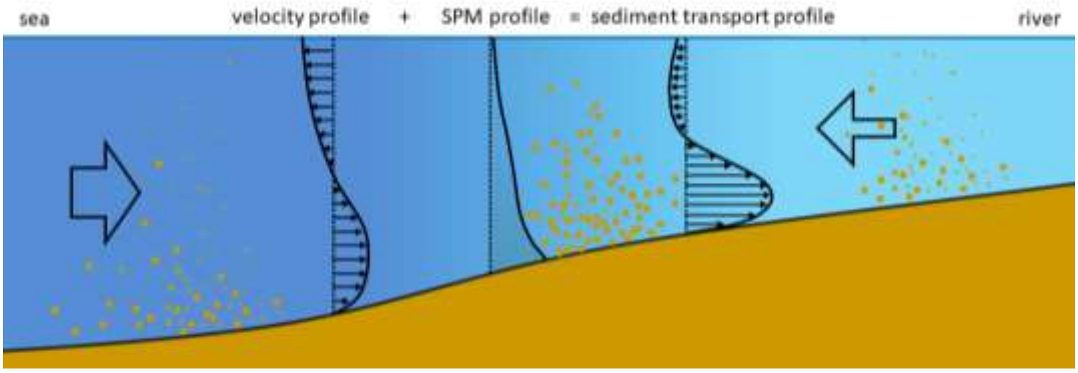


Figure 2.4 Gravitational circulation resulting from the density difference between denser sea water (left) and lighter fresh river discharge (right), resulting in a residual velocity profile with near bed landward flow and near surface seaward flow (left profile), which combined with higher near bed SPM levels (middle profile) gives net landward sediment transport (import; right profile).

Wind

Wind direction and force can result in a set-up or set-down of the water level, influence currents and generate local waves (wind waves). During storms, the wind set-up can be large and when the local water depth is large (also depending on the tide), the waves may be large. Especially at higher intertidal areas and in salt marshes, such events are important, as in normal tidal conditions hydrodynamic forces are small or even completely absent herein. In tidal channels wave forcing is typically (very) small compared to tidal forcing.

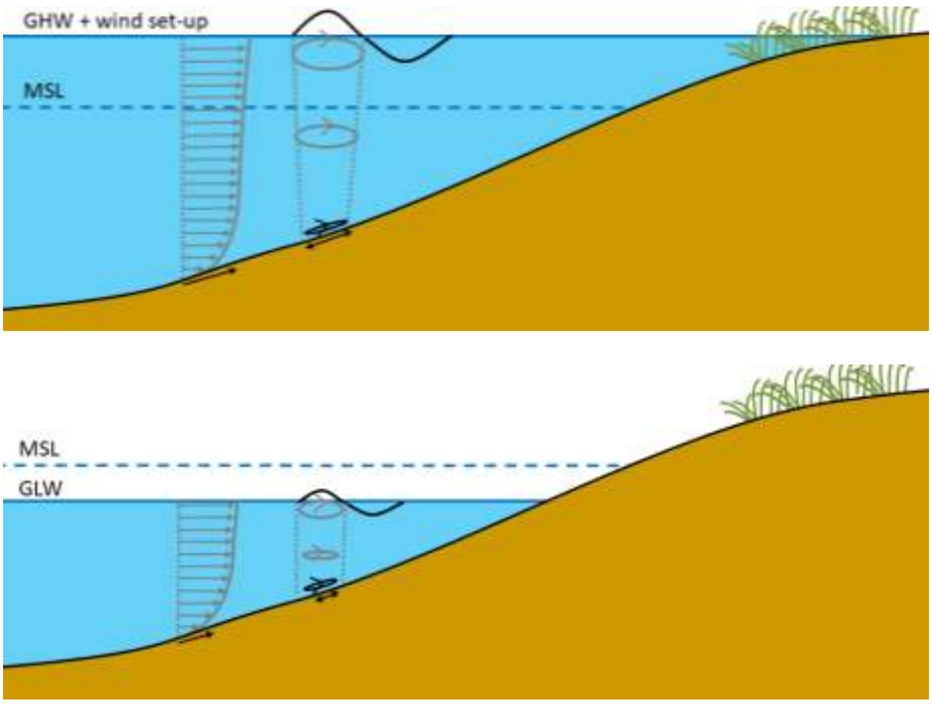


Figure 2.5 Event during high water level, with larger waves, larger bed shear stresses and higher intertidal and supratidal inundated (top) and event during low water level with smaller waves and smaller bed shear stresses (bottom).

Turbulence
Turbulence, i.e. instabilities in the flow due to currents, waves and bed roughness, and mixing determine the vertical distribution of SPM (and salinity) over the water column, which on its turn is important for (net) sediment transport and salinity stratification. On the other hand, sediment concentration has an influence on the turbulent characteristics of the flow, which is still an area of active (fundamental) research.

2.3.3 Mud properties

Mud properties influence erosion and sedimentation. We introduce (see Figure 2.6) critical shear stress, erosion rate, settling velocity and dry density. As these properties can change over time and vary over the estuary, we also discuss the processes that affect them: consolidation, bioturbation, biostabilisation, flocculation and hindered settling.

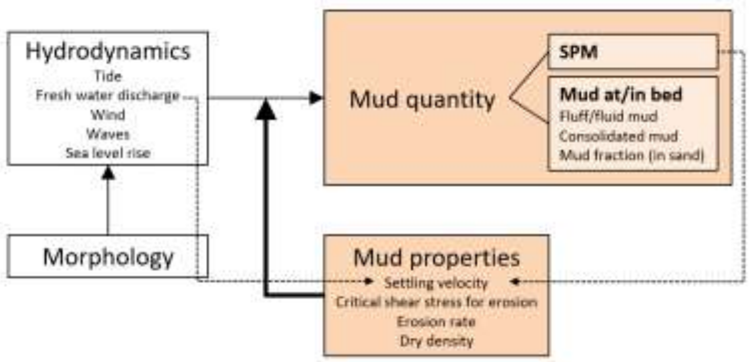


Figure 2.6 Impact of the mud properties on the exchange of mud between water column and bed. Hindered settling and flocculation by salinity are indicated with dashed arrows.

The previous section described how bed shear stress influences erosion. If and how much erosion occurs is also dependent of mud properties, especially the ‘resistance against erosion’. This is described with the parameters ‘**critical shear stress** for erosion’ and ‘**erosion rate**’. The critical shear stress is defined as a threshold above which mud starts to erode. The erosion rate determines the amount of erosion per unit time when the threshold is exceeded. Erosion can be limited by the availability of mud on/in the bed.

The process of sedimentation is controlled by different parameters: the sediment concentration and the **settling velocity** (how quick does a particle settle from suspension) in combination with the water depth (larger depths require more travel time and show less sedimentation than shallow water, all else being equal).

The **dry density** of the mud (already introduced above) is defined as mass per volume. It is an important property of the mud when we try to convert the mud mass (for example SPM in kg/m^3) to volume (for example bed level change in m) or vice versa.

Consolidation will compact the mud over time, increasing the dry density and increasing the resistance against erosion (increasing the critical shear stress and decreasing the erosion rate).
Worms, shells and other macrofauna living in and on the mud may reduce the strength and dry density by creation of tubes and hollows in the mud and by vertically mixing the mud, a process we call **bioturbation**.
Algae on top of and in the bed produce a biofilm that may glue mud particles together and increase the resistance against erosion (an example of ‘**biostabilisation**’).

The settling velocity varies due to **flocculation**, a process whereby individual particles or smaller flocs merge into (larger) flocs. Variations in salinity (over the estuary) and algae may induce flocculation. Flocs may break up due to turbulence. Floc formation and break-up may happen over the course of a tidal cycle, varying the settling velocity within the tidal cycle and possibly causing asymmetry in properties. This variation may show seasonality, as the amount and type or organic material influencing floc formation also varies on a seasonal scale. The settling velocity may also be reduced by a large SPM concentration, which is called '**hindered settling**'. When the SPM level is high (exceeding approximately 10 g/l), the settling of flocs and particles is hindered by the upward flow of water caused by neighboring settling flocs and particles.

Relations between settling velocity, flocculation and hindered settling
The settling velocity of unflocculated fine sediment is typically low, in the order 0.1 mm/s resulting in quasi-uniform vertical concentration profiles. However, in the presence of salinity and/or organic matter flocs can form, resulting in a larger settling velocity in the order of 1 mm/s or even larger. In this case more skewed concentration profiles (larger difference between top and bottom of water column) are expected, with important consequences for residual transport and accumulation (typically enhancing net sediment trapping).

Aggregation and break-up of flocs may be described with a dynamic flocculation model, but often the floc size distribution is approximated as constant. Nevertheless, even for a static overall distribution the average settling velocity of all classes may change within the tide and with position because of sorting processes. Compared to a single sediment fraction with constant settling velocity, this introduces additional asymmetries that influence residual transport.

At (very) high concentration the settling velocity will be reduced by hindered settling, i.e. the flocs hinder each other and are hindered by the counterflow of water. At even higher ('gelling') concentration a space-filling structure is formed and settling stops altogether. However, outflow of water from the bed will continue by self-weight consolidation. Until significant effective stress develops, the concentrated sediment layer is still fluid.

2.3.4 Net sediment transport is determined by asymmetries

The net sediment transport is determined by asymmetries in hydrodynamics, mud quantity and mud properties.

Tidal asymmetries can be spatial and temporal. Important temporal asymmetries are peak flow velocities, the asymmetry in duration of the slack water periods, and mixing asymmetries. For example, if the high-water slack period has a longer duration than the low water slack period, more sediment may settle to bed during high water than during low water. The net result is a landward transport of fine sediment.

Spatial asymmetries in flow velocity (or hydrodynamic energy) drive a residual transport from areas where the sediment is regularly resuspended (the channels) to areas with low resuspension rates (such as the flats). An example of an asymmetry in mud quantity on a tidal time scale is if the mud availability during flood is larger than during ebb. This can occur when less mud is advected to this area during ebb than during flood, resulting in a net landward transport (given equal flow velocities at ebb and flood).

Other asymmetries also play a role, such as asymmetries in bed composition, as during some phase of the tide more mud may be available on or in the bed than during another phase. If strong peak flood currents coincide with small mud availability on the bed, peak flood concentrations may be low. If weaker ebb currents coincide with large mud availability on the bed, peak ebb concentrations may still be high. In this case, flood dominance for hydrodynamics is paired with ebb dominance for sediment transport. For fast settling sediment this is very exceptional (and even impossible for equilibrium transport), but for fine sediment this is quite common. So, tidal and longer-term variations in bed composition (combined with bed shear stress steering the source term in the sediment transport equation) are key to understand fine sediment transport.

As illustration, we consider the effect of these dependencies on the im- or export of sand and mud across the vertical plane exactly at the mouth of an estuary. As sand is usually transported at transport capacity, the tidal asymmetry in the estuary mouth steers the residual sand transport into the estuary. For mud on the other hand, transport in the mouth is typically far below transport capacity and therefore supply-limited. The residual transport in the mouth is hence steered by the balance of erosion/deposition within the estuary and within the coastal sea. This implies that the sand and mud balance of an estuary may respond quite differently to changes in the estuary, e.g. of bathymetry, freshwater discharge, local sediment sinks and sources.

2.3.5 Mud properties and the response to hydrodynamics: limitation by supply or transport

The relation between hydrodynamic forcing and SPM levels depends on mud properties and mud availability. The crucial difference is whether the SPM concentration is limited by the sediment supply or by the transport capacity. The response of SPM and the sediment balance to changes in an estuary can be very different for transport- or supply-limited conditions.

The role of settling velocity

Transport capacity, i.e. the maximum rate of sediment transport that can be carried by the flow (see §2.2), is inversely related to settling velocity. Fast settling particles are more likely to be limited by the transport capacity than slow settling particles, which are typically limited by sediment supply.

There is a strong link between local hydrodynamic forcing and local transport for fast settling particles. These respond quickly to changes in hydrodynamics and sedimentation and erosion patterns can be derived from local gradients in the hydrodynamics. Decelerating flow implies sedimentation and accelerating flow implies erosion.

For fine sediment that settles slowly, the link between sediment transport and local hydrodynamic forcing is much weaker. Advection (i.e. horizontal exchange) dominates over sedimentation/erosion (i.e. vertical exchange), likely resulting in non-equilibrium sediment transport. Transport is determined by the conditions in a wide area rather than driven by local conditions. Fine sediment transport may quickly interchange between supply-limited (erosional) and depositional situations, both in time (within a tidal cycle; deposition during slack water and erosion during peak flow) and in space (erosion from old mud deposits and deposition in harbors) but is slow to respond to these transitions. This means that residual fine sediment transport is very sensitive to sinks and sources unrelated to local hydrodynamics, e.g. sedimentation in harbor basins or release of dredged mud.

Fluid mud

In areas with a large mud supply, fluid mud may occur. If fluid mud layers are persistent over the tidal cycle, transport may be considered permanently transport-limited. If fluid mud is mixed over the water column at maximal ebb or flood velocity, transport is partly supply-limited and partly transport-limited. Fluid mud that is permanently present may consolidate and become more resistant to erosion. So even if neither hydrodynamic forcing nor mud quantity change, consolidation (i.e. change in mud properties) may result in a change from transport to supply limitation.

Fluid mud formation near the bed can occur when high SPM levels increase the density of the sediment-water mixture and vertical mixing is damped, thereby enhancing sediment settling. Above a fluid mud layer trapping of mud becomes easier, as turbulence and mixing at the interface between fluid mud and overlying water are suppressed. For a more in-depth discussion on fluid mud and hyperturbidity see §4.3.

2.3.6 Morphology influencing hydrodynamics

In this section and the following we discuss the feedback loops highlighted in Figure 2.7.

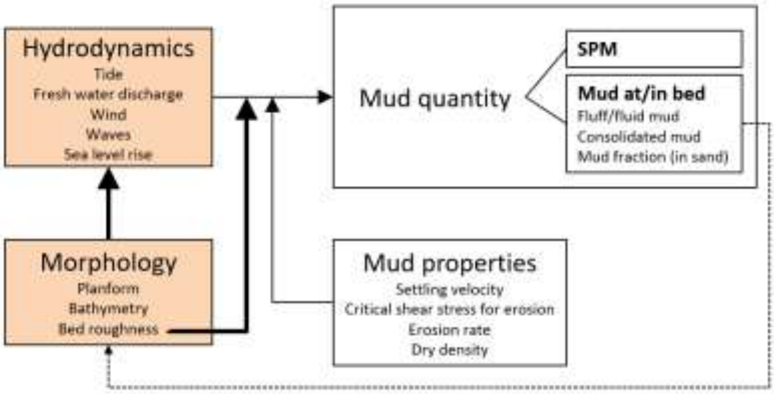


Figure 2.7 Interaction between morphology and hydrodynamics, including the feedback loop between mud deposition and morphodynamic changes with dashed arrow. The long-term feedback of changed hydrodynamics to morphology is not shown separately.

Morphology refers to the shape of the estuary (planform shape and bathymetry), but also to the shape of bed forms. The combination of the planform shape and the bathymetry determines how the tide is propagating into the estuary. A trumpet-shaped estuary funnels the tide through an increasingly narrow section, leading to tidal amplification and hence a larger tidal range in landward direction until the point where bed friction becomes dominant and results in tidal dampening beyond this point (Figure 2.8).
The planform and bathymetry of the estuary also determine its sensitivity to waves and wind-driven currents. If the wind blows over long distances (the so-called fetch lengths, Figure 2.8), unhampered by local shallows, waves may grow higher, and a larger wind set-up may develop than at short distances.

The bed forms and grain size distribution (‘skin friction’) make up the bed roughness. The bed roughness determines the degree to which the tidal propagation is dampened. The bed roughness also directly impacts the bed shear stress. Smoother beds (typical for estuaries with large amounts of fine sediments) generate lower bed shear stresses.

The local bathymetry determines the local flow velocity. Flow velocities in channels are typically higher than over tidal flats. Local bathymetric changes such as channel migration, strongly affect the local flow velocity at a fixed location.

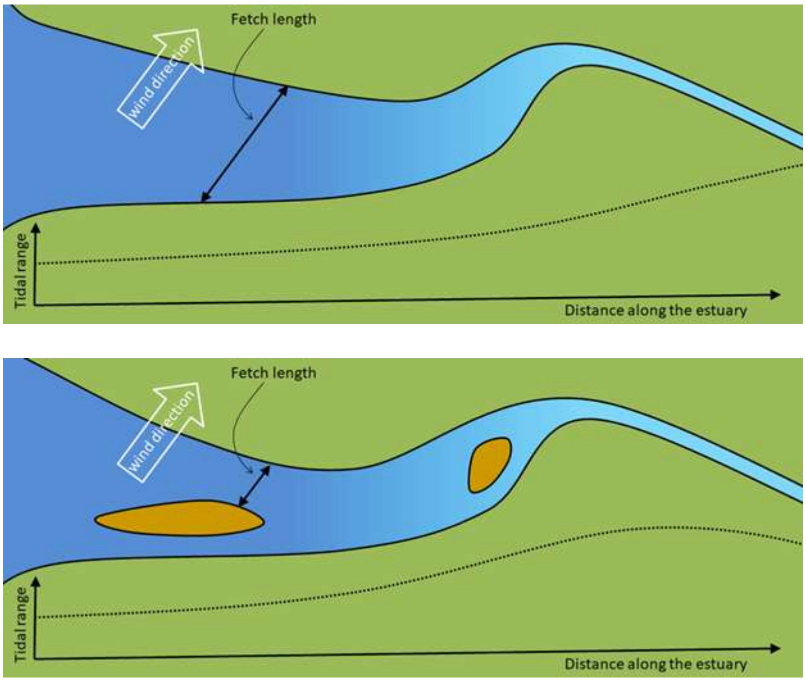


Figure 2.8 Impact of estuary geometry and bathymetry on tidal amplification and fetch lengths. When shoals are present (lower panel) tidal amplification may be stronger in the mouth due to funneling and weaker in the back due to friction. Also, the fetch length is reduced by the shoals.

On shorter timescales (days to weeks) we can neglect morphological changes, but over longer time scales these changes may become so large that they influence hydrodynamics (and hence transport).

On the long term, changes in tidal propagation - such as the amplification of the tidal range - impact the tidal prism (the volume of water that is transported in and out of an estuary during each tidal cycle). This in turn modulates the magnitude of the currents in the channels and over the tidal flats. When the travel time ('looptijd') of the tidal wave changes, the magnitude of the currents is also affected as the tidal prism then needs to be pumped in or out during a different amount of time. Long-term changes in tidal range of an estuary are studied and used to understand long term changes and interrelations between the driving forces. At this timescale also sea level rise and changes in freshwater discharges play a role. Sea level rise (and subsidence) affects the water depth and hence the tidal propagation and currents. Changes in freshwater discharges affect salinity-induced density currents and fluvial sediment supply, with both short- and long-term effects.

2.3.7 Mud sedimentation influencing bed roughness

When channels and flats become muddier, bed forms may disappear and friction may decrease, affecting the bed roughness, and modifying the tidal propagation and flow velocities (see dotted line in Figure 2.7). A lower local bed shear stress may further enhance mud deposition, inducing a positive feedback loop with more import and a muddier (or even hyperturbid) estuary. This feedback loop may be coupled to the feedback with the turbulence damping, as mentioned in section 2.3.3. It should be realized that such transition may require substantial time to accumulate sufficient mud. Counteracting dispersive mechanisms may become dominant after some time preventing that the concentration level is reached at which the positive feedback loop becomes significant. Also, the increase in mud quantity may remain a local phenomenon without expanding towards other parts of the estuary.

2.4 Estuarine turbidity maxima: sediment convergence

Estuaries usually show a variation of SPM over space, with certain areas of higher SPM levels caused by residual transport towards these areas, i.e. convergence. This can lead to an estuarine turbidity maximum (ETM). A classic example of this is coupled to the head of salinity intrusion, i.e. the location where salinity decreases to (near) zero. Due to gravitational circulation (see 2.3.2), flocculation and asymmetries in tidal velocities and vertical mixing, an area with higher SPM can exist at the head of salinity intrusion.

In most ETM's, including these at the head of the salinity intrusion, the sediment convergence balances longitudinal dispersion by tidal currents, resulting in a dynamic equilibrium concentration. When for some reason (for example due to river flushing) the ETM temporarily disappears, sediment transport convergence makes the ETM reappear.

Sediment properties affect ETM formation. Section 2.3.3 mentioned the process of flocculation that changes the settling velocity. This contributes to the ETM formation at the head of salinity intrusion, as the settling velocity affects the amount of sediment that can be transported. The mechanisms can be explained in the following way: a settling velocity of 0 results in infinite transport capacity, but no settling or water-bed exchange. Particles just follow the flow and don't generate an ETM. They can only disperse and cannot accumulate, i.e. residual mud transport from low to high concentration zones is not possible without settling. However, with settling, residual mud transport against the concentration gradient becomes possible. Accumulation becomes stronger for increasing settling velocity.

But there is a limit to this. An infinitely large settling velocity results in zero transport capacity as particles settle immediately to the bed, so an ETM can't be formed either. The 'sweet spot' of maximum sediment trapping and ETM formation typically occurs for settling velocities between 0.5 and 5 mm/s (depending on hydrodynamic forcing). Particles with much higher settling velocity values limit gross sediment transport too much, while particles with much lower values limit residual transport towards an ETM too much and are flushed out of the estuary. The rather uniform vertical SPM distribution of the particles with low settling velocities and small deposition (and hence resuspension) fluxes are unfavorable for trapping as all trapping mechanisms (as discussed in §2.3.4) need non-uniform sediment concentration profiles or substantial water-bed exchange.

For more information on the effects of changes in settling velocity on residual transport and ETM formation we refer to Horemans et al. (2021). Convergence mechanisms are described in detail in Burchard et al. (2018) and Dijkstra et al. (2019).

2.5 Human interventions

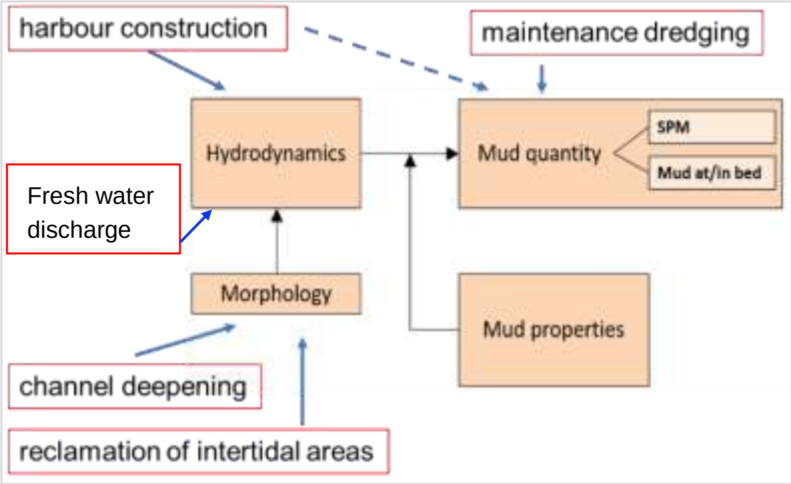


Figure 2.9 Human interventions brought into the conceptual model

In the past decades to centuries, many estuarine systems are modified by human interventions with effect on fine sediment dynamics. In chapter 4 we discuss the sustainability of four types of interventions, with respect to the Scheldt estuary: channel deepening, reclamation of intertidal areas, harbor construction and maintenance dredging. Figure 2.9 shows how these types of interventions are placed in the conceptual model. These are not the only interventions, as the construction of sluices, weirs and dams upstream and modification of the freshwater discharge into the estuary have definitely impacted sediment sources and sinks.

Channel deepening and land reclamation on SPM is via a change in hydrodynamics (see e.g. Kuijper, 2013 and Van Rijn, 2011). The construction of harbors and maintenance dredging have limited to no effect on hydrodynamics but directly influence sediment sinks, sources and residual transport. Dredging and disposal influences mud quantity (when for example mud is brought on land) or the distribution between SPM and mud on/in the bed (for example by causing a dredging plume). A method to evaluate the importance of dredging and disposal of mud in comparison with natural mud dynamics in an estuary is discussed in the text box on the disturbance ratio (see text box below).

Reducing the freshwater influx upstream influences the sediment distribution in the estuary and leads to higher sediment concentrations upstream.

The effect of human interventions on mud properties is indirect and less straightforward. This is not shown in Figure 2.9. A good illustration is the effect of water quality. Contaminants and/or excess of nutrients can affect algae growth and algae may induce flocculation of mud particles or increase the resistance against erosion of the bed (‘algae mats’). An example in the Scheldt estuary hereof is the construction of wastewater treatment plants which have strongly improved the water quality over the past decades and may have changed floc properties (Cox et al., 2019 and Horemans et al., 2021). However, seasonal variations in sediment dynamics also have a strong physical origin resulting from seasonal variations in freshwater discharge, fluvial mud supply and marine mud supply by wind- and wave-induced resuspension (Van Kessel et al., 2011 and Horemans et al., 2021).

Disturbance ratio
To quantify the effect of dredging and disposal in an estuary, we consider the net sediment transport and the dredging volumes. The effect of human interventions such as dredging and disposal may seem small compared to the gross natural sediment transports. It can, however, be substantial compared to the net sediment transport. If this occurs interventions have a significant influence on the sediment balance of the system, affecting the mud quantity and SPM.

The human influence can be quantified with a disturbance ratio R, defined as: $R = D/(D+N)$, where D is total volume of maintenance dredging and N is the volume of 'natural' sedimentation in the estuary (i.e. in the absence of anthropogenic effects). If R is close to zero, the sediment balance is governed by natural fluxes and the additional sediment source by e.g. dumping of dredged material is relatively small and hence has little impact on SPM levels, inducing a slight increase in D only. Likely, recirculation effects are small as well. On the other hand, if R is close to unity, the sediment balance is mostly steered by anthropogenic effects and an additional sediment source is likely to increase SPM levels further. Also, recirculation effects may become more important, being highly sensitive to the release location.

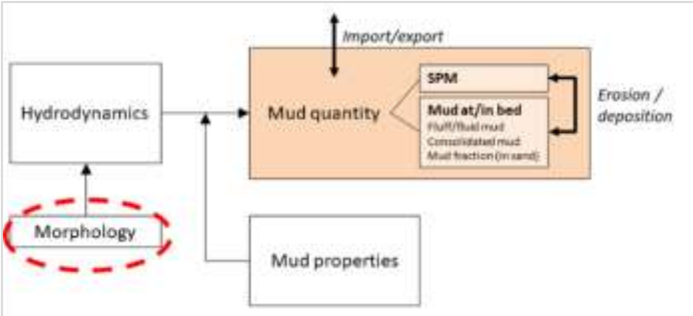
It is fair to state that estuaries with $R \rightarrow 1$ lack a local safety valve, i.e. additional release of disposed mud will hardly result in additional (permanent) local sedimentation, but will mostly flow back to harbors or towards sea, which can only occur if a substantial SPM gradient is established to force that seaward flux. For systems with weak flushing, this may result in high SPM levels leading to ecological damage and prohibitive dredging costs. Enhanced SPM levels can also cause feedback mechanisms as discussed in 2.3.5 (see hyperturbidity) and further worsen the situation.

3 Fine sediment dynamics in the Scheldt estuary: description and specifying the conceptual model

This chapter describes the sediment dynamics in the Scheldt estuary. It uses the generic conceptual framework of the previous chapter. First the main characteristics of the estuary are discussed. This is followed by hydrodynamics, mud distribution in the water column and in the bed and its mud properties. Subsequently, we translate the generic conceptual model to a specific one for the Scheldt estuary.

3.1 Characteristics of the estuary

3.1.1 Morphology and geometry



The Scheldt estuary stretches over a distance of 156 km from its mouth at Vlissingen to the limit of tidal influence at the weir in Ghent (Figure 3.1). The Flemish part, the Sea Scheldt (Zeeschelde), is a tidal river, with one tidal channel. The Dutch part is called the Western Scheldt (Westerschelde) and is characterized by a multi-channel system of evasive ebb- and flood channels, separated by tidal flats. These form so-called macro cells for (sandy) sediment transport (Winterwerp et al. 2001, Figure 3.2). The deeper channel of the two is used and maintained as the navigational channel and sills between the macro cells and local narrows are dredged to accommodate to accommodate maritime traffic to the Scheldt harbors. The mostly sandy material dredged in this part of the estuary is disposed into the estuary again. The tidal flats are increasing in height (Alkyon, 2006; De Vet et al., 2017) and at some locations even vegetation is developing recently (such as at Hooge Platen and the shoal of Walsoorden). The largest salt marsh in the Scheldt estuary is the Verdronken Land van Saeftinghe. Vegetated areas play a role in capturing fine sediment. Other locations where fine sediment can accumulate are higher intertidal areas and margins of the estuary.

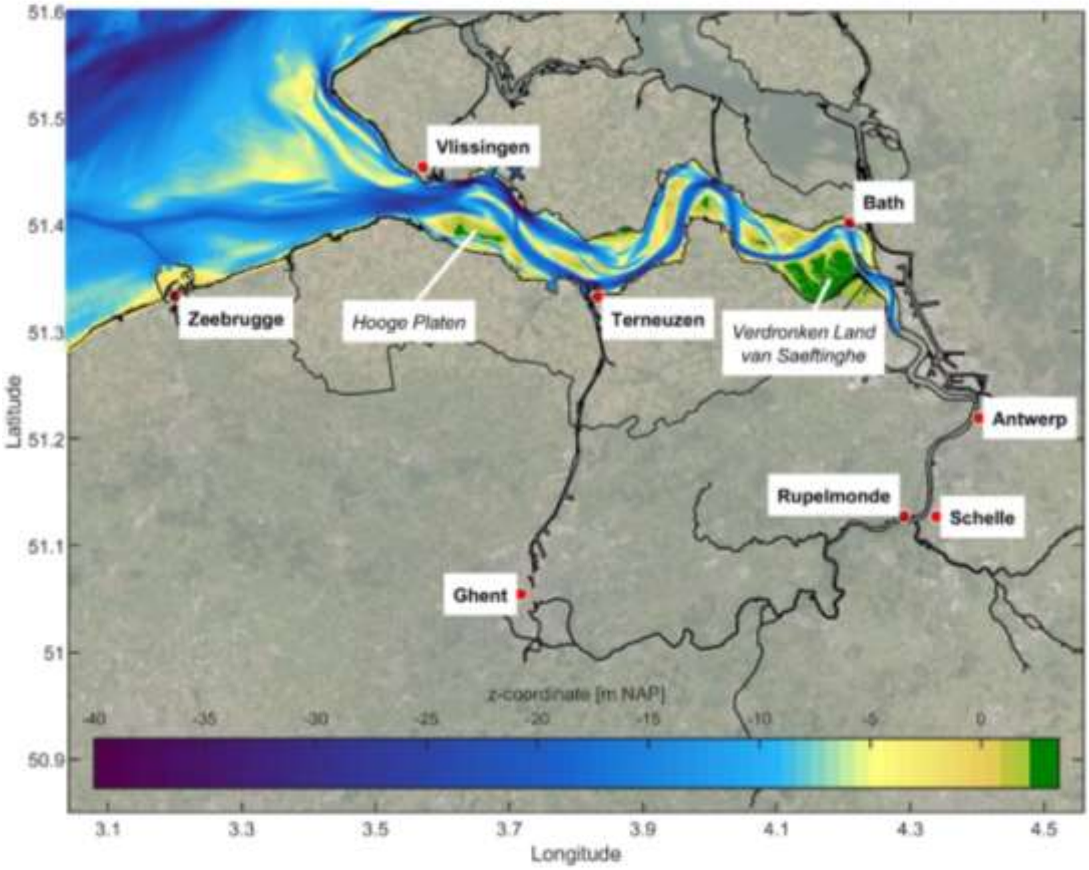


Figure 3.1 Bathymetry (relative to Dutch refence level NAP) and places along the Scheldt estuary.

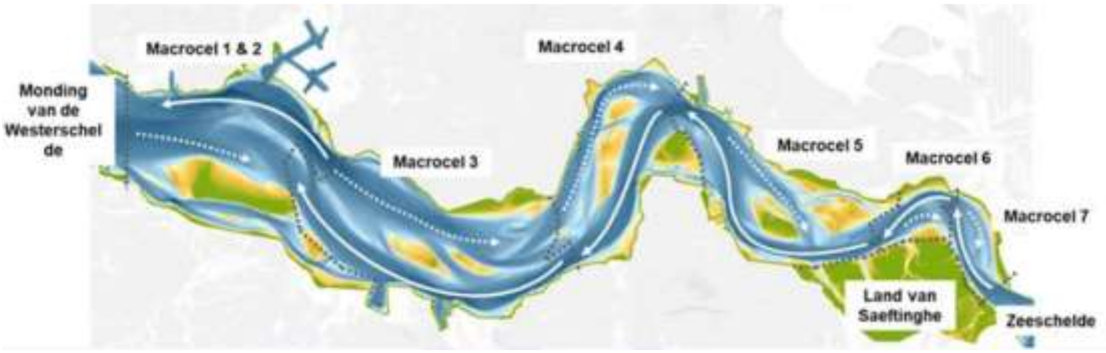


Figure 3.2 Macrocells in the Western Scheldt (Kater & Cleveringa, 2019).

Historical interventions in geometry

In the past centuries the estuary has become much more constrained as side-branches such as Sloe and Braakman have been reclaimed and along the estuary salt marshes have been diked (Dam, 2017; Figure 3.3). This trend was sometimes temporarily reversed by flood disasters, when dikes breached, and reclaimed land was lost to the sea again. Not always the dikes were restored, an important example of a drowned polder is the 'Verdronken (Dutch for 'drowned') land van Saeftinghe', which at present is one of the most elevated areas along the estuary apart from the coastal dunes. Here sediment accretion continued over time, whereas the reclaimed areas were cut off from sediment supply and gradually lowered because of soil subsidence.

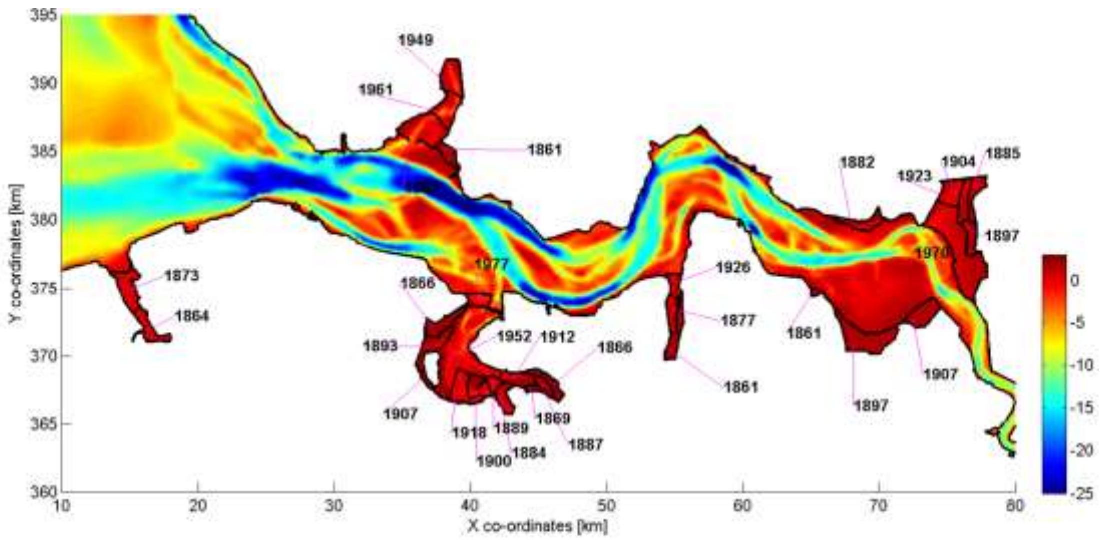
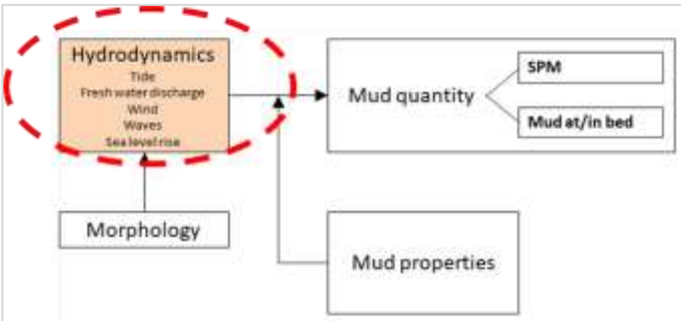


Figure 3.3 Bathymetry of the estuary with impolderings since 1860 (Dam, 2017)

At many locations, hard structures have been constructed to prevent erosion, notably near dikes and intertidal flats. This implies that the natural system is more and more constrained and natural morphodynamics can only occur within anthropogenic constraints. The morphodynamics are locally additionally influenced by erosion-resistant layers composed of compacted old clay deposits that are not or only very slowly eroding.

Recently the estuarine area is increased, especially in the Sea Scheldt. This is done with permanently wet reduced tide areas controlled by culverts (FCA-CRT)) and controlled flooding areas that can be used only during extreme high-water levels (FCA) and depolderings. The largest depoldering is Hedwige-Prosperpolder, which is partly in the Netherlands.

3.2 Hydrodynamics



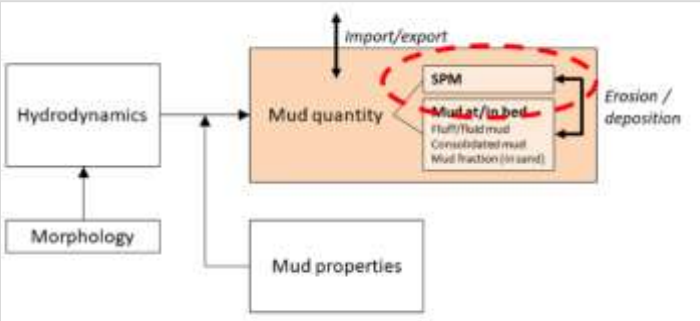
The tide, with a mean tidal range of 3.85 m in the North Sea at the mouth (km 0), is amplified in the estuary, resulting in a mean tidal range of 5.24 m at Schelle (km 91). The spring-neap tidal cycle increases and decrease the mean tidal range to 4.46 and 2.97 m at the mouth and 5.93 and 4.49 m at Schelle. The tidal range has strongly increased over the past century by anthropogenic changes such as ongoing channel deepening for navigation and impoldering / embankments (Kuijper, 2013). During storms, the water level set-up can flood supratidal areas such as the highest part of salt marshes and feed them with (fine) sediment. The dominant SW and NW wind direction and the presence of tidal flats limit wind waves in the estuary. At the mouth, close to the port of Zeebrugge, larger waves occur, with an average significant wave height in the order of 0.5 m with maxima over 4 m.

The salinity intrusion reaches up to Rupelmonde (km 92). This point of zero salinity can shift over about 40 km, depending on freshwater discharge. Upstream of the salinity intrusion point the Upper Sea Scheldt forms one of the largest fresh water tidal rivers in Europe. Downstream the salinity gradient is mixed over the water column by the relatively large tidal range, generally resulting in vertical salinity differences of about 1 ‰. A partially mixed zone between Antwerp (km 75) and the border (km 58) exists where the vertical salinity difference can be up to 4 ‰ during spring tide (Claessen 1988; Van Kessel et al. 2011).

Freshwater discharges from the Upper Scheldt River and side branches Rupel and Dender range from 30 m^3/s during dry summers at Schelle (OMES, 2021) to 300 m^3/s during wet winters. The average discharge is 120 m^3/s, which is small compared to the tidal discharge of 50.000 m^3/s at the mouth. The tidal volume is about a billion (10^9) m^3. The residence time of freshwater in the estuary is estimated at 2–3 months (Van Kessel et al. 2011; Wollast & Peters 1978).

3.3 Mud quantity

3.3.1 Turbidity maxima



The Scheldt estuary shows three turbidity maxima:
1) in the mouth ((or ‘Coastal Turbidity Maximum’, CTM, see Figure 3.4);
2) around Antwerp near the head of salinity intrusion; and
3) in the freshwater zone.

The CTM at the mouth of the estuary (#1) exists due to sediment trapping due to tidal flow conditions (Vanlede, 2022). It is further maintained by a positive feedback loop between erosion of old mud deposits in the bed, formation of near-bed high SPM layers leading to damping of turbulent mixing that are susceptible to sediment- and salinity-driven density currents (Van Maren et al. 2020). Release of mud dredged from Zeebrugge harbor and onshore near-bed residual circulation generated by cross-shore salinity gradients also play a role in maintaining the CTM.

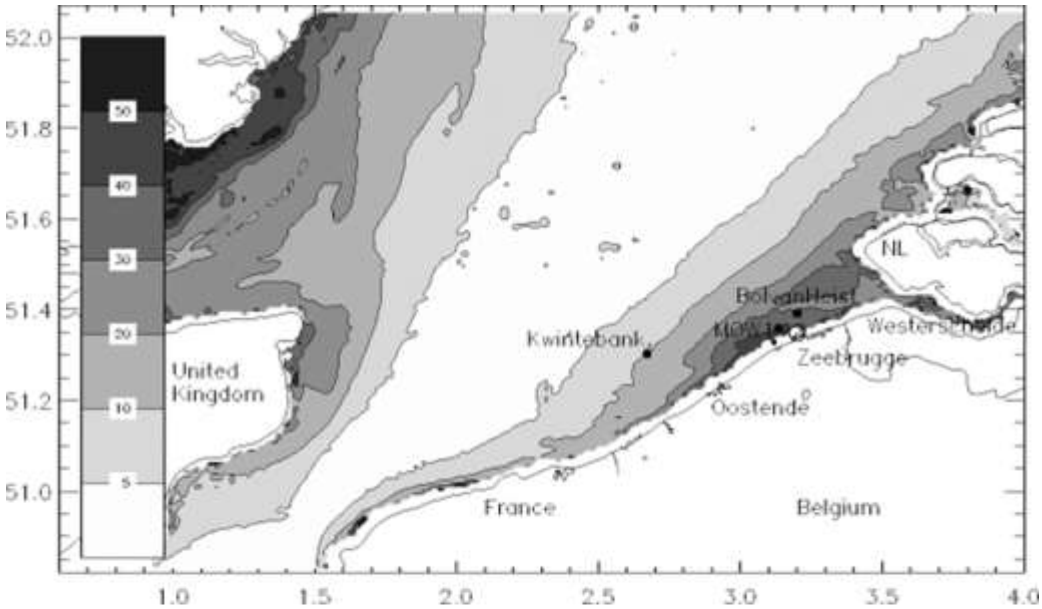


Figure 3.4 Map of the southern North Sea with the in-situ SPM concentration measurement stations MOW1 and Kwintebank. The background consists of the yearly averaged surface SPM concentration (mg/l) in the southern North Sea, from MODIS images (2003–2008). From: Fettweis & Nechad (2011).

The ‘classical’ ETM near Antwerp (#2) is usually explained by a combination of estuarine circulation, tidal pumping and flocculation. This ETM is situated around maximal tidal energy, approximately following the head of the salinity intrusion (Van Kessel et al., 2011).

The ETM in the freshwater zone (#3) is not persistent but may be formed by tidal pumping during periods of low freshwater discharge and flushed out during high discharge peaks (Winterwerp et al., 2013; Cox et al., 2019; Dijkstra et al. 2019).

In the Western Scheldt there is substantial interannual variation in SPM dynamics, but (depending on monitoring station) no to only weak long-term trends. In the Sea Scheldt long-term trends are observed (Vandenbruwaene et al., 2016; Cox et al., 2019).

3.3.2 SPM-data Western Scheldt

Figure 3.5 shows long-term averages for the six MWTL measurements of SPM. These measurements are long-term monthly or biweekly observations on SPM from near-surface water samples at fixed positions. None of these positions lies within one of the ETMs. The most upstream station Schaar van Ouden Doel lies closest to an ETM and shows much higher values compared to the other locations.

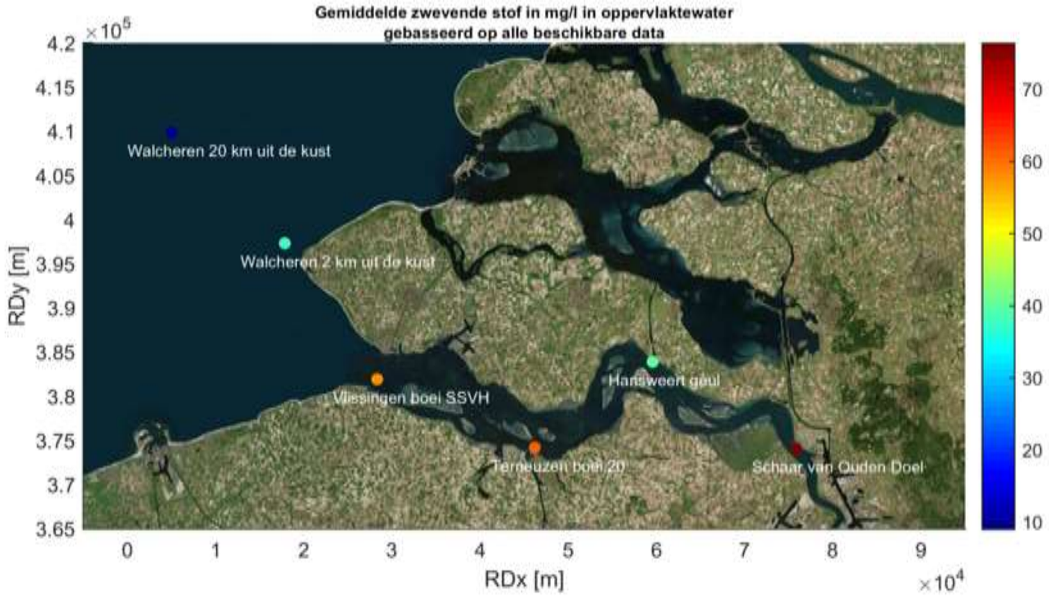


Figure 3.5 SPM at Dutch MWTL locations, averaged over 1996-2018 (http://publications.deltares.nl/1209394_183.pdf)

On the timescale of years, the SPM levels near Terneuzen correlate with freshwater discharge most of the time, with higher discharges coinciding with higher SPM levels (Figure 3.6). It is uncertain if this correlation is causal, although a stronger longitudinal salinity gradient near the mouth is likely to enhance (residual) marine import of SPM. At locations more upstream (beyond the ETM) an inverse correlation is observed because the ETM migrates in seaward direction under influence of a higher river discharge. Even further upstream (in the freshwater zone) the correlation becomes positive again for high discharges when they cause local resuspension of mud deposits. For example, at high discharge the weir at Merelbeke is opened and mud accumulated behind the weir may flow towards the Sea Scheldt.

Over long timescales (1990-present), the running mean SPM over a period of 13 months, expressed as the relative anomaly, show some multi-annual variations that are similar for all stations in the Western Scheldt (for example a reduction around 2008, see Figure 3.7). At Vlissingen and Schaar van Ouden Doel, the SPM seems to be increasing over time[2] (Figure 3.8). To investigate how the SPM will develop in the future, we need to understand the mechanisms controlling temporal reductions in SSC (such as around 2008) and the recent increase that is observed at some of the stations.

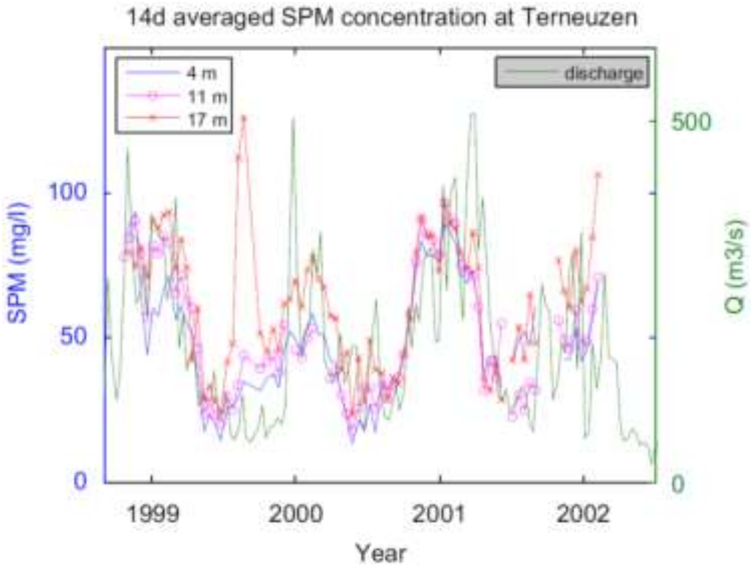


Figure 3.6 14 d-mean SPM concentration at Terneuzen (location DOW-jetty) at 3 vertical levels and 14 d-mean river discharge. From Van Kessel et al. (2011) based on high-frequency monitoring data in the framework of the Western Scheldt tunnel project (12/1998 – 2/2002).

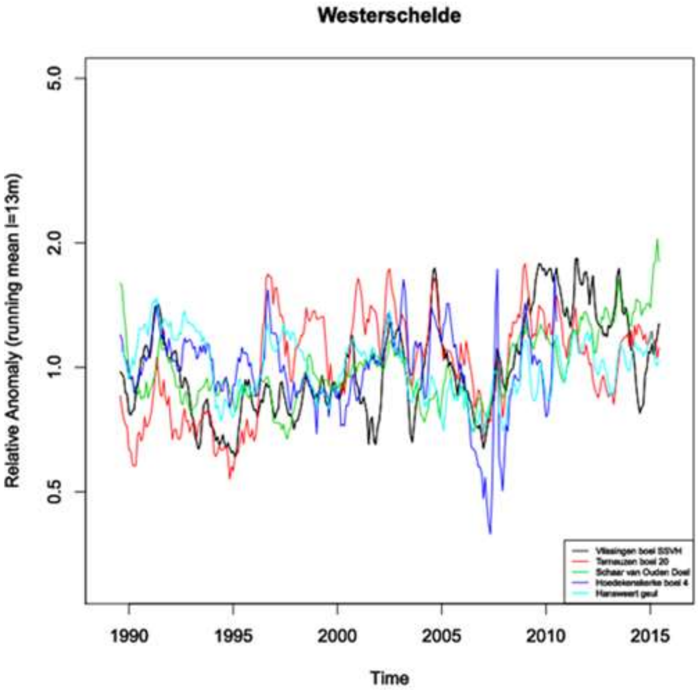


Figure 3.7 Long-term trends, expressed as 13-month moving averages of the relative anomaly of SPM (from Herman et al. 2018). Stations are Vlissingen boei SSVH, Terneuzen boei 20, Schaar van Ouden Doel, Hoedekenskerke boei 4 and Hansweert geul.

[2] Data before 1990 need to be omitted because the sampling technique doesn't allow for consistent data analysis.

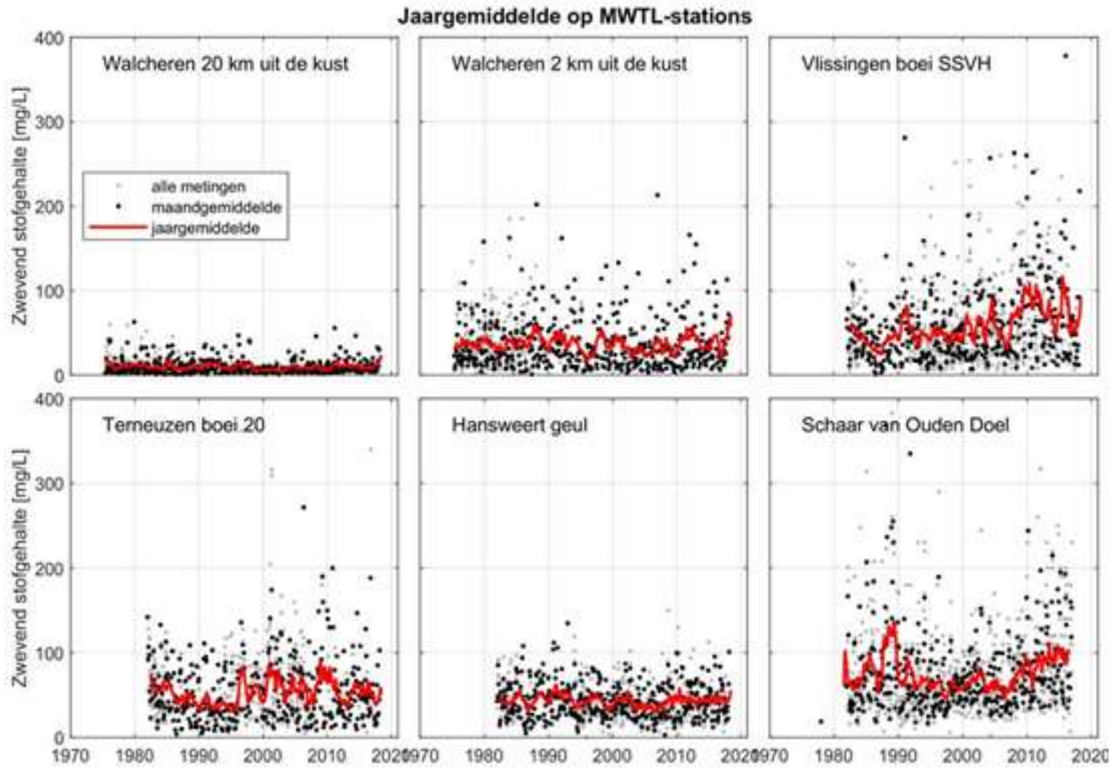


Figure 3.8 Yearly averaged running mean of the suspended particulate matter concentration near the surface for the MWTL stations.

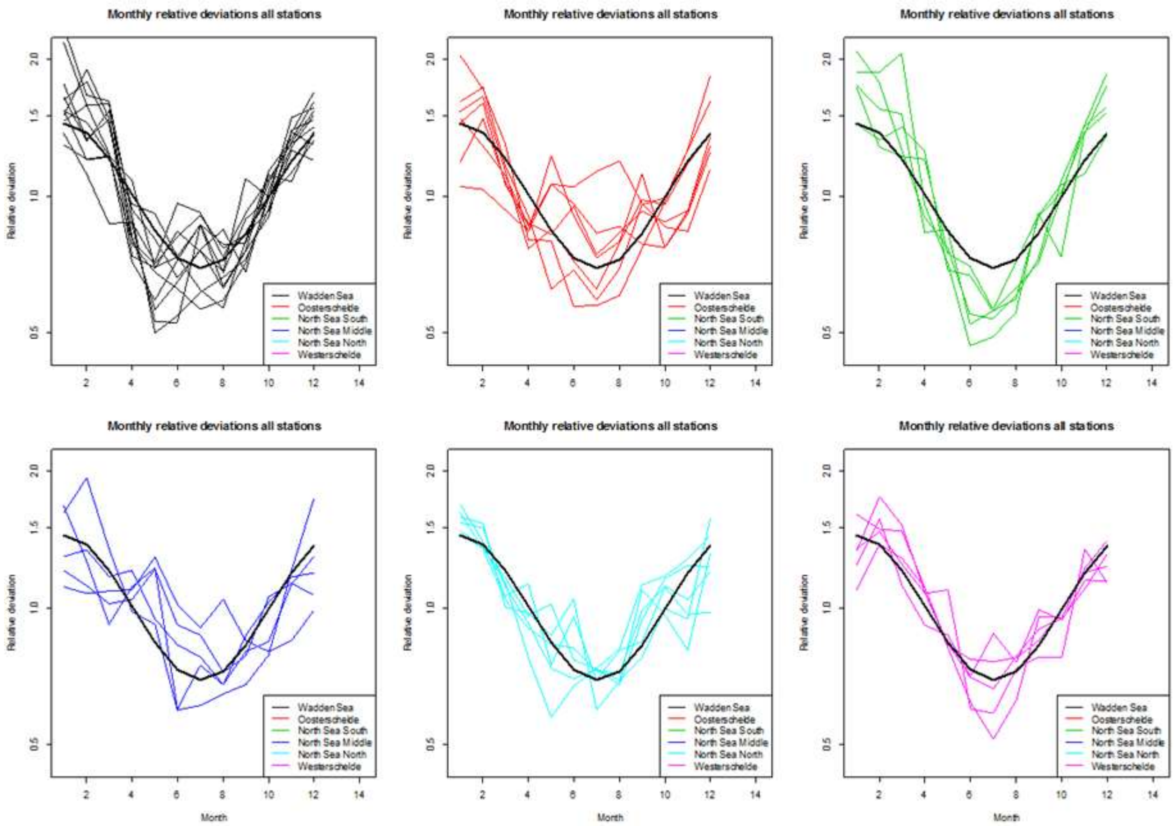


Figure 3.9 Monthly relative deviations from the long-time average concentration of SPM in the different systems of the Netherlands continental shelf. The thick black line is a fitted periodic function and is the same in all graphs (from Herman et al. 2018). Lower right figure presents the Western Scheldt.

The seasonal pattern is very similar to other coastal systems (Wadden Sea, Eastern Scheldt, North Sea, Western Scheldt; Figure 3.9). For the Dutch Wadden Sea and the North Sea, the seasonal variation seems mostly driven by wave-driven resuspension from the bed, strengthened by biological activity such as flocculation by algae in summer and retention of fine sediment at the intertidal area by microphytobenthos biofilms. As the Western Scheldt has a higher tidal range and much smaller fetch lengths, the wave-driven resuspension is less dominant compared to shallow and extensive systems like the Wadden Sea, except for the mouth area. The seasonal pattern may therefore be more strongly driven by variations in marine supply, salinity gradients and related density currents induced by freshwater discharge and biological activity, which all show substantial seasonal variations.

On the short time scale the SPM varies with the tide. The current available long-term SPM dataset (MWTL) contains every two weeks to one month a data point and does not reveal variations on short time scales, and hence does not give information on the effect and relative importance of wind-driven transport or wave-driven resuspension during storms.

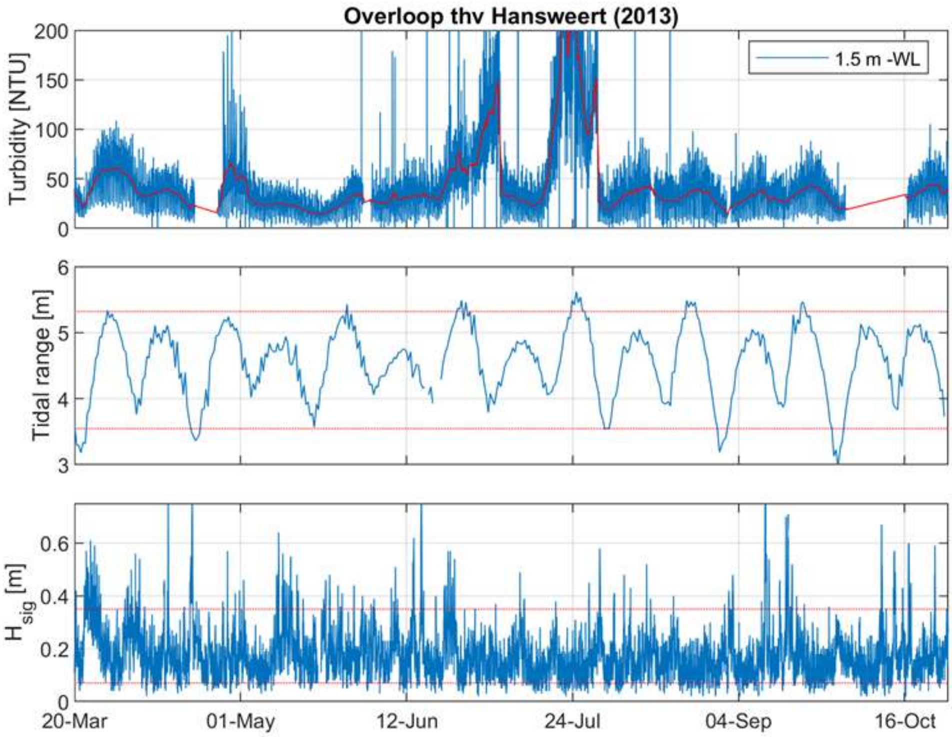


Figure 3.10 Timeseries turbidity, tidal range and significant wave height at OvHW in 2013. Red solid line is the daily moving average (top). Red dotted lines indicate the 5- and 95-percentiles (middle and bottom plot).

Occasional observations with higher measuring frequency in time were done at Overloop van Hansweert[3] in the summer periods of 2012-2014, at 1.5 m below the water surface, using a measurement pole on the side of the channel. In the summer period, some periods with increasing/high turbidity are visible, caused by biofouling of the sensor. This should therefore be ignored. The turbidity observations reveal a clear spring-neap tidal cycle (Figure 3.10 and Figure 3.11). The turbidity varies roughly between the 20 and 80 NTU, depending on the phase of the tide. The low water slack shows the lowest turbidity values, while the high-water slack shows much higher values (Figure 3.12). This could be related to local hydrodynamics and mud availability that vary over time.

[3] The coordinates of the measurement pool are 51°24'28.22" N and 3°58'00.52" E (RDx: 056180m, RDy: 380852m). View location in Google Maps.

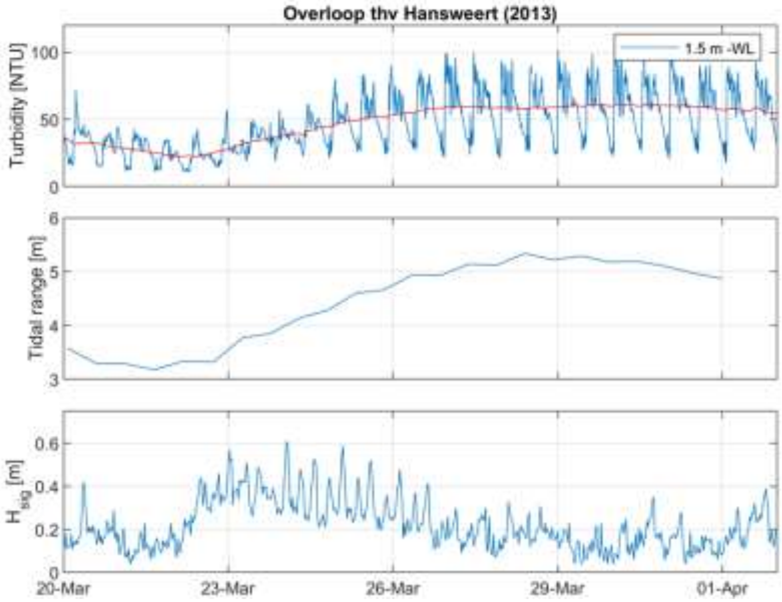


Figure 3.11 Timeseries turbidity, tidal range and significant wave height at OvHW in March 2013. Red solid line is the daily moving average (top).

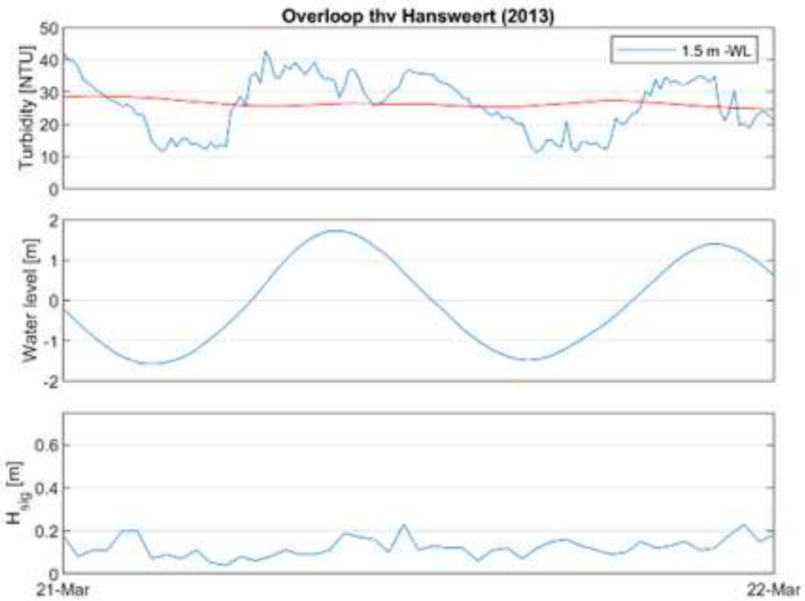


Figure 3.12 Timeseries turbidity, water level and significant wave height at OvHW in 2013. Red solid line is the daily moving average (top).

Figure 3.11 and Figure 3.13 suggest that at the Overloop van Hansweert, the effects of waves on turbidity are limited. In September 2012 and March 2013 there are more energetic conditions, without a clear increase in turbidity peaks. It can be argued that there is an effect of waves on the turbidity values during slack water periods. These seem slightly higher than during lower wave conditions. The large tidal range in combination with the relatively small fetch lengths in the Western Scheldt may explain the tidal dominance in these turbidity observations. The strong spring-neap tidal signal leads to a negligible impact of high(er) wave events, at least at the observation location that is located at the edge of the tidal channel.

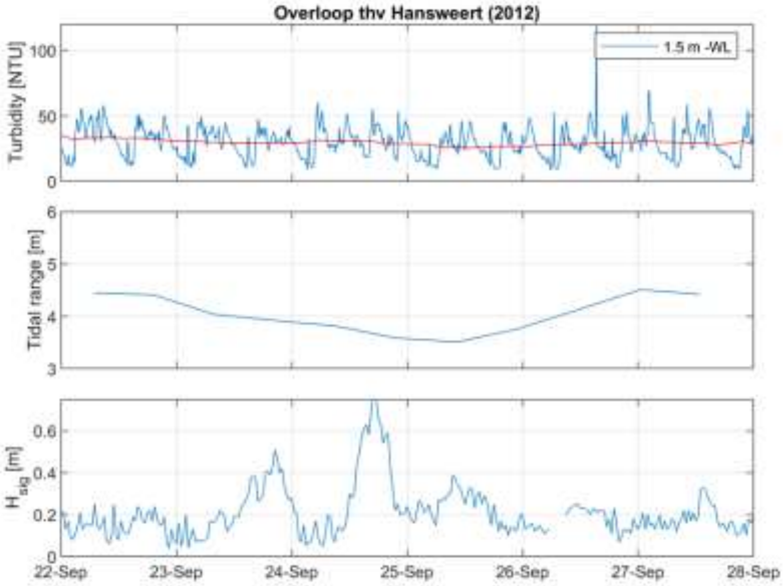


Figure 3.13 Turbidity, tidal range and significant wave height during storm in September 2012. Red solid line is the daily moving average (top).

3.3.3 SPM-data Sea Scheldt

For the Sea Scheldt the OMES data combined with data from fixed monitoring stations provide a rich data set on SPM levels, their variability and steering factors. Data sets are available at http://www.omes-monitoring.be/en/imis?module=dataset&dasid=1381. From these data ensemble averages can be constructed as illustrated in Figure 3.14 (Vanlede, 2022). At Boei84 near Antwerp a strong ebb-dominance in sediment concentration is observed, probably related to the cycle of dredging and dispersion of harbor mud (see also the discussion in Sections 3.5.4 and 4.4.

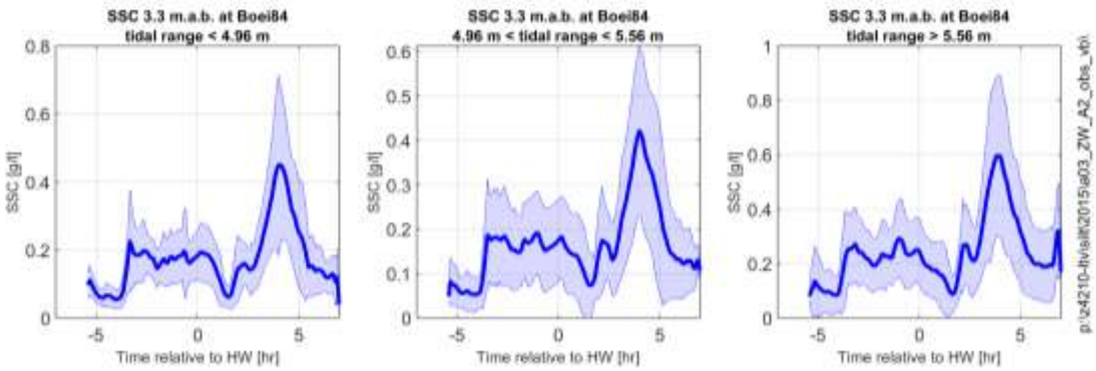


Figure 3.14 Ensemble averages of SSC (g/l) at Boei84 near Antwerp at 3.3 m above bed (from Cronin et al., 2018). Ensemble based on observations for the entire year 2010. The light blue band represents variability.

Based on the OMES data, several analyses have been made, e.g. Cox et al. (2019), Plancke et al. (2020) or Horemans et al. (2021). Compared to the Western Scheldt, the influence of freshwater discharge and maintenance dredging on SPM levels is more prominent, as the estuary is much narrower in landward direction. The effect of morphological changes on tidal propagation, salinity intrusion and SPM levels are more prominent for the same reason.

Cox et al. (2019) discuss that compared to the Western Scheldt typical SPM levels in the Sea Scheldt are higher, with two turbidity maxima, one in the lower Sea Scheldt near Antwerp, another in the upper Sea Scheldt beyond Rupelmonde (Figure 3.15). The Western Scheldt

shows no clear long-term trend in SPM levels (previous section). This contrasts with the Sea Scheldt, where SPM levels increased after 2009, notably in winter in the lower Sea Scheldt and in summer in the upper Sea Scheldt (for some years, with exceptions). Around this year the Deurganckdok became fully operational and the third deepening and widening of the Scheldt was carried out (Lankriet and Cronin, 2018).
Plancke et al. (2020) discuss a multivariate statistical model on the factors influencing SPM levels in the Sea Scheldt. They conclude that in the lower Sea Scheldt the effect of the release of dredged material is dominant, whereas in the upper Sea Scheldt residence time (linked to freshwater discharge) is dominant.

Horemans et al. (2021) discuss the influence of flocculation (affecting setting velocity) on SPM dynamics and ETM formation. This mechanism results in additional transport asymmetries, altering residual sediment transport. This illustrates the importance of sediment properties in the conceptual model.

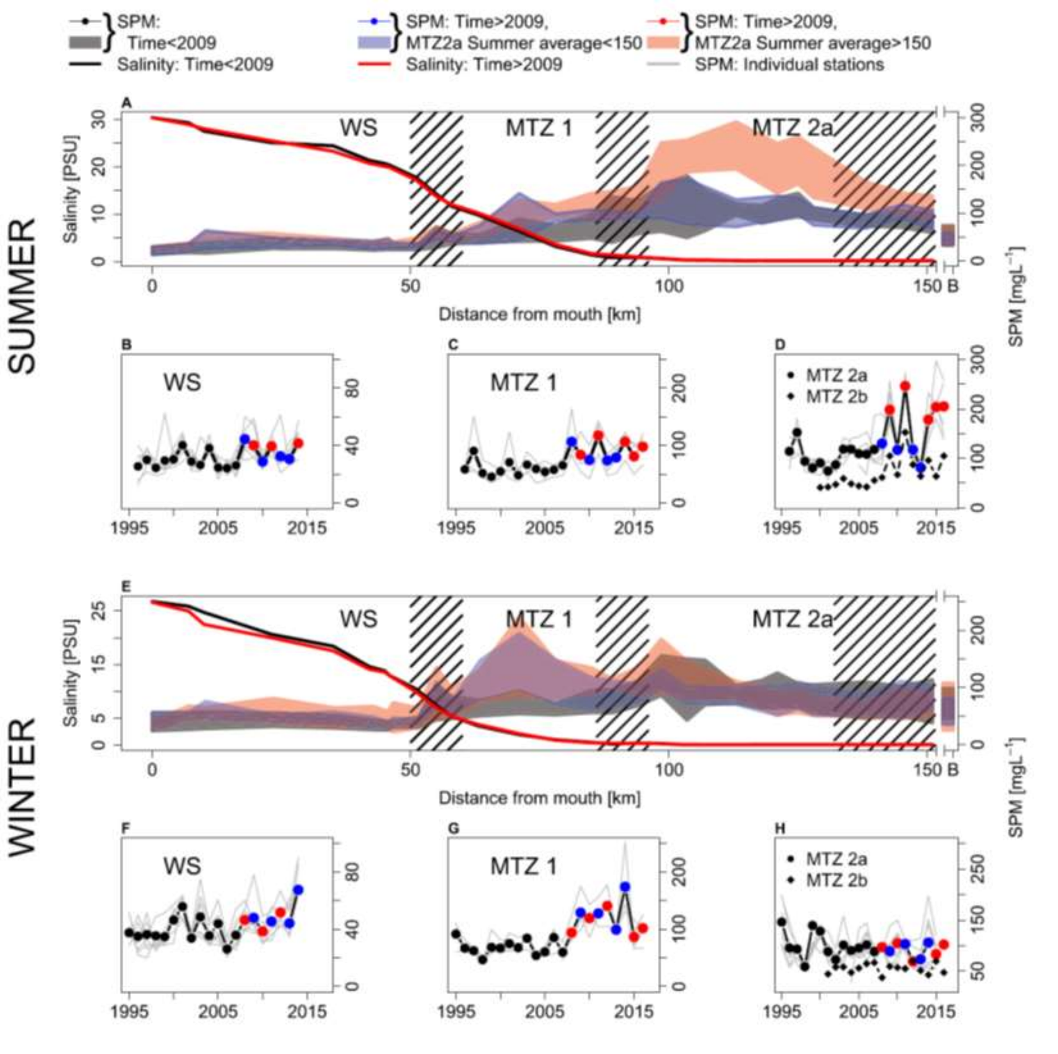
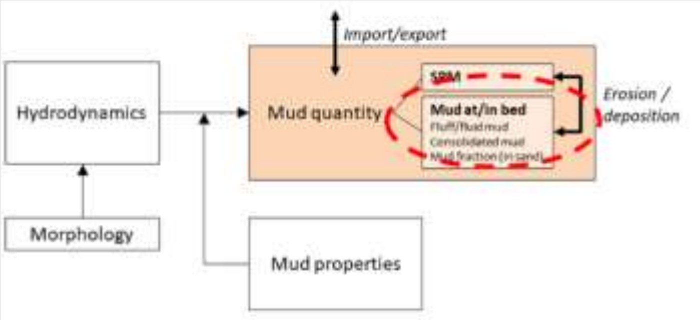


Figure 3.15 Spatio-temporal patterns. Longitudinal distribution of salinity and SPM in summer (A), winter (E). White bands indicate the characteristic zones of the estuary regarding SPM dynamics. Hatched out areas represent transitions between characteristic zones. "B" on x-axis gives concentrations at boundary (upstream weir). Summer (B–D) and winter (F–H) averaged time series of SPM in characteristic zones (note the different scale on y-axes). Light grey lines represent time series at all individual monitoring stations within each zone; black lines and black, blue and red dots represent zone-averaged time series. Taken from Cox et al., 2019.

3.3.4 Mud in the bed



Western Scheldt
The map of mud distribution in the bed shows that mud is mostly accumulating at the margins of the Western Scheldt (Figure 3.16). Also, in the salt marsh Verdronken land van Saeftinghe mud accumulates. The Middelgat (secondary channel of macrocel 4) forms a permanent sink of mud due to the continuous sedimentation in this channel (Figure 3.17). At least half of the net import of mud into the Western Scheldt is accumulating in the Middelgat, in some periods even more than the net import due to local redistribution within the estuary. See Section 3.5.4 for a discussion on the mud balance of the estuary. As the hydrodynamics in the channels and deeper parts are relatively constant over time, it is assumed that the mud content in the deeper parts is also quite constant. The intertidal areas have however undergone significant changes such as the increase in mean flat height (Alkyon, 2006) and the disappearance and stabilization of cross-channels, that are important for flat regeneration. It is unknown what the effect of these changes on the intertidal mud content is. The Sea Scheldt, where one of the ETMs is located, is characterized by much muddier beds (Cleveringa & Dam, 2013).

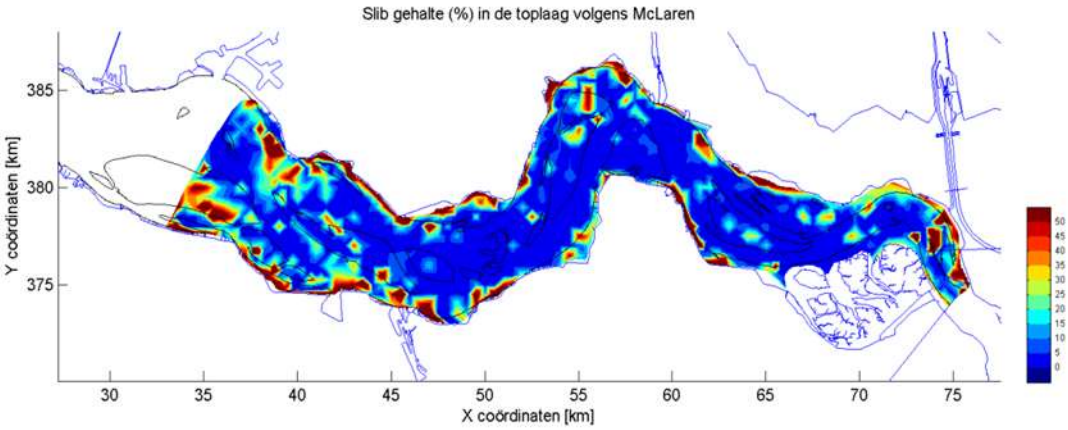


Figure 3.16 Mud content from measurements of McLaren (Cleveringa & Dam, 2013)

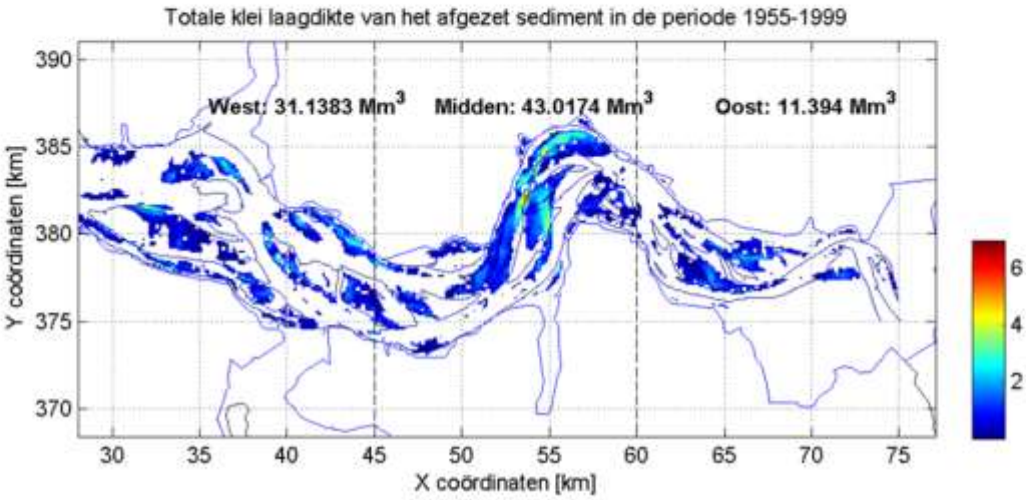


Figure 3.17 Thickness of the clay layer deposited over the period 1955-1999 according to TNO GeoTop data (Dam, 2017). Per sub area the total amount of clay import over this period is indicated in million m^3.

Figure 3.18 Mud-rich low dynamic area (yellow and brownish), supratidal low dynamic area (bright green) and salt marsh (dark green) in the Ecotopenkaart 1996 (top) and 2020 (bottom). Source: RWS.

Sea Scheldt

With regard to the Sea Scheldt, Vandenbruwaene and Levy (2017) present maps of observed bed composition analyzed in the framework of a sediment balance study (see Figure 3.19) Similar to the Western Scheldt, the bed composition of the main channel where current velocities are high is predominantly sandy, whereas more sheltered side branches, tidal flats, access channels and harbor basins are muddier. Overall, the mud content of sediments in the Sea Scheldt is higher than in the Western Scheldt. This is consistent with observations on suspended sediment concentration, which show a similar gradient.

Plancke et al. (2021) discuss the results of a monitoring campaign on the seasonal variation of the bed composition. They conclude that spatial variation, also at a small scale, is much larger than temporal variation. Because of this, no quantitative conclusion can be drawn on the amplitude of the seasonal variation, if any.

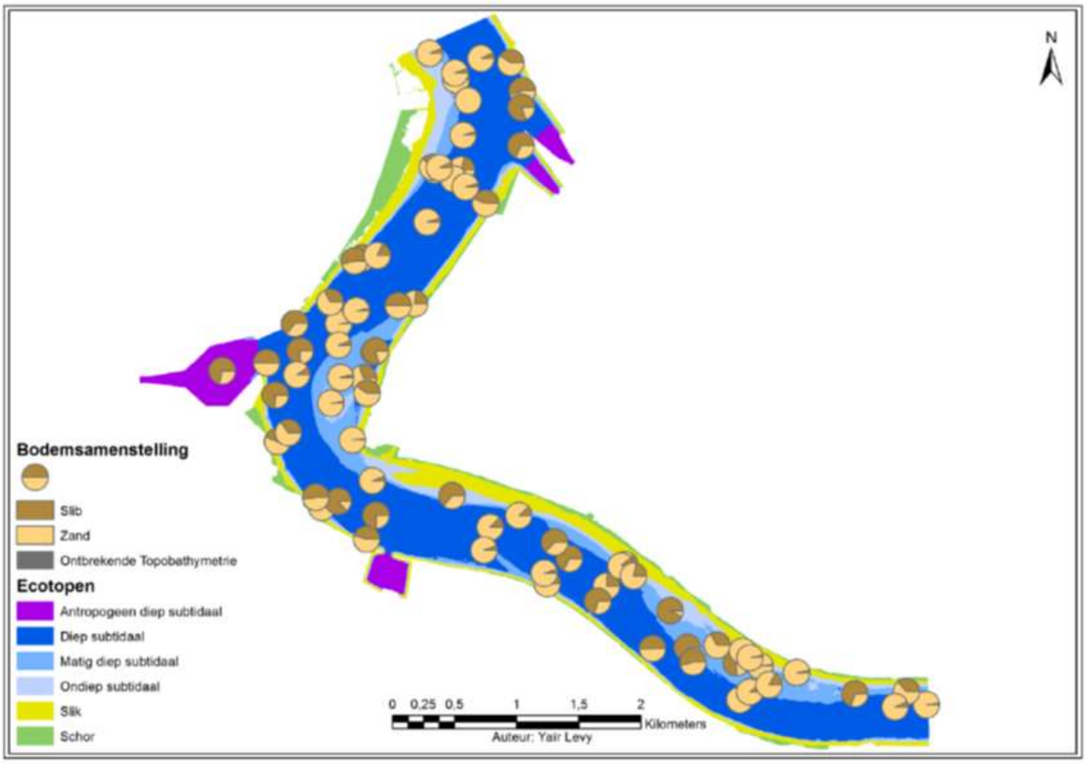
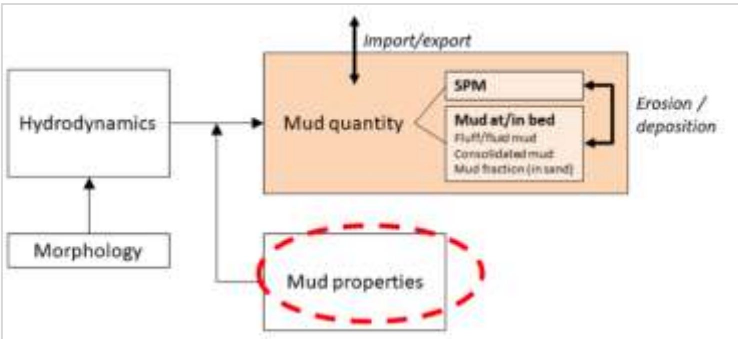


Figure 3.19 Mud content in the bed near Kallo-Antwerp (Vandenbruwaene and Levy, 2017)

3.4 Mud properties



Mud properties have much influence on SPM levels and (residual) transport. The most important properties are settling velocity, critical shear stress for erosion and dry density (and its increase in time by consolidation. These and more properties are discussed in detail by Van Kessel (2007) and Manning et al. (2011). The following is an overview.

3.4.1 Settling velocity

In the Scheldt the typical settling velocity of macro-flocs is in the range of a few mm/s (Manning et al, 2011; Mulder, 1995). The micro-floc settling velocity is in the range of a few tenths mm/s. This is illustrated in Figure 3.20, in which also isolines of excess floc density are drawn. This figure shows that macroflocs have a lower excess density than microflocs, i.e. they have a more open structure and likely contain more organic matter.

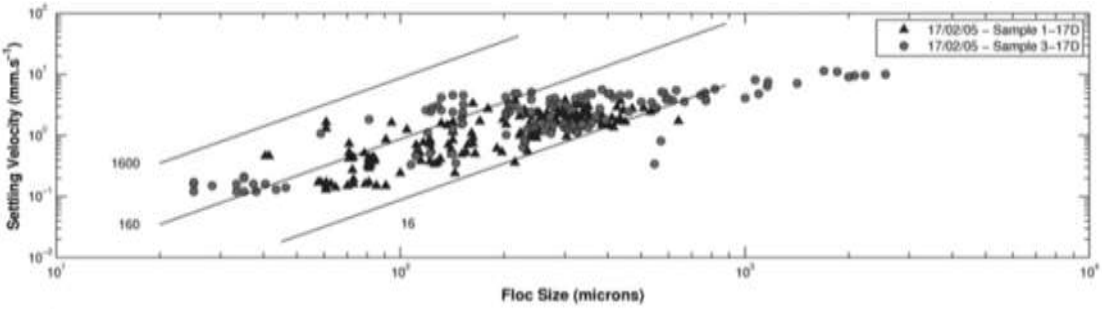


Figure 3.20 Settling characteristics of flocs near Deurganckdok (Antwerp) (Manning et al., 2011).

3.4.2 Critical shear stress for erosion and erosion rate

These parameters depend much on the state of the bed. Fresh fine-grained deposits may form a 'fluff' layer on the bed with a low critical shear stress for erosion (order 0.1 – 0.2 Pa). With time they may compact and gain strength (order 0.5 – 1 Pa). Also, the erosion rate constant M depends on the state of the bed. This rate may be up to 10^{-3} kg/m^2/s for fresh deposits, down to 10^{-4} kg/m^2/s or less for consolidated sediments. In the HCBS field campaign (Vanlede, 2008) M ranged between 1 10^{-5} and 3 10^{-4} kg/m^2/s for subtidal cohesive sediment beds (Van Kessel, 2007). As discussed in 2.3.3, bed erodibility may change both in time) and space, which is confirmed by the HCBS results.

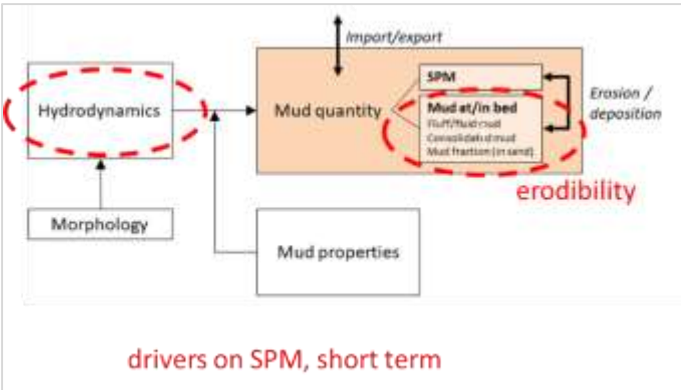
3.4.3 Dry density and consolidation parameters

Dry density may range between ~160 kg/m^3 for gelled mud beds prior to consolidation to ~1600 kg/m^3 for pure sand. In the HCBS field campaign, dry densities ranged between 380 and 760 kg/m3 for subtidal cohesive beds (Van Kessel, 2007). The rate of consolidation depends on permeability, layer thickness, overburden etc. A typical permeability value for gelled mud bed in the Scheldt is k = 10^{-5} – 10^{-4} m/s, resulting in an initial consolidation rate of $r_i = k \times (\Delta\rho/\rho) = 10^{-6} - 10^{-5}$ m/s, i.e. after 1 h a settlement of a few mm to cm (for a sufficiently thick mud deposit, thin deposits < 1 cm may fully consolidate within a tidal cycle). At mud flats and salt marshes, consolidation may be influenced by horizontal drainage, evaporation and vegetation growth.

3.5 The conceptual model for the Scheldt estuary

Based on the general conceptual model (see Chapter 2) and the characteristics of the Scheldt estuary (this chapter) the conceptual model is elaborated / specified to the Scheldt estuary. The different time scales as presented in chapter 2 give the organizing principle.

3.5.1 The conceptual model for the short term



On the short term, the SPM level in the Scheldt estuary is steered by hydrodynamics and the easily erodible mud stock on and in the bed. Since the Scheldt estuary has a relatively large tidal range, tidal currents are important for the mud dynamics. A distinct neap-spring variation of SPM levels is observed steered by tidal forcing (Figure 3.21). Due to its orientation with respect to the dominant southwestern wind direction and its high tidal flats, the effect of waves on the mud dynamics is relatively small compared to tidal forcing, apart from in the mouth of the estuary where storms result in elevated SPM levels. Waves resuspend sediment from the tidal flats, but during normal conditions deposition exceeds resuspension. Only occasionally during storms significant erosion is observed. The recent salt marsh formation on the Hooge Platen demonstrates the limited effect of waves at this tidal flat.

Also, the volume of fresh water discharged from the Scheldt River and smaller tributaries is small compared to the tidal volume. Still, freshwater discharge exerts a major influence on the location and magnitude of the most upstream turbidity maximum. At high discharge, this ETM tends to be flushed and disappear. It reappears at low discharge, although in recent years it is observed less often.

In seaward direction the impact of river discharge becomes mostly indirect through horizontal salinity gradients enhancing (residual) import of marine SPM. These salinity variations influence SPM levels at Terneuzen (Van Kessel et al., 2011) and Zeebrugge (Van Maren et al., 2020 and Vanlede, 2022).

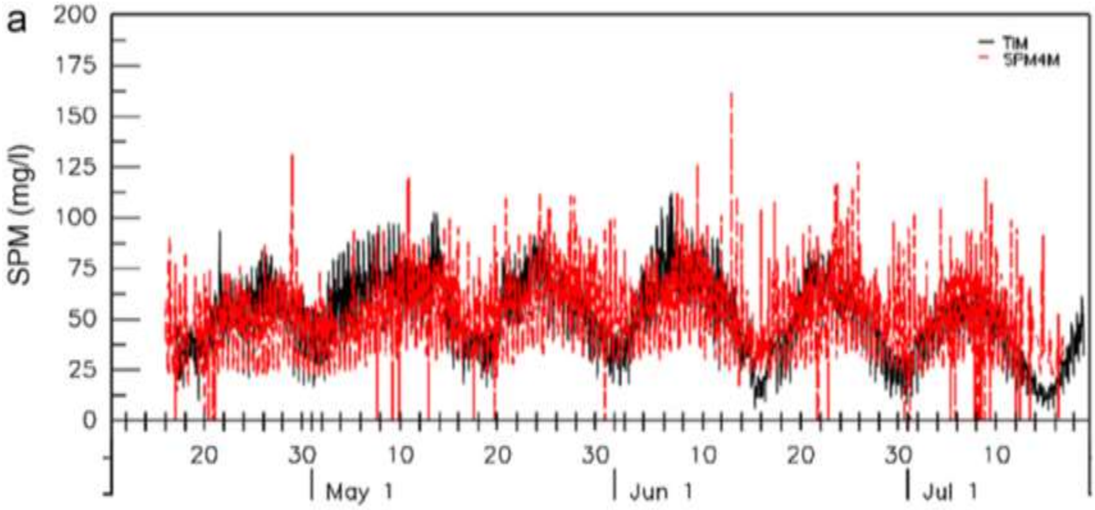
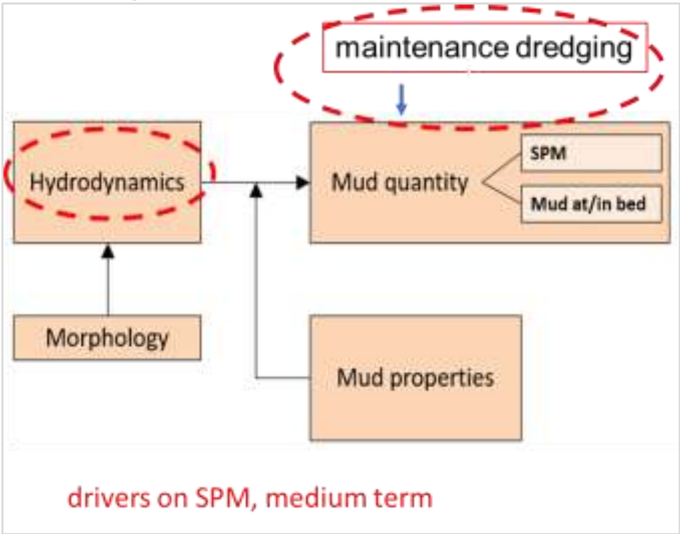


Figure 3.21 Observed (red) and modelled (black) neap-spring variations of SPM near Terneuzen (Van Kessel et al., 2011).

Fluid mud dynamics do not play an important role at the scale of the Scheldt estuary. Most vertical exchange is between the water column and a thin fluff layer on top of a firm sediment bed. However, temporarily and locally, a fluid mud layer with significant thickness may develop in areas with abundant mud supply and limited tidal currents to enhance settling, notably in harbors and access channels.

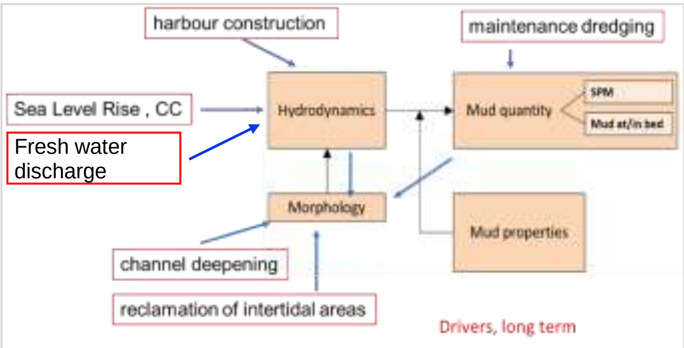
3.5.2 The conceptual model for the medium term



Seasonal variations in SPM and the mud distributions in the bed may be influenced by biological activity and seasonal variation in freshwater discharge and weather patterns. The relative importance of each of the processes for the Scheldt estuary has not yet been fully quantified, although variations in physical forcing factors appear dominant over biological controls in the Western Scheldt (Van Kessel et al., 2011). In the upper Sea Scheldt biological controls may be more important, however. The seasonal variations in SPM are within a factor 2. Seasonal variations in the mud content in the bed are not measured at system scale. With respect to the multi-annual variations in SPM, the lower SPM levels around 2008 are remarkable (Figure 3.7). On the medium term, also dredging and disposal activities influence the mud dynamics. Disposal results in a local and temporal increase of the SPM levels (see §4.2 for further discussion).

The cumulative effect of both short- and medium-term residual transport may significantly change the local availability of fine sediment. The time scale required to reach (dynamic) equilibrium for sediment availability is typically much longer than the time scale at which the driving forces vary. Hence such equilibrium may never be reached, the system is rather in a permanent transient state chasing its tail.

3.5.3 The conceptual model for the long term



The long-term residual fluxes and fine sediment budget for the Scheldt estuary are important for several reasons. First, they influence morphodynamics, (both sand and mud). In the Western Scheldt, the contribution of sand to the morphodynamic evolution is dominant in most places (Röbke et al., 2020). This is beyond the scope of this report. Second, a long timescale is required to determine a representative average of the fine sediment budget. Interannual variations can be important, extrapolation of fluxes of a single year towards the long term may result in wrong conclusions on the long-term fine sediment balance. For example, model scenarios with the fine sediment transport model of the Scheldt estuary show that residual year-average fluxes show a large difference from year to year (Cronin et al., 2018). This is discussed in more detail below.

On the long-term, changes in morphology including the effects of channel deepening and land reclamations or setbacks also change SPM dynamics via changes in hydrodynamic forcing and changes in sink and source terms. The longer the time scale, the larger the effect of residual transport on sediment availability. Both for the long term and medium term, the question is whether changes are temporary (i.e. variations) or persistent (i.e. trends).

3.5.4 Fine sediment budget as part of the conceptual model

Figure 3.22 shows the fine sediment budget of the Western Scheldt. Along the coast of the Belgian and Dutch North Sea, a shore parallel residual fine sediment transport in the order of 30 million ton/yr. is present (Fettweis et al. 2007). The gross exchange of mud between the North Sea and the Western Scheldt is of similar magnitude: 25-30 million ton/yr., based on a tidal prism of 10^9 m^3 and SSC = 40 mg/l. The net transport is much smaller, around 0.9 million ton/yr. from the North Sea towards the Western Scheldt. This net import is highly dependent on the wind and wave conditions, storm set-up or set-down and salinity gradients at the mouth. During some years a net export may occur, during other years an above-average import. In this mud balance, it is assumed that about 0.5 million ton/yr. (net) is transported from the Western Scheldt into the Sea Scheldt (Cleveringa and Dam, 2013). This means that only 0.4 million ton/yr. accumulates in the Western Scheldt (or 0.3 million ton/yr. according to Van Maldegem, 1993). However, the residual mud flux across the border is uncertain. Vandenbruwaene et al. (2017) report 0.2 million ton/yr. export from the Sea Scheldt towards the Western Scheldt.

The net accumulation of 0.4 million ton/yr. in the Western Scheldt (mostly on mudflats or in side channels, as in the main channel mud hardly deposits and mud deposited in harbors is dredged and released back into the estuary) is 4% of the ‘dynamic mud stock’ in the Scheldt estuary. This amount of mud in the bed of the Scheldt estuary that is available for frequent resuspension is estimated at > 10 million ton (Van Maldegem, 1997). This means that on the short term the fine sediment dynamics are governed by local resuspension by natural processes and dredging and disposal. On the longer term (longer than ~5 years) the net marine import and export to the Sea Scheldt, in combination with net sinks and sources are important.

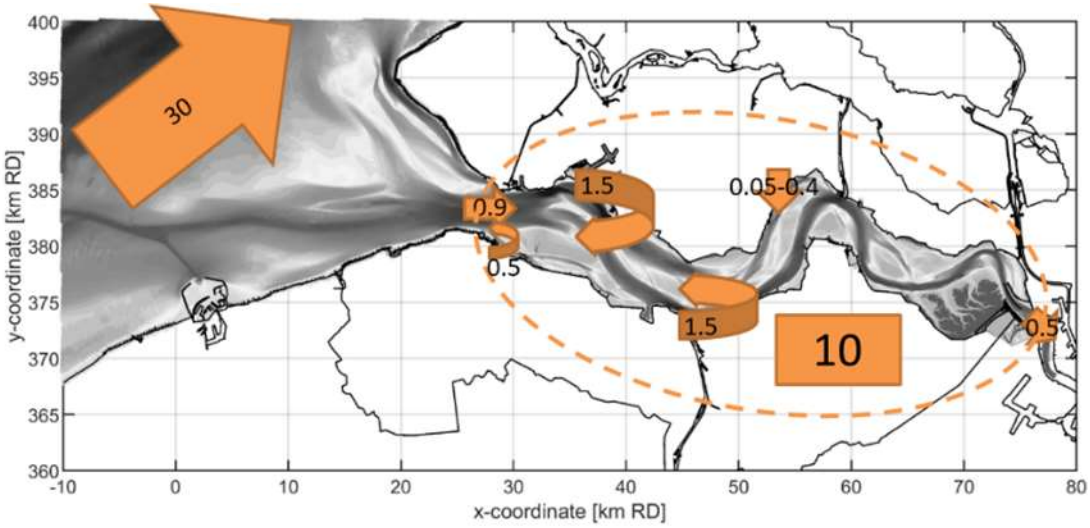


Figure 3.22 Net mud transport along the North Sea coast, net import into the Scheldt estuary, redistribution by dredging and disposal (in Mt/y), the dynamic mud stock (in Mt) and export to the Sea Scheldt. See main text for origin and discussion of numbers.

In Figure 3.23 the mud balance of the Scheldt estuary is shown as derived from computations with a numerical model (Cronin et al., 2018) for the years 2006 and 2014. The ETM around the port of Antwerp is fed by the marine import of fine sediment via the Western Scheldt and the fluvial supply. The results of 2006 are consistent with residual fluxes estimated from observed changes in bed level and bed composition according to Cleveringa and Dam (2013). The results of 2014 are consistent with more recent estimates on residual mud fluxes (Vandenbruwaene et al., 2017).

Figure 3.24 shows the mud balance of the Sea Scheldt based on long-term observations on changes in bed level and bed composition. Fluvial input is about 0.15 million m^3/year and export to the Western Scheldt is estimated at 0.25 million m^3/year = 0.2 million ton/year. This contradicts with the numbers in Figure 3.22 in which a mud import from the Western Scheldt to the Sea Scheldt of 0.5 million ton/year is estimated. A very strong increase in the residual mud flux is observed near Antwerp (up to 5 million m^3/year), which is caused by the strong influence of maintenance dredging on the local mud fluxes. This flux from the release locations for dredged mud back to harbor basins and access channels is balanced by an opposite flux in the hold of dredging vessel from dredging areas to release locations. This is further discussed in Section 4.3.

Analysis of both observations and model results shows that the overall mud balance is rather variable from year to year and that both changes in hydrodynamic forcing, mud properties (i.e. model sediment parameters settings) and sinks and sources (e.g. addition of harbor basins, mudflat area, dredging strategy) play an important role, consistent with the conceptual model description. For 2006 a mud import of nearly 1 Mt/year is computed, whereas for 2014 an export of 0.2 Mt/year is computed. The only difference between both scenarios is the hydrodynamic forcing specific to each year, all other model settings are identical. This illustrates the importance of looking at multi-year timescales when analyzing the mud balance. A single year might be exceptional and not representative for the long-term average.

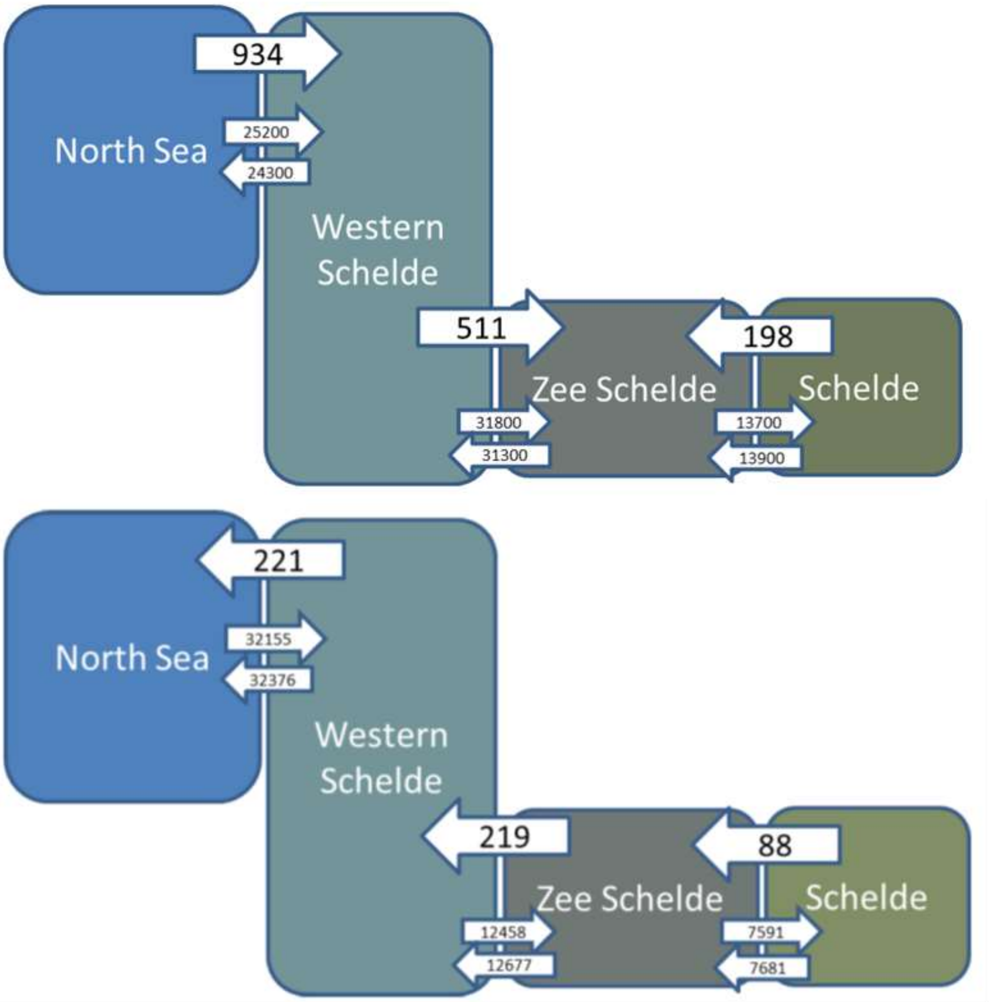


Figure 3.23 Computed mud balance of the Scheldt estuary in kton/year for 2006 (upper panel) and 2014 (lower panel) (Cronin et al.,2018).

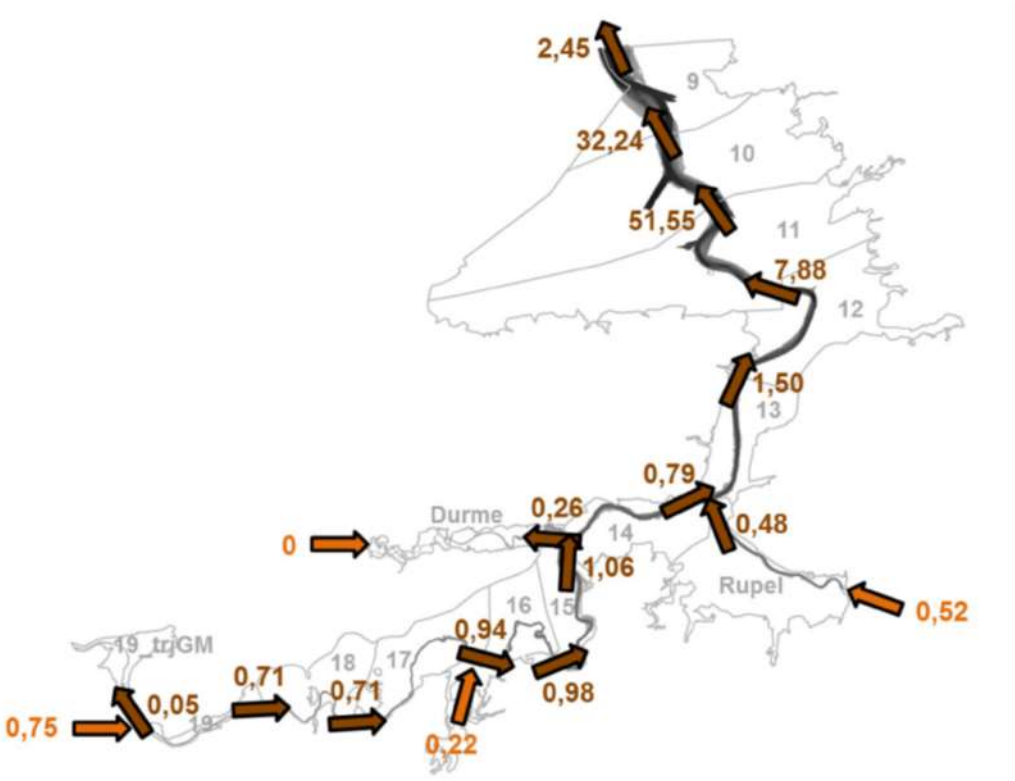


Figure 3.24 Schematic representation of cumulative mud transport in Mm³ over a 10-year period (2001-2011). Orange arrows represent fluvial inputs (source: Vandenbruwaene et al.,2017). Assuming an average bulk density of mud deposits of 1.45 ton/m³, the conversion factor between m³ and ton dry solids is 0.73 i.e. 1 million m³ = 0.73 Mt.

3.5.5 Effect of morphological changes within the long-term conceptual model

The effect of channel deepening and removal or creation of intertidal area is discussed in chapter 4.3 and 4.5. Other long-term changes that have occurred in the Scheldt estuary or are still occurring are the increase in height of the tidal flats (De Vet et al., 2017), the reduction of the length of the low water line (‘smoother’ shaped flats) and the lower migration speed and size reduction of connecting channels through the intertidal flats. Also, the Middelgat tidal channel is accreting providing a sediment sink.

The estimated sedimentation of mud in the Middelgat is about 0.05-0.4 million m³/yr. (Cleveringa & Dam, 2013). This is in in line with sedimentation in the secondary channels as estimated by Manni (1986) of 0,14-0,4 million ton/yr. This indicates that the Middelgat is an important sediment sink. Comparison of ecotope maps shows that the mud-rich low dynamic areas in macrocell 4 (including Middelgat) have decreased in surface area.

The net accumulation of mud at the salt marshes is estimated at 0,03-0,29 million ton/yr. by Manni (1986) and hence of similar magnitude as the mud sedimentation in the secondary channels. The sedimentation at the intertidal flats is even lower, viz. 0.04-0.2 million ton/yr. (Manni 1986). The number by Manni might be slightly outdated, because the intertidal flats in the Western Scheldt have increased in height and some have developed a vegetation cover (see ecotope maps in Figure 3.18). This affects the mud sedimentation.

4 Human interventions and lessons for sustainable management

4.1 General

A generic conceptual model for fine sediment dynamics was presented in chapter 2. This was elaborated in chapter 3 with data for the Scheldt estuary. This chapter gives analysis and conclusions on (case studies of) four types of interventions in the Scheldt estuary: dredging and disposal, harbor construction, channel deepening and ‘adding or removing areas’. All have impact on fine sediment dynamics.

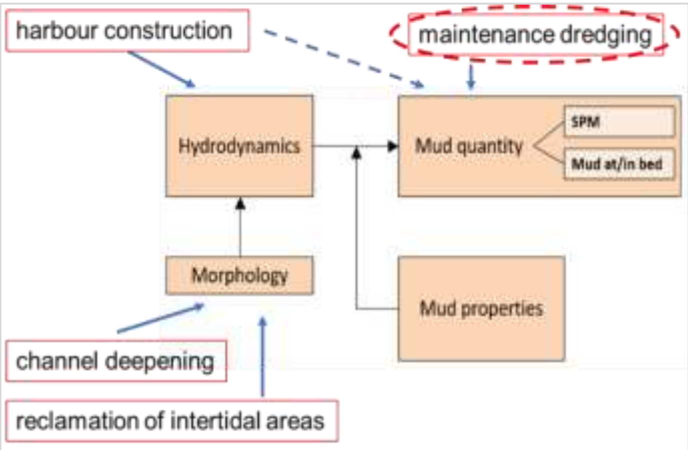
Closures (see Figure 3.3) have, amongst others, resulted in less accommodation space for fine sediment deposition. Also, in combination with fairway deepening they have modified the tidal propagation significantly (Kuijper 2013). This important type of intervention is discussed as part of adding or removing areas (4.5).
Bed/bank protections (Figure 4.1) have reduced the natural morphological evolution of the tidal channels by avoiding migration too close to dikes, but is not discussed as separate case.

Several studies have concluded that the effect of maintenance dredging on SPM levels in the lower Sea Scheldt is significant, whereas the effect of the third (widening and) deepening is not (e.g. Van Kessel et al., 2008; Dijkstra et al., 2019). Dijkstra et al. (2019) established that the risk of the Scheldt estuary becoming hyperturbid as a result of past deepening operations is limited.

Figure 4.1 Substrate with stones in the Western Scheldt (From Ecotopenkaart 2018, RWS)

4.2 Case 1: Dredging and disposal,

4.2.1 Western Scheldt



Maintenance dredging in the Western Scheldt takes place within the main shipping channel and in the ports to retain the required nautical depth. The dredging of the shipping channel is dominated by sand and is briefly summarized here. The dredging at the ports is reported in more detail because that dredged material consists mostly of fine sediment.

The sediment dredged from the shipping channel is released in the estuary at strategic positions, to minimize return flow and to minimize the impact on the existence of the multiple channel system. Extracting sediment (without disposal within the system) does not occur anymore, to prevent further erosion of the channels ('uitruiming') with negative consequences such as an increase in tidal range.

WVL (2007) reported a morphological analysis and dredging and disposal intensity of the navigational channel in Western Scheldt estuary and the Lower Sea Scheldt for the period 2000 – 2005 and concluded that the sill near Hansweert and overflow near Valkenisse required the most maintenance dredging. The average dredging volume was 7.6 million in-situ m^3/year in the Western Scheldt estuary for the studied period. With a mud percentage of only a few % the amount of mud recirculation that is caused by maintenance dredging of the Western Scheldt main shipping channel is small (order 0.2 Mt/yr.) compared to maintenance dredging of muddy sediments from harbors.

IMDC et al. (2013) studied sedimentation and erosion in the disposal areas of the Western Scheldt. The study concluded that disposed sandy sediment is locally redistributed and that typically 20-30% remains within the disposal site. On the other hand, finer fractions are redistributed on a larger spatial scale (tens of kilometers). Locally, the sediment concentration is altered by dredging and disposal. For example, model simulations show that after disposal near Vlissingen the sediment concentration west of the port entrance slightly decreased while logically at the disposal area itself the concentration increases. Overall, sedimentation results in a lowering of SPM and disposal in an increase of SPM. However, these are local effects and the net effect of these activities on SPM levels in the Western Scheldt is considered limited (Van Kessel et al., 2015).

As part of this study, the dredging and disposal volumes within the ports in the Western Scheldt[4] (Rijkswaterstaat, 2019) were analyzed. Most of these ports are managed by RWS DZL and North Sea Port, however some ports are managed by other parties. Note that available data is incomplete; only yearly data is available and no data on the sediment composition (sand/mud fraction) exists. The volumes were reported in in-situ cubic meter, however from 2014 onwards the values for the RWS DZL managed ports are 'beun' volumes.

[4] Vlissingen (Koopmanshaven, Buitenhaven, Oost-havens), Terneuzen (Braakmanhaven, Autrichehaven, kanaalhavens, Veerhaven, Oost -en Westbuitenhaven), Breskens (Veerhaven, Handelshaven, Jachthaven), Perkpolder Veerhaven, Hansweert Buitenhaven, Kanaal Gent-Terneuzen t.h.v. draaibruggen.

‘Beun’ volumes were converted to in-situ volumes using a factor 0.5 by the dredger (Rijkswaterstaat 2019). This factor reveals a relatively large difference between ‘beun’ and in-situ volumes, that possibly indicates that the material is rich in mud. For sandy material, a correction of 10% for ‘beun’ and in-situ volumes is common practice. The yearly average dredging volume for these ports combined is 3.23 million m^3/y (in-situ) for the period 1985-2018 (Table 4.1). Using a dry density of 700 kg/m^3 for mud deposited in ports and 30% of sand in the dredged volumes, this volume is equivalent with a mass of 1.6 million tons/yr.

Table 4.1 Dredging volumes in million m^3/year in-situ.

	Vlissingen	Terneuzen	Breskens	Hansweert	DGD	Antwerp	All
Mean	1.33	1.26	0.54	0.10	1.0	2.0	6.2
Standard deviation	0.66	0.56	0.15	0.13			

The overall average dredging volume in the Western Scheldt ports increased from 1985 to the early 2000’s (Figure 4.2). This is mainly steered by increased dredging activities in Terneuzen and Vlissingen ports. The dredging volumes have remained stable at a value of 3-4 million m^3/y in-situ during the last two decades, although there are significant interannual variations. This is consistent with the SPM observations in the Western Scheldt, which do show interannual variations but don’t show long-term trends either.

For each location designated disposal areas are prescribed (Rijkswaterstaat, 2019). The dredged sediment is unequally distributed over these areas (Figure 4.3). Most material is disposed at two sites (W13 and W15H), and those sites are used by the ports near Vlissingen and Terneuzen respectively.

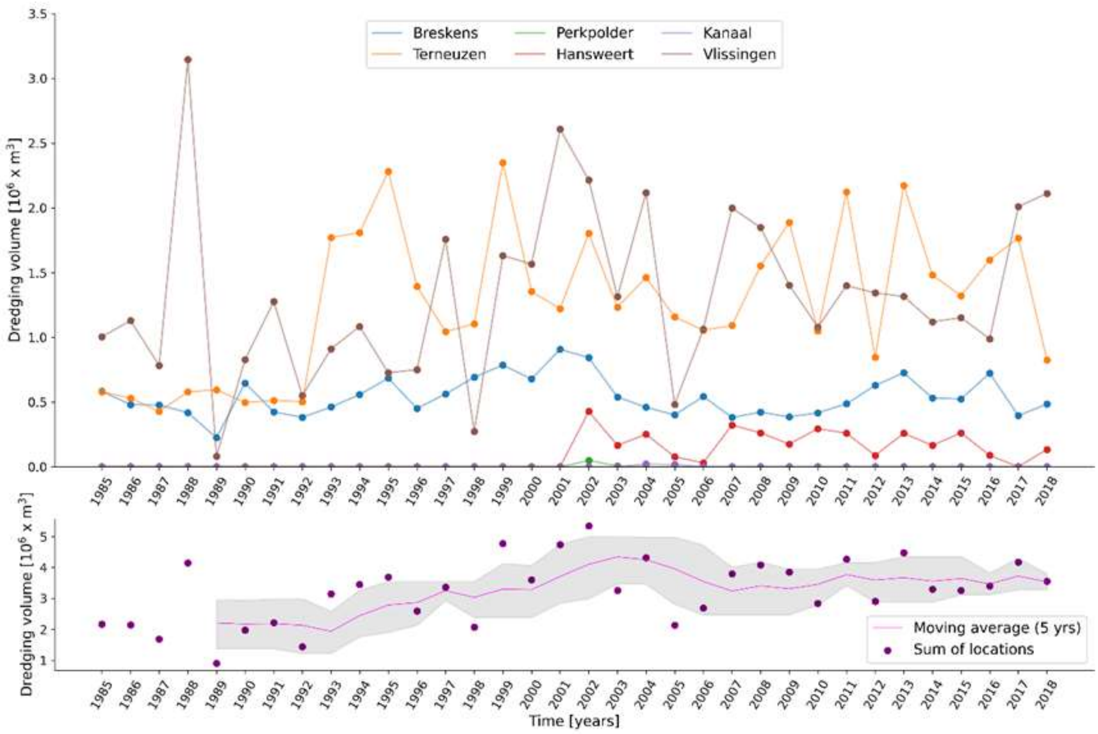


Figure 4.2 Yearly dredging volume time series for six locations in the Western Scheldt area (top). Sum of the dredging volumes of the six locations (bottom). Band indicates the 15- and 85-precentiles.

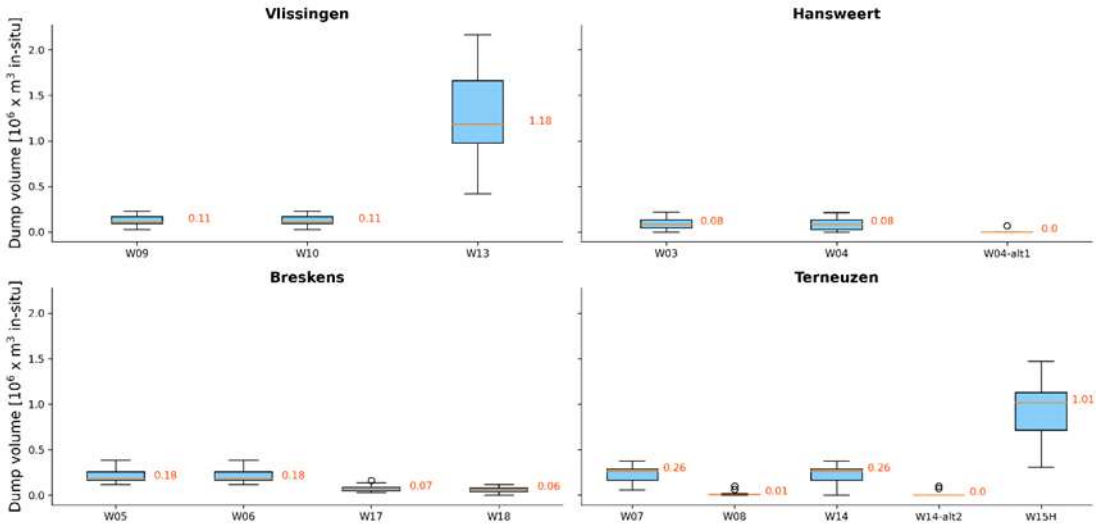


Figure 4.3 Boxplots indicating the yearly disposal volume for different disposal sites belonging to Vlissingen, Hansweert, Breskens and Terneuzen.

4.2.2 Sea Scheldt

In the Sea Scheldt near Antwerp the situation is different. Here a significant increase in dredging volumes over the last two decades has been observed. An important factor herein has been de opening of Deurganckdok in 2005, a large tidal dock requiring intensive maintenance dredging. Also, SPM values in the Sea Scheldt are more sensitive to variations in freshwater discharge than in the Western Scheldt, explaining stronger interannual variability. Figure 4.4 shows the evolution of the dredging volume around Antwerp. The construction of Deurganckdok has resulted in a marked increase of the dredging volume, but after the complete opening and maintenance of DGD at design bed levels in 2011 numbers have stabilized.

For the Sea Scheldt effects of dredging and disposal on SPM are more pronounced than in the Western Scheldt, as the estuary is much more confined, while the maintenance dredging volume is similar. This is further elaborated in Section 4.4.

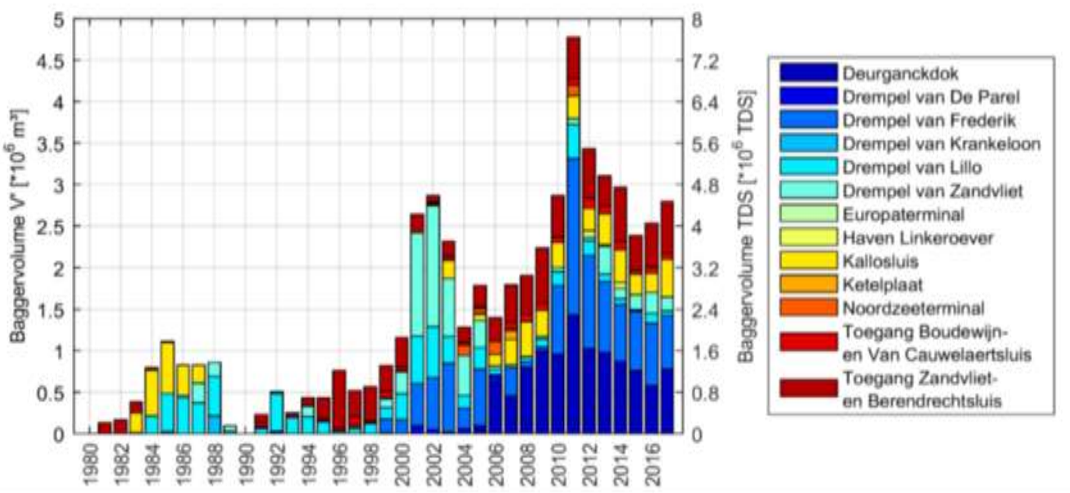


Figure 4.4 Development of dredging volumes at the Port of Antwerp (Lankriet and Cronin, 2018).

4.3 Case 2: Channel deepening

Channel deepening changes the morphology and can influence large scale hydrodynamics and strengthen transport convergence, with increase of local SPM levels. Based on the conceptual model, we consider the hydrodynamics, the sediment properties and the mud quantity.

The effects of channel deepening have been much analyzed and discussed because of possible parallels with other estuaries such as the Ems and Loire in which large deepening has resulted in a strong increase of SPM levels and even very substantial fluid mud formation near the bed. These estuaries have experienced a 'regime shift' (e.g. Winterwerp and Wang, 2013; Winterwerp et al., 2013) and the question is whether such regime shift might also occur in the Scheldt estuary. If such regime shift occurs, all main elements of the conceptual model will change strongly, i.e. hydrodynamic forcing due to the presence of fluid mud, mud quantity and mud properties (the bed then is in a soft, unconsolidated state).

The Ems tidal river is a strong example of how deepening can have drastic consequences. The deepening of this tidal river initiated a 'positive' feedback loop between tidal amplification, increase in SPM, drag reduction and sediment-induced turbulence damping, resulting in hyperturbidity (e.g. Van Maren et al., 2016; Dijkstra et al., 2019). Estuarine managers of the Scheldt estuary want to know how vulnerable the estuary is for such regime shift. Several studies on the vulnerability of the Scheldt estuary to such a regime shift[5] have been carried out.

On the short term the effects of channel deepening may still be limited, but if sufficient mud accumulation builds up and persist in time, this might become the trigger for regime shift. The main short-term effects of deepening depend on whether the effect on tidal amplification is negligible:

1. If it is negligible the deepening results in lower current velocities in the main channel (as the same tidal volume passes through a larger cross-section) and lower SPM levels (a lower velocity implies less vertical mixing, less resuspension and more deposition).
2. If it is not negligible the deepening results in higher current velocities in the main channel and hence higher SPM levels.

The long-term effects of channel deepening include changes in transport convergence. A deeper channel can enhance flood-dominant transport while other convergence mechanisms such as estuarine circulation can also be affected (Dijkstra et al., 2019). This may affect the mud quantity.

Short- and long-term impact of deepening may differ: e.g. an initial SPM decrease by lower channel velocities switches in time to an SPM increase by enhanced residual transport towards the ETM. Effects can also differ between locations: e.g. if the ETM shifts in up-estuary direction SPM will decrease at the original location but increase at the new location of the ETM.

Results by Dijkstra et al. (2019) are based on an idealized model excluding effects of intertidal areas and intra-tidal variations of sediment availability on residual transport. A hypothesis is that resilience is higher when the estuary has enough intertidal area (wider geometry) and as long as the relative depth increase is limited. Earlier, the impact of deepening was also studied with a 3D numerical model with realistic bathymetry including intertidal areas. Figure 4.5 shows the effect of the second fairway deepening in 1997 and

[5] A hypothesis is that resilience is higher when the estuary has enough intertidal area (wider geometry) and as long as the relative depth increase is limited.

1998, when about 2 m of the top of the sills in the main channel of the Western Scheldt were removed by dredging (Van Kessel et al., 2008). It shows simulation results on the difference in near-surface SPM due to deepening. The differences are minor (up to a few mg/l only, also at the long-term, ignoring bed level changes other than fairway deepening). There is a slight SPM increase in the estuary mouth and a slight decrease near the Dutch-Belgian border towards Antwerp. Apparently on the long term the transport convergence mechanisms (tidal asymmetry, estuarine circulation) have not changed significantly. This implies that there is no evidence that the Scheldt estuary is susceptible to a regime shift towards hyperturbidity.

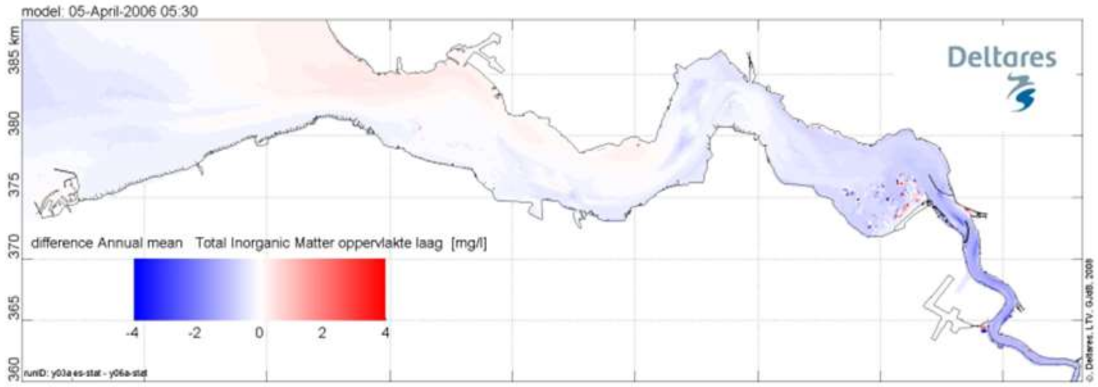


Figure 4.5 Modelled absolute (mg/l) change in average surface SPM concentration caused by the 2nd deepening of the Western Scheldt (Van Kessel et al., 2008).

Dijkstra et al. (2019) analyzed the effect of deepening in detail by using a semi-analytical model. They concluded that - contrary to the tidal Ems river - SPM levels in the Scheldt estuary decreased after deepening. This agrees with the results of the process-based model (Figure 4.5). This remarkable difference in response is caused by the different interplay between hydrodynamic forcing, settling, deposition and resuspension and sediment availability in the bed. In the Scheldt, SPM levels in the ETM near Antwerp are limited by local erosion (a lower bed shear stress then implies lower SPM levels, but this relation also depends on the availability of mud, with higher SPM levels after local dispersion of dredged mud). Also, deepening does not increase the sediment import through the mouth influenced by the phase difference between the M_2 and M_4 tide throughout the estuary. This work applies to the Western Scheldt and the Lower Sea Scheldt, but not to the Upper Sea Scheldt beyond Antwerp. There a freshwater ETM may develop and local deepening (unrelated to the second deepening in the Western Scheldt) may influence salinity intrusion and SPM levels more substantially. This is discussed by Cox et al. (2019).

4.4 Case 3: Harbor construction and (re)location of disposal sites

The construction of harbor basins has a minor effect on large scale hydrodynamics of an estuary, if the extra tidal prism is negligible compared to the existing tidal prism[6]. However, as harbors are very effective sediment traps, the impact on the sediment balance and SPM levels can be very significant.

When a harbor is constructed along an estuary, the SPM levels will initially decrease, as the harbor is a sink for fine sediment. Mud enters the harbor basin and can hardly escape. After this (short) period maintenance dredging is (and will regularly be) necessary. The disposal of the dredged sediment (with a relatively high percentage of fines) is a sediment source. This results in a local and temporary increase of SPM levels. If all dredged material is released

[6] This does not include the effect of channel deepening, see 4.3, that is sometimes linked with harbor construction

back into the estuary, sinks and sources level out on the scale of the estuary, but not at smaller scales of time and space. The question is what the net effect will be.

The conceptual model (with a fair assumption that hydrodynamics will change only locally, and sediment properties will not change[7]) tells us that mainly changes in mud quantity (and the mud balance) should be considered.

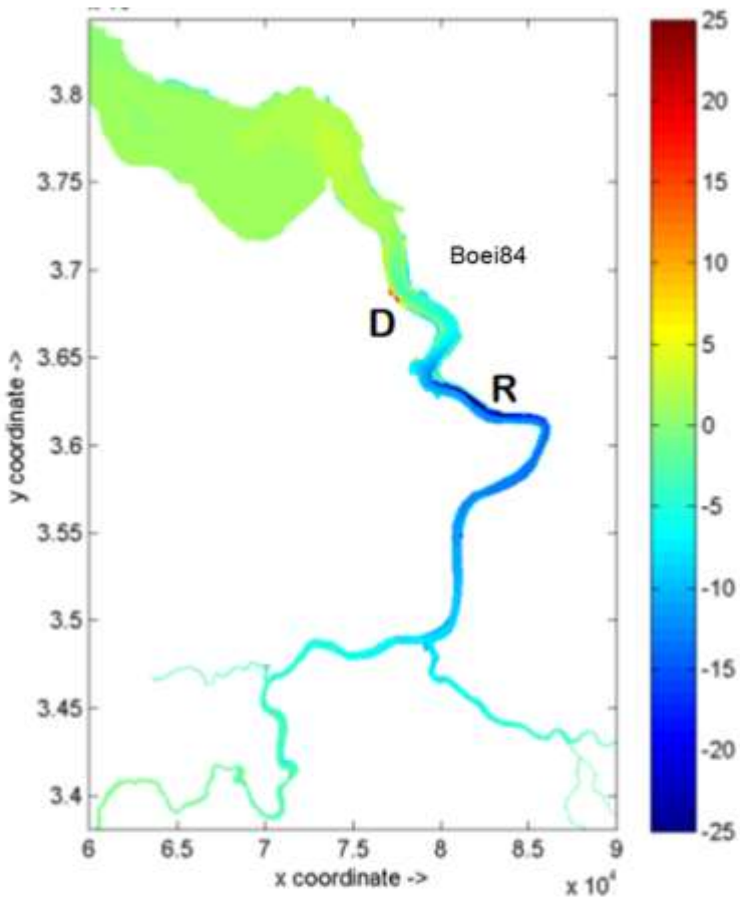


Figure 4.6 Impact of Deurganckdok on time- and depth-averaged SPM (%). "D" represents DGD dock location and "R" release location. Negative values reflect lower SPM for the reference case (no dock).

These effects can be studied with an appropriate model for SPM. Such research has been done for the Scheldt estuary (Van Kessel et al., 2011; Van Kessel et al., 2015). Figure 4.6 shows the computed relative difference in time-averaged, depth-averaged SPM-concentrations for simulations with and without a tidal dock at location D and with and without disposal at location R. As expected, SPM is lower without dock, with reductions between 5 and 15% in a substantial part in the Lower Sea Scheldt. The largest difference is near location R. In this part of the estuary, the increase in SPM by disposal dominates over the concentration-decreasing effect of sediment trapping by the dock. Down-estuary of the dock, however, the opposite happens. In a scenario without dock SPM is up to 5% higher according to the model. However, such down-estuary SPM decrease after dock construction is not visible in observations at station Schaar van Ouden Doel, maybe because of the large variability in this data due to variations in dredging, river discharge, storms etc. Although the dock maintenance results in an increase in the SPM levels in the local ETM, it is not the cause for this ETM as it already occurred before construction of DGD.

[7] Possibly apart from the distribution between the states of suspended mud, fluid mud, soft mud, consolidated mud

These results suggest that it might be beneficial to relocate disposal to more down-estuary locations. This would be a location that is close to or even across the Belgium-Dutch border. This however has substantial, legislative/political, complications.

Comparison of the computed net mud balance and harbor siltation rates (section 3.5.3) learns that anthropogenic-induced sediment fluxes are locally much larger than the "natural" net sediment fluxes and form a substantial part of the gross fluxes. Note that these "natural fluxes" are affected by previous human interventions in the river as well. This is confirmed by a study with a simulation in which the various mud sources (natural or originating from maintenance dredging) were 'labelled' (Figure 4.7). Only 30% of the suspended mud is 'fresh', i.e. not related to the dumping and dredging cycle in the estuary. This 'fresh' mud has both fluvial and marine origin. The lower Sea Scheldt is in a mixing zone of sediment of fluvial and marine origin, with typical fractions of 0.6 and 0.4 near the Deurganckdok (depending on tidal phase and freshwater discharge, see Verlaan, 1998). Figure 4.7 shows that about 40% of the mud (i.e. nearly 60% of the 'anthropogenic' mud) originates from sediment mobilized from the disposal location belonging to the Deurganckdok. This underlines the potential of optimizing the local dredging and disposal strategy on SPM levels. Note that this does not imply that construction of the Deurganckdok increases SPM levels with 40% as the dock also is a sediment sink (Figure 4.6).

Note that the high degree of sediment recirculation (Figure 4.7), in combination with the facts that the material is deposited upstream (Figure 4.6) and that the residual mud transport around DGD is directed downstream (Figure 3.24), imply that the siltation and subsequent maintenance of Deurganckdok increases the residence time of mud in the system, and increases the amount of mud that the estuary can 'trap'.

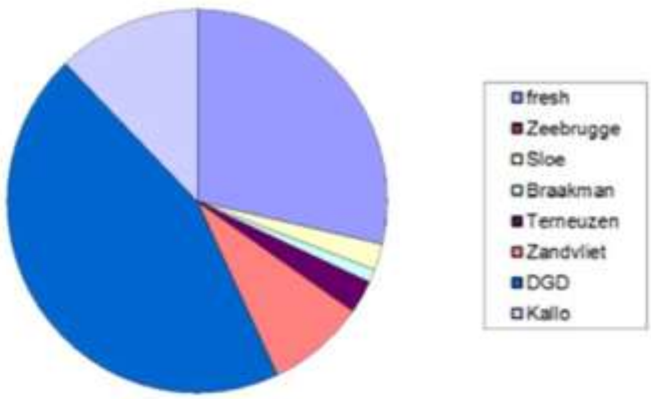


Figure 4.7 Computed average mud composition of suspended mud at Boei84, close to Antwerp harbor. 'Fresh' reflects natural mud not originating from dumping of dredged sediment from one of the harbors.

The beforementioned simulation required a period of multiple years to reach a dynamic steady state for the labelled sediment fractions. This indicates that the memory of the system is long and that in addition to a near-instantaneous response to changes in maintenance strategy, a long time is required to attain a new dynamic equilibrium for SPM gradients, residual transport and bed composition. Such model study was carried out on the effect of maintenance dredging of Deurganckdok on SPM levels in comparison with the effect of annual variations in freshwater discharge (Lankriet and Cronin, 2018). Conclusion was that the high SPM levels observed in 2011 are likely caused by an increase in dredging activities during that period, not by the low discharge during the same period.

The conceptual model and the case study underline that dredged and subsequently disposed sediment will partly:

1. recirculate towards the harbor basins and access channels - these are maintained, within a dredging-disposal cycle.
2. deposit on mudflats, shallows or abandoned side or secondary channels, which are net sinks.
3. export towards sea if SPM increases over a larger part of the estuary. As disposal is up-estuary, this does not occur. Instead, a (slight) increase in transport from sea is computed as the sediment demand at DGD exceeds the sediment supply from the release location.

Analyses like the above have resulted in the definition of a disturbance ratio *R* (see chapter 2) that gives a quantification of the dominance of anthropogenic effects. For the Scheldt estuary near Antwerp it was estimated at around 0.8 to 0.9[8] (Winterwerp et al., 2021, Chapter 15). When, as in this case, anthropogenic effects are dominant, the risk is that the SPM levels will be substantially influenced by further interventions. However, a high R ratio is not the only determining factor, as a system with strong flushing may experience only a small SPM increase for high R.

In the Western Scheldt the amount of dredging from harbors such as Sloe and Braakman is similar to those near Antwerp. The estuary is, however, much wider at these locations. This means more tidal dispersion and more accommodation space (in secondary channels and on mudflats and salt marshes). Recirculation and effects on SPM are hence much smaller as was demonstrated with a model study (Van Kessel et al., 2012).

4.5 Case 4: Changing the intertidal surface area

Changes in the surface area of an estuary will have an effect on fine sediment dynamics. Such changes can be less area (e.g. after embankments) or adding new intertidal area. Examples of the latter in the Scheldt estuary are the controlled flooding areas (used only during extreme high-water levels, GOG in Dutch) and the reduced tide areas along the Sea Scheldt (controlled by a weir, GGG in Dutch). New intertidal area can also be created for ecological purposes primarily (e.g. the Hedwige-Prosperpolder).

How do these changes in intertidal surface area affect the SPM dynamics? Again, following the conceptual model, there is impact via changes in hydrodynamic forcing (and hence a potential change in sediment convergence) and direct impact on the mud availability or quantity (areas act or did act as a net sediment sink). The sediment properties are assumed not to change by these types of interventions.

Changes in tidal prism and channels

Studies on the impact of ‘impoldering’ and ‘depoldering’ on hydrodynamics of the Scheldt estuary are Jeuken et al. (2007), Maximova et al. (2010), Kuijper (2013) and Nnafie et al. (2017). Impoldering initially causes an increase in tidal range near the polder area, caused by the reduction of water storage that was possible in the area that became polder. The reduction of the tidal prism decreases tidal velocities between the mouth and the new polder area.

However, up-estuary of the polder area the tidal prism increases because of the increase in tidal range (but smaller than the decrease as result of reduced water storage). Both changes affect tidal prism and trigger a morphological response. This is enhanced accretion between the mouth and the new polder and enhanced erosion upstream of it. Tidal propagation adapts to this response and the tidal prism changes (partly) to the former value. The overall effect of impoldering on the scale of the estuary is accretion. The overall effect of depoldering is

[8] R = D/(D+N) and dredging volume D = 3.3 million tons and natural sedimentation N = 0.3 − 1 million tons per year.

opposite to this. These effects scale with the change in tidal prism induced by im- or depoldering. Polders close to the mouth trigger smaller responses than polders up-estuary, as the relative change in tidal prisms for polders close to the mouth is smaller. Such response applies predominantly to the sandy main channels.

Changes in fine sediment dynamics
The response in fine sediment dynamics is related to the tidal flats and salt marshes. We discuss the case study of depoldering of the Hedwige-Prosperpolder (together 465 ha). The increase of tidal prism and velocities between the mouth and the location of depoldering may enhance SPM. This is a minor effect in the Western Scheldt, as the contribution to the tidal prism is minor. Up-estuary the velocities decrease, because of a reduction in tidal prism, caused by the decrease in tidal range as result of additional storage area. This may somewhat reduce SPM. This reduction is also caused by the impact on mud quantity as the new intertidal area is a sink for mud. The short-term effect on SPM that is triggered by changes in hydrodynamic may change in time. There will be a morphodynamic response and changes in fine sediment convergence (see previous section). As the new intertidal area gradually silts up, its effect on hydrodynamics will gradually diminish.

The new intertidal area is a significant sink for fine sediments. The yearly siltation is small (estimated at ~0.1 million ton/yr. initially, gradually decreasing as the tidal prism of HPP decreases by mud sedimentation) compared to that in the harbor of Antwerp (~2.5 million ton/yr.), but it is, in contrast to what silts up in the harbor, not disposed back in the estuary. The amount of 0.1 million ton/yr. is in the order of 10% of the net import of mud of the estuary through the line Vlissingen-Breskens (Elias et al, in prep).

The overall impact of depoldering of the Hedwige-Prosperpolder on the SPM levels in the Scheldt is not investigated yet with a model study. Estimations based on expert judgement are that the minor local increase in tidal prism (2%) leads to a reduction in SPM level in the order of 1% (~1 mg/L) or less (Taal, 2018). The depoldered area traps only a small fraction of the tidal fluxes (around 30 million ton/yr. at this location, see also Figure 3.23). The depoldered area has however a significant impact on the *residual* mud budget, when we compare the estimated deposition of 0.1 million ton/yr. with the present net flux towards the Sea Scheldt of about 0,5 million ton/yr.

In view of the discussion on the disturbance parameter *R* (see chapter 2 and section 4.3) the depoldering enhances resilience, as long as the polder is not completely filled with mud. However, the increase in natural sedimentation N is modest compared to maintenance dredging volume D, so present realignment schemes have a small impact on SPM levels. This can, of course, change if realignment schemes are implemented at a much larger scale.

4.6 Future scenarios

Sea level rise, changes in freshwater discharge or fluvial or marine fine sediment supply will have an impact on the fine sediment dynamics of the Scheldt estuary. These are not yet discussed herein as they still require further study, which is recommended to better support the management of the estuary.

5 Knowledge gaps

5.1 Priorities for improving system understanding

The conceptual model / framework supports the identification of uncertainties that are most pressing for decision making. This gives (assuming that there is an opportunity to reduce the uncertainties) priorities for (additional) monitoring and research.

Decision making is more and more faced with questions and uncertainties of the long-term impact of climate change, sea level rise and human interventions. The conceptual model has revealed that the relationship between currents, SPM levels and residual transport can be very different for a longer period compared to the short-term effects (that are more frequently investigated). The mud pool plays an increasing important role on longer timescales[9]. Hence, for long term effects more attention is needed to the size of and variations in the mud pool, both quantitatively (in availability) and qualitatively (in properties). The residence time of mud in the estuary is linked to this and is an important indicator for the response timescale of the system to changes, either natural or anthropogenic. The variations on tidal, seasonal and interannual scale may influence residual transport significantly. For example, Horemans et al. (2021) demonstrated this regarding variations in settling velocity due to flocculation, but a similar importance is expected for variations in erodibility.

This leads to two key messages:

1. The system understanding on long time scales, when a combination of changes in hydrodynamic forcing, mud availability and mud properties play a role, should be improved. Morphological changes and feedbacks by it further increase the system complexity on the long term. Although the presented conceptual framework includes these aspects qualitatively, quantification of these aspects is still limited and uncertain.
2. Observations on SPM dynamics at tidal, seasonal and long-term scale contribute greatly to system understanding, but should be accompanied by more long-term observations on mud accretion, mud properties and vertical profiles of bed composition.

5.2 Data and monitoring

A large amount of data is available on fine sediment dynamics in the Scheldt estuary, especially on SPM. Weekly or monthly data are sufficient to quantify seasonal variations and long-term trends, but not for the understanding tidal short-term dynamics. For this high-frequency data are needed. These are scarce, especially in the Western Scheldt. In the Sea Scheldt permanent frames and buoys have been installed to measure SPM dynamics with a temporal resolution of 10 minutes. Without these data calibration of numerical models is less accurate, as well as the evaluation of the extent in which the SPM response to short-term variations in hydrodynamic forcing is site- and time-specific. SPM data are also useful for statistical models on SPM concentration, which have been developed for system understanding and scenario analysis.

[9] Traditionally, the strongest academic focus is on the interplay between hydrodynamics and suspended sediment dynamics. The role of the bed with a variable sediment pool of soft or consolidated mud and sand-mud mixtures is, although recognized, often included with limited detail compared to the description of hydrodynamic processes.

Data on bed composition and dynamics are scarcer. These data are important to make estimates on the mud budget of the Scheldt estuary more accurate and better identify the dominant steering factors, especially on the medium-term time scales. Estimates on the ‘mud pool’, i.e. the amount of mud potentially available for resuspension and transport, require an update. For this update recent data of bed composition and dynamics (i.e. changes in bed level, composition and properties) are needed.

New in-situ tracer studies can refine the present estimates on mud pool and typical residence times in the water column and bed, as well as burial rate and vertical mixing in the bed. However, tracer studies often have the limitation that insufficient tracer material is retrieved to draw firm conclusions on transport pathways, residence time and fate of fine sediments.

In addition to monitoring SPM concentration, bed composition and bed level changes based on regular monitoring campaigns in combination with data from permanent stations, also the properties of the mud (such as floc size, settling velocity, critical shear stress for erosion) should be monitored to identify possible trends at an early stage. To disentangle the contribution of hydrodynamic forcing, mud availability and mud properties, all should be sufficiently monitored.

It is also recommended to intensify the monitoring of human interventions on mud dynamics to validate the predictions based on numerical or analytical models and expert judgement. In the Sea Scheldt there is a rich dataset on high-frequency observations from fixed frames and buoys, but in the Western Scheldt these data are scarce. In addition to SPM monitoring, tracer studies could shed more light on the dispersion of dredged mud within the estuary, its residence time and fate. This will also allow to validate, improve and extend the conceptual framework proposed herein. In a heavily engineered estuary, the natural dynamics and background SPM can’t be understood well without considering anthropogenic influences. A consistent and complete overview of dredging and disposal data from the ports and the navigation channel, including the sediment composition of the dredged material, should be available.

5.3 Improving possibilities of numerical modelling for system understanding

5.3.1 Modelling processes on short term

The processes operating at the shortest time scale (settling, deposition and resuspension in the vertical in combination with horizontal transport) are generally reasonably well known and incorporated into existing mud dynamics models, although further refinement of the process description of settling (e.g. influence of flocculation), deposition and resuspension (e.g. multi-layer bed models with a more detailed representation of mud availability for erosion as a function of bed shear stress) is still desirable, including both physical and biological aspects. With currently available measurements in the Western Scheldt (mainly MWTL) we lack insight in and calibration data of SPM variations over the short time scales. In the Sea Scheldt more SPM data with high temporal resolution is available from fixed mooring stations. It is expected that further model improvements can also be attained by improving resolution and local hydrodynamic and wave forcing, as sensitivity studies show that computed spatial SPM gradients and temporal SPM variations depend on these factors and a better representation hereof increases model skill.

Present SPM models are quite good in reproducing short-term SPM dynamics under influence of hydrodynamic forcing if sediment availability and properties are locally constrained. However, since the unconstrained model skill tends to decrease with longer calculation time, this suggests that the present process formulations in combination with model resolution still lack sufficient understanding.

5.3.2 Modelling processes on medium term

Existing 3D SPM models would benefit if the following important uncertainties can be reduced:

- Seasonal changes or long-term trends in sediment properties induced by physical, chemical or biological factors (properties). Neglecting these effects often results in the underestimation by models of the observed SPM seasonal variations.
- Uncertainty about the active mud mass and its residence time in the system (quantity)
- Underestimation of the deposition of mud on intertidal areas. Lack of resolution of local forcing by currents and waves may play a role in this, but also the erosion formulations which don't consider the influence of bottom drainage and surface evaporation on intertidal areas.
- Uncertainty on the influence of sediment concentration on the turbulent characteristics of the flow.
- Limitations in the accuracy of hydrodynamic forcing. This can have a cumulative effect on residual transport and the evolution of mud quantity. Such uncertainties are likely to result in a deteriorating model performance in time. This requires regular recalibration or, preferably, a better process description. Such inclusion of changes in mud quantity and mud properties gives a significant increase in system complexity.

Existing modelling studies do not, or limitedly, include interactions that are relevant on these time scales, such as effect of ecology via microphytobenthos, flocculation and filter feeders and sand-mud interaction.

It is remarked that the large step between the qualitative conceptual model and detailed 3D numerical model presented in this report may be bridged by other types of models, e.g. statistical or other data-driven models on siltation or suspended sediment concentration or more idealized analytical or numerical models (e.g. Decrop, 2010; Dijkstra et al., 2019; Horemans et al., 2021; Plancke et al., 2020 & 2022). Together they contribute to enhanced system understanding and quantitative impact assessments.

5.3.3 Long term

The study of long-term developments of mud distribution in sediments requires a different modelling approach. The feedback of bed level changes to hydrodynamic forcing becomes very important at long time scales and morphodynamically coupled models are required. Note that sand transport dominates the morphodynamic evolution of the Scheldt estuary. Hence a mixed sand-mud morphological model is needed. A discussion of such model is beyond the scope of this report. Examples hereon are given by Röbke et al (2020) for the Western Scheldt and van Maren et al. (2016) for the Ems-Dollard.
Morphostatic SPM models, applying the historic bathymetry and hydrodynamic forcing, can help in the hindcast of historic states, e.g. prior to land reclamation, channel deepening, harbor construction etc. These models may be both numerical and idealized model. For both types of models an important question is how representative the computed effects of scenarios are for the real estuary. If essential processes are not included or in insufficient detail, the validity of long-term predictions is uncertain. Modelling the interactions between SPM dynamics and long-term morphological evolution is preferred, but there is still limited experience with this. Hence this is a knowledge gap for both long-term SPM and morphodynamic modelling.

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