Enabling Delta Life

Update of the LTV mud model

Deltares

Update of the LTV mud model

11202233-000

Deltares

Title
Update of the LTV mud model

Project	Attribute	Pages
11202233-000	11202233-000-ZKS-0026	45

Keywords
LTV mud model, Western Scheldt, dredging, dumping, 2014 hydrodynamics

Abstract
Since the 2005 treaty the Netherlands and Flanders execute joint policy and management on the Scheldt estuary. The basis for this joint policy and management is joint monitoring and research. Within this framework it was found of upmost importance to have a fine sediment model of the estuary. Fine sediment dynamics are controlling both the amount of material that needs to be dredged and light penetration in the water column. The latter has been shown to be the most controlling factor of the primary production.

The LTV mud model has been developed in 2006. Following advances in knowledge on fine sediment dynamics in the region and improved modelling capabilities updates were made. This report presents the baseline model (2010 version) both with the hydrodynamics forcing of 2006 and 2014. An important improvement is the inclusion of two mud fractions (microflocs and macroflocs). Also spatially varying parameter settings are no longer used and extra validation is done. The reproduction of suspended sediment concentrations both up-estuary and near the estuary mouth (Zeebrugge) has improved substantially. The intra-tidal variability is also improved in the model, but is still less than observed. Siltation rates in the harbours and docks are in the right order of magnitude. Sedimentation rates on the intertidal flats are less than observed in the Western Scheldt and higher than observed in the Sea Scheldt.

It can be concluded that the LTV mud model is again state-of-the-art and can be applied to explain observations in the mud dynamics of the estuary. It can also be applied in effect-studies and/or outlooks for developing policies for the Scheldt estuary.

Versie	Datum	Auteur	Paraaf	Review	Paraaf	Goedkeuring	Paraaf
	jul. 2016	Katherine Cronin		Bas van Maren			
		Thijs van Kessel					
	oct 2018	Bob Smits		Bas van Maren	BM	Frank Hoozemans	

Status
final

Contents

1 Introduction

The LTV mud model has been built in the period 2006 – 2010. From 2010 onwards it has been applied for several scenario studies, such the impact of the release of dredged material from designated sites in the Western Scheldt, the impact of the relocation of some of these disposal sites on turbidity and harbour siltation, the effect of a saline discharge at Bath on turbidity and the impact of dredged material release near Antwerp harbour on the strength and location of the local estuarine turbidity maximum (ETM).

However, no further model developments on the LTV mud model have been carried out since 2010 despite known shortcomings (such as the underestimation of mud deposition on the tidal flats). In the meantime, there have been model and knowledge developments in nearby areas such as the Western Scheldt mouth and the North Sea. In addition more observations on suspended particulate matter (SPM) dynamics in the Scheldt and its mouth have become available which provide important additional validation data. Therefore for several reasons, the LTV mud model requires an update. The results on this work are discussed in the present report.

The Delwaq LTV model to simulate suspended sediment was updated with the hydrodynamics inputs of the year 2014. Results for these updated hydrodynamics are compared to results with hydrodynamics of the year 2006.

2 Objective

The objective of this study is to update the LTV mud model with new knowledge developed and validation data acquired in recent years, and publish this as a technical report (the present document) and a peer-reviewed paper (work in progress).

The improvements include:

- More emphasis on intra-tidal suspended sediment concentration variations;
- More emphasis on the siltation rate on the natural (intertidal) mud flats (and not only on the siltation rate in harbour basins and access channels);
- Synchronisation of settings with other studies that have been developed in recent years in the framework of studies on mud dynamics in the North Sea (Arentz et al., 2012 and Cronin and Blaas, 2013), Wadden Sea (van Duren et al, 2015), Ems (van Maren et al., 2014) and the Scheldt estuary mouth (Vroom et al., 2016), which include two mud fractions (microflocs and macroflocs) rather than one fraction as in the LTV mud model;
- The abandonment of spatially varying parameter settings to make the model more transparent;
- The use of more and more recent validation data on SPM dynamics.
- Update the model settings for 2014 hydrodynamic input and compare results to previous settings

Previous results with the LTV mud model have been published in a number of technical reports (e.g. van Kessel et al., 2008; van Kessel and Vanlede, 2009; van Kessel et al., 2010) and a paper (van Kessel et al., 2011).

3 Methods

The mud transport model was set up using the Delft3D-WAQ software coupled offline with hydrodynamics from TRIWAQ, a module of SIMONA for the year 2006 (runID G34). The Delft3D-WAQ model applies the buffer parameterisation developed by van Kessel et al., 2011 for deposition, storage and erosion of sediments. The hydrodynamic model has six layers with a double logarithmic layer distribution (Table 3.1) which gives the model a higher resolution near the water surface and near the bed. Wave forcing is included adopting a simple fetch length approach. This model has gradually evolved in the period 2006 – 2010 (with regard to grid schematisation, boundary conditions and process description etc.) and a detailed description of the evolution towards the current model set up can be found in previous reports (e.g. Van Kessel et al., 2006, 2007, 2008, 2009, and 2010). No updates in the model setup occurred since 2010 and so this report describes the first improvements since 2010.

Table 3.1 Model layer distribution in the vertical

Layer	Thickness (%)
1 (top)	10
2	20
3	30
4	20
5	15
6 (bottom)	5

Prior to a discussion on these changes, first a small recap of the main characteristics of the original model is presented.

3.1 General model philosophy

The LTV mud model was originally developed as a model to investigate the long-term behaviour of mud in the Scheldt estuary, including mud behaviour in the water column and in the seabed. The model was and is used to calculate the direct effects of potential developments, both anthropogenic and natural in the Scheldt estuary on SPM dynamics such as deepening, alternative freshwater discharge scenarios, changes in fluvial discharges or marine mud supply, new harbour basins or dike realignments. Indirect effects of these developments on the system, such as the change in mud availability in the seabed are also considered. Indirect effects are much more difficult to assess in reality as they make take months to years to become apparent, steered by the amount and residence time of mud in the system.

A model is an ideal tool to estimate the magnitude of such indirect impacts of system changes. For example, a channel deepening that results in a decrease in current velocity typically also results in a decrease in SPM levels in the short term. However, gradually more mud may be imported into the deepened area as the system tries to reach a new equilibrium, resulting in an overall increase in SPM levels at the long term as more mud becomes available for resuspension. 'Classical' mud models aimed at the short term may only account for the short-term reduction in flow velocity and therefore give inaccurate predictions on the long-term effects. This was and is the rationale behind the development of the LTV mud model.

The computations presented in this report have all a long spin-up time (a couple of years) as such time is required to make the mud distribution (and notably that in the bed) independent from initial conditions. However, full dynamic equilibrium has not always been achieved because of limitations in available computer time. SPM levels are all very close to dynamic equilibrium, but the residual mud balance of some computations is still influenced by transient effects as the buffer layer still acts as a net year-averaged sink or source term.

The availability of mud in the sea bed is modelled with the so-called 'buffer model' within Delft3D-WAQ, which is described below.

3.2 Buffer model

The buffer model is a bed module (within Delft3D-WAQ) that accounts for buffering of fine sediments in the bed at various timescales (spring neap, seasonal). Fine sediments are stored in the seabed during calm conditions and released from the seabed during stormy conditions (Van Kessel et al., 2011). This model contains two bed layers which interact in a specific way. The thin fluffy layer forms during slack tide and is easily resuspended by tidal currents. This layer accounts for rapid resuspension and settling that in reality is thought to occur in fluffy patches on the sea floor. The total sediment mass in this layer is small. The sandy buffer layer, on the other hand, can store fines for longer times and releases SPM only during highly dynamic conditions, such as spring tides or storms. Detrainment of silt from the matrix of sand occurs only beyond critical mobilization conditions for the sand grains, whereas slow entrainment occurs during calm conditions. The time-averaged sediment fluxes between the buffer layer and the water column are small, whereas the storage capacity of silt in the sea bed may be large, depending on the assumed mixing depth. As a result, the overlying water column is directly interacting with both layers but with different rates, representing the different physical process that play a role. Figure 3.1 illustrates the exchanges between both bottom layers and the water column for the buffer parameterization.

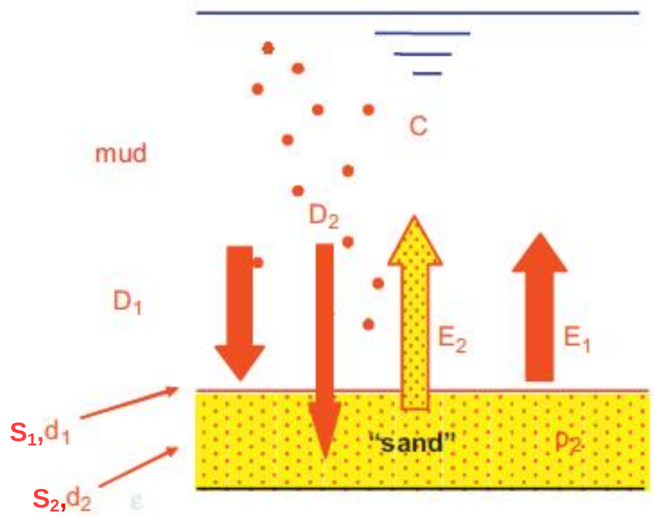

Figure 3.1 Schematic representation of the buffer model. Layer S_1, thickness d_1: thin fluff layer. Layer S_2, thickness d_2: sandy sea bed infiltrated with fines. D_j deposition flux towards layer S_j, E_j erosion flux from layer S_j ($j \in [1,2]$) and C: SPM concentration. (Adopted from Van Kessel et al., 2011)

Deposition towards layer S_1 and S_2 is determined by settling velocity V_{Sed}, and a factor α«1 that distributes the flux to the fluff and buffer layer. A critical shear stress for sedimentation is not applied, but the deposition probability p_{Sed} is set at a (constant) value smaller than unity (typically 0.1). Hence the deposition flux is samller than the settling flux, promoting higher near-bed concentration levels.

$$D_{1,IM_i} = p_{Sed}(1-\alpha_{IM_i})V_{Sed,IM_i}C_{IM_i} \quad (Eqn\ 3.1)$$

$$D_{2,IM_i} = p_{Sed}\alpha_{IM_i}V_{Sed,IM_i}C_{IM_i} \quad (Eqn\ 3.2)$$

with C_{IMi} the concentration of fraction inorganic matter IM_i, and α dependent on the fraction class. Deposition of fines in the buffer layer (Equation 3.1) will stop if the silt fraction reaches a user-defined saturation rate ($FrTIMS_{2,Max}$). In this case all deposited sediment will be stored in the fluff layer S1 (α_{IM_i} = 0).

Resuspension E_1 of each fraction out of the fluff layer is proportional to the excess shear stress times a grain size dependent first-order rate (V_{Res}) until a certain saturation concentration in the bed is attained beyond which a uniform zero-order rate (Z_{Res}) applies (see Eq. 3.3 for details). The coarse and fine fractions have a different critical shear stress for resuspension (τ_{cr}). The zero-order formulations are based on Partheniades (1962), the first order expression is based on Van Kessel et al. (2011). The process is implemented for all three sediment fractions IM_i.

For the resuspension flux E_2 from the buffer layer, a Van Rijn (1993) type of pickup formulation is applied, with Van Rijn's empirical power of the excess stress of 1.5. The fines are only detrained from this layer when the shear stress exceeds the mobilization threshold (Shields stress, τ_{Sh}) for the sand amongst which the fines are stored. In summary, the erosion fluxes for supercritical conditions read:

$$E_{1,IM_i} = \min\left(Z_{\mathrm{Res},IM_i}, V_{\mathrm{Res},IM_i}M_{i,1}\right)\left(\frac{\tau}{\tau_{\mathrm{cr},S_1IM_i}}-1\right) \quad (Eqn\ 3.3)$$

$$E_{2,IM_i} = F_{\mathrm{ResPUp}}M_{i,2}\left(\frac{\tau}{\tau_{\mathrm{Sh}}}-1\right)^{1.5} \quad (Eqn\ 3.4)$$

In this formulation, the following definitions hold:

E_{j,IM_i} Resuspension flux of SPM fraction IM_i from layer S_j [g m^{-2} d^{-1}]
τ Bottom shear stress [Pa]
$\tau_{\mathrm{cr},S_1IM_i}$ Critical shear stress for silt resuspension fraction i from fluff layer S_1 [Pa]
τ_{Sh} Critical Shields stress for sand mobilization in buffer layer S_2. [Pa]
Z_{Res,IM_i} Zero-order resuspension rate from layer S_1 [g m^{-2} d^{-1}]
V_{Res,IM_i} First order resuspension rate from layer S_1 [d^{-1}]
F_{ResPUp} Van Rijn (1993) pickup factor from buffer layer [-]

$M_{i,j}$ Mass of sediment fraction *i* in layer *j* per surface area [g m^{-2}]

Since the fluff consists of pure mud, the mass for layer S_1 is proportional to the stored mass of fraction *i* per unit bed area for each computational segment. For layer S_2 the mass depends on the mud fraction with respect to the sand: $M_{i,2} = f_{IM_iS_2} d_2 (1\text{-Por}_{S_2}) \rho_{sand}$, with thickness d_2 and

$f_{IM_iS_2}$ the fines fraction with respect to total bed,

Por_{S_2} the volumetric porosity of the bed,

ρ_{sand} the mass density of sand.

3.3 Data availability

As described in the previous chapters, a further update of this mud transport model was undertaken in order to synchronise the model with other recent model development for adjacent areas, to validate the sedimentation rate on the intertidal mud flats and to compare the results with newly available high resolution SPM data. This included data at A2/MOW, WZ buoy (Figure 3.2), Boei 97 and Boei 84 (Figure 3.3).

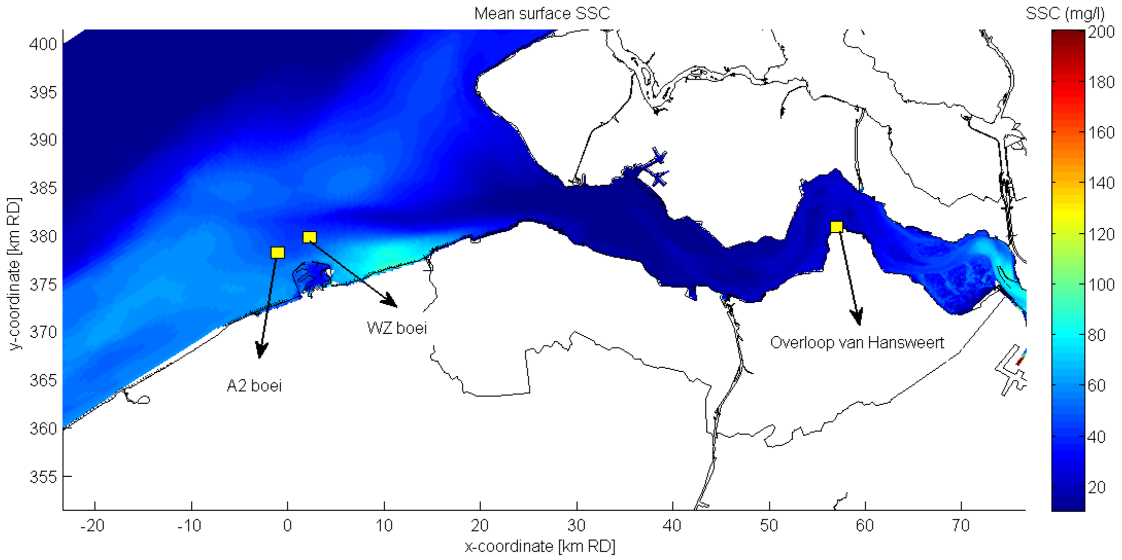

Figure 3.2 Offshore observation stations with background colours indicating the yearly averaged SSC computed in the surface layer

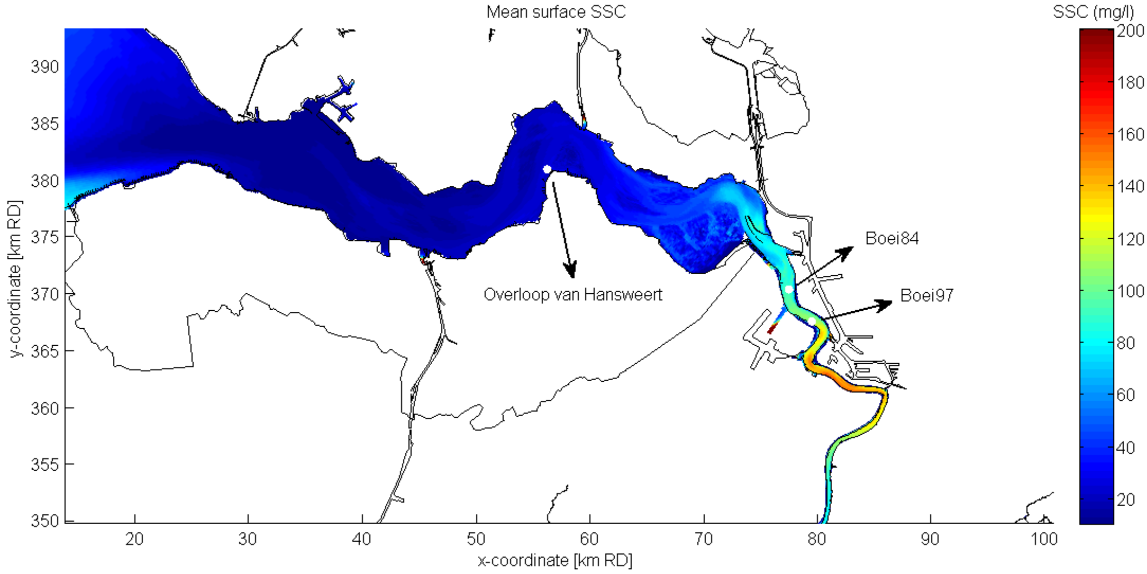

Figure 3.3 Up-estuary observation stations with background colours indicating the yearly averaged SSC computed in the surface layer

Figure 3.4 - Figure 3.7 show the time series of data used in the comparison to model observations. Two of the locations (WZ and A2) are just offshore of Zeebrugge, where wave data is also available. The other two stations (Boei 84 and Boei 97) are located just downstream of Antwerp across from the Deurganckdok. The period covered by this data is shown in Table 3.2.

Table 3.2 Observation station time coverage

Measurement location	Time Period	Position in water column [meters above bed]
WZ buoy	2013 (with gaps)	0.2 and 2.2 m.a.b.
A2/MOW	2013 (with gaps)	0.2 and 2.2 m.a.b.
Boei 84	2006 (with gaps)	0.8 and 3.3 m.a.b.
Boei 97	2006 (with gaps)	0.8 and 3.3 m.a.b.

The data was not collected in the same time period (2006 and 2013, see Table 3.2) as the model simulation (variable years) and as a result the model results cannot be compared with the data in the time domain. Therefore a data-model comparison was made as a function of the tidal phase.

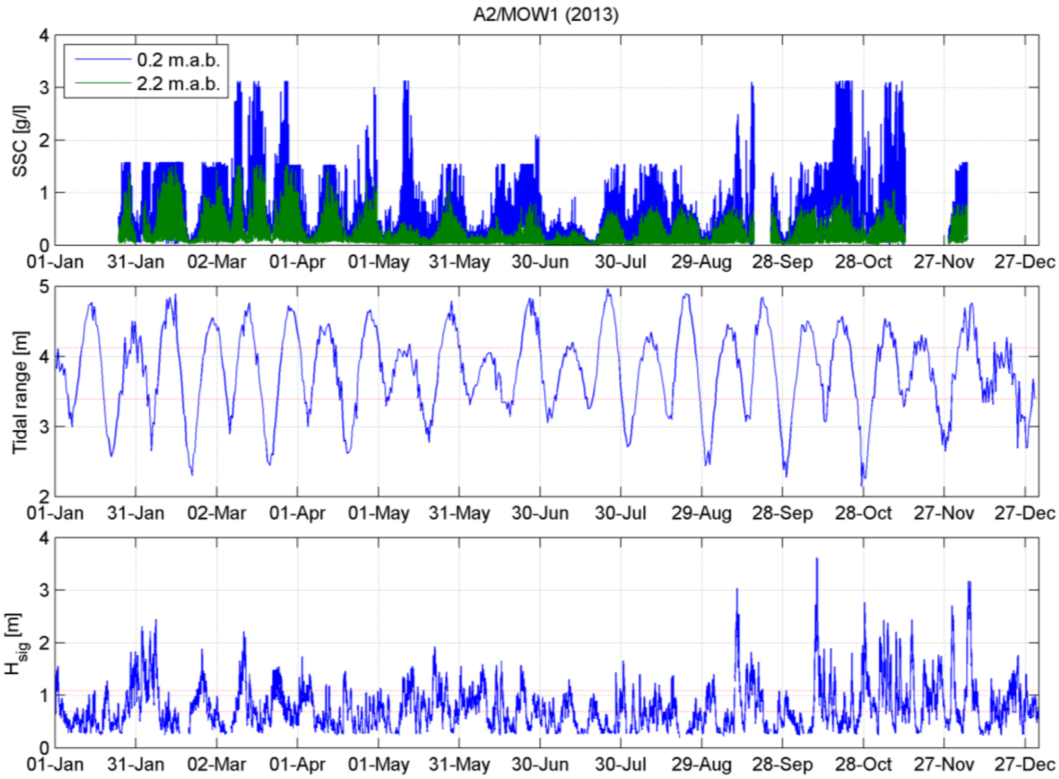

Figure 3.4 Timeseries of SSC, tidal range and significant wave height at station A2/MOW1 for 2013

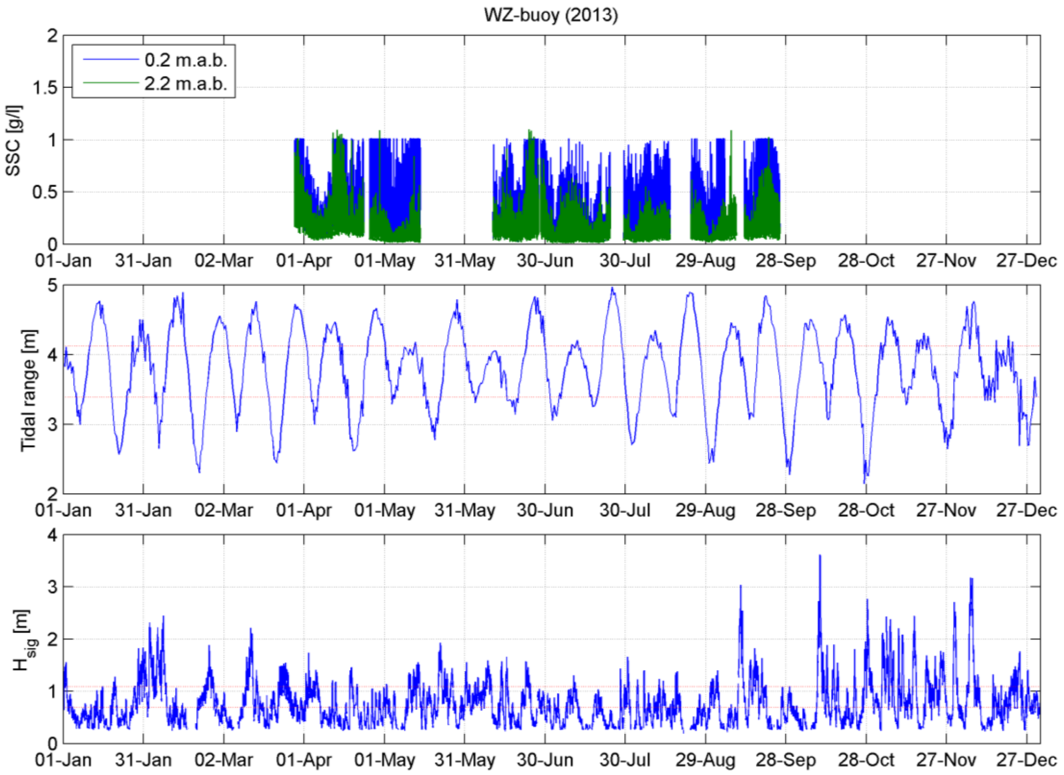

Figure 3.5 Timeseries of SSC, tidal range and significant wave height at station WZ buoy for 2013

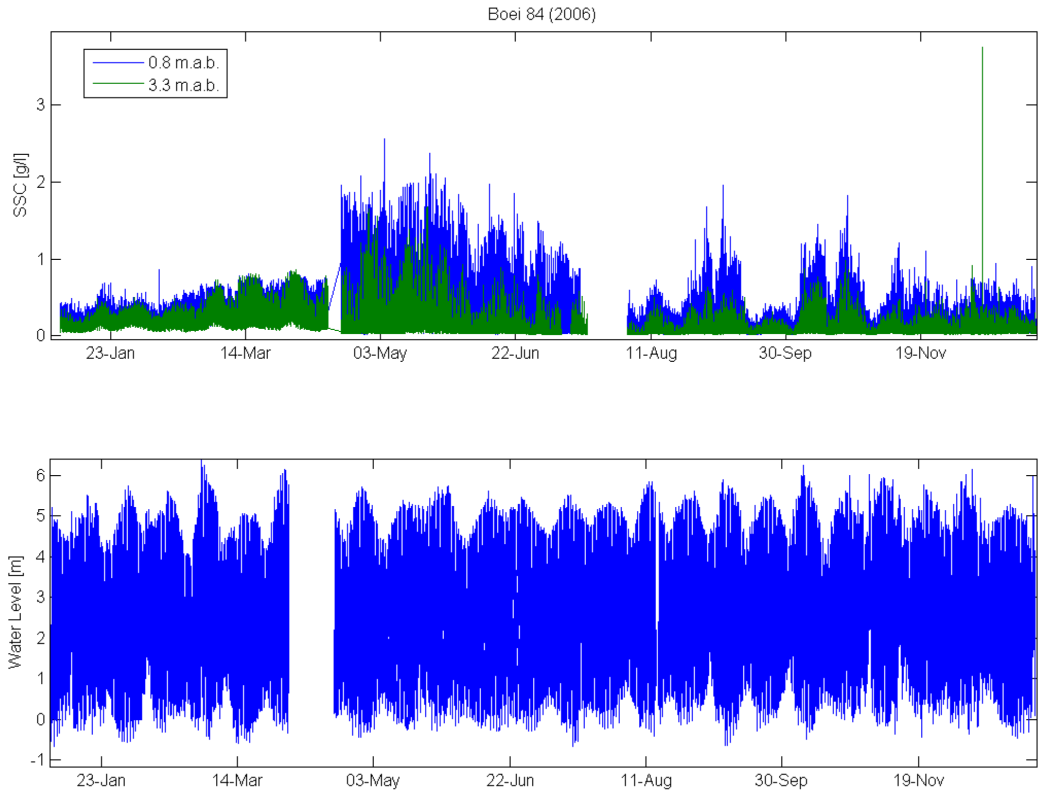

Figure 3.6 Timeseries of SSC and water levels at Boei 84 for 2006

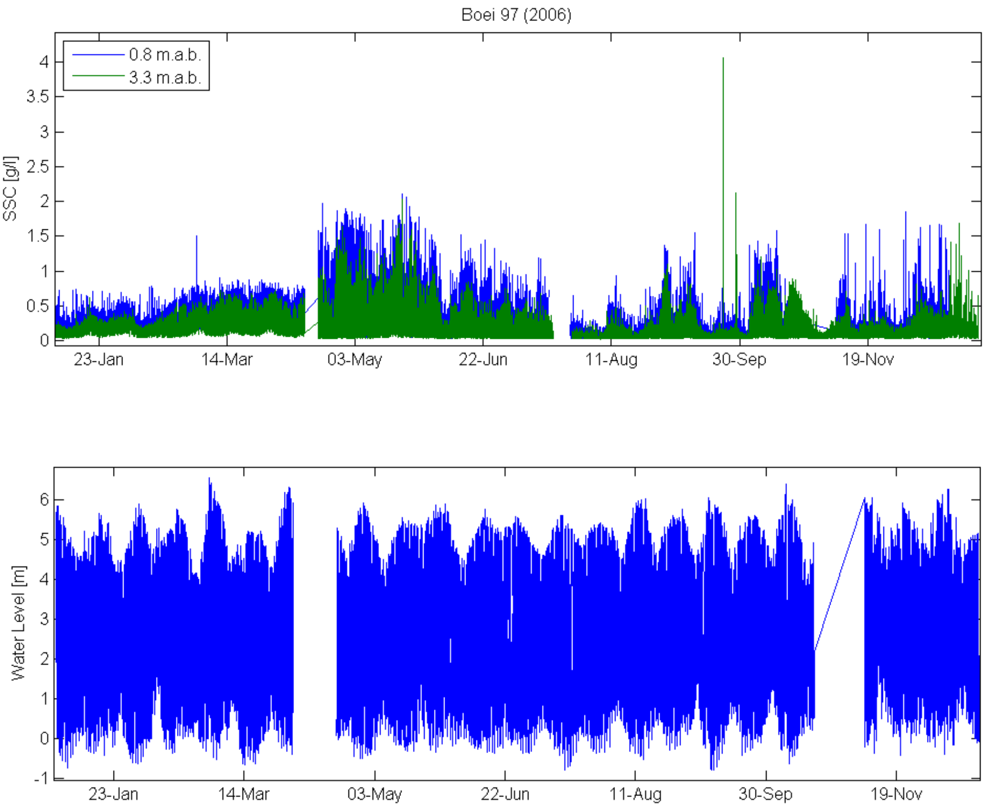

Figure 3.7 Timeseries of SSC and water levels at Boei 97 for 2006

3.4 Set up of new runs

In the previous baseline model (LTV2010), two fine sediment sources (but with the same settings for settling velocity and erodibility) were included in the model, one representing a marine fraction and the other a fluvial fraction. Parameter settings for the buffer model formulations as described in Section 3.1 are shown in Table 3.3.

Comparison of the model to remote sensing data in van Kessel et al., (2010) revealed that in the outer estuary the variability in near-surface SPM levels can be attributed to the tide (both semidiurnal and neap-spring) and wind (waves). In the inner estuary the tidal effect is stronger as the effect of wind (waves) is less prominent. However in the inner estuary, the effect of freshwater discharge becomes much more important towards Antwerp. A higher discharge results in higher SPM levels, (1) caused by a higher fluvial sediment load, (2) enhanced estuarine circulation, and (3) seaward migration of the turbidity maximum. SPM levels near Antwerp are also significantly influenced by the release of dredged material from harbour maintenance, as a substantial part of the sediment flux becomes temporarily trapped in access channels and in the Deurganckdok. In the Western Scheldt this effect is much smaller, as the siltation rate in the harbours of Vlissingen and Terneuzen is limited compared with the natural gross sediment flux (van Kessel et al., 2010).

Table 3.3 Original parameter settings used in LTV mud 2010 (From table 5.1 of the LTV report. For those parameters with a spatially varying value, the value used for the majority of the domain is given

Parameter	Value	Units	Value	units
	Fraction 1		Fraction 2	
V_{Sed}	1	mm/s	1	mm/s
α	0.1	-	0.1	-
τ_{cr} (spatially varying)	0.1	Pa	0.1	Pa
V_{Res} (spatially varying)	1	s^{-1}	1	s^{-1}
D	0.05	m	0.05	m
τ_{Sh} (spatially varying)	0.5	Pa	0.5	Pa
M_2 (spatially varying)	1.75×10^{-7}	$kg/m^2/s$	1.75×10^{-7}	$kg/m^2/s$
Z_{Res}	8.64×10^{4}		8.64×10^{4}	
P_{sedmin}	0.1	-	0.1	-

Update of the model focussed on (1) improving SPM concentrations in comparison to the high resolution data buoys and (2) to achieve a better level of siltation in the harbours and on the intertidal flats of Hansweert in The Netherlands and the Zeeschelde mudflats in Belgium by modifying the settings in Table 3.3. As part of the improvements the effect of a third a (coarser) sediment fraction was tested in some simulations (e.g. A06), aiming to improve suspended sediment concentrations in the upper estuary and net sedimentation rates on the mudflats.

Several settings were tested in the latest update of the model. Only the settings that resulted in substantial improvements are shown in Table 3.4. The rationale for the new parameter settings is as follows:

- The new parameter settings should include at least 2 fractions with different settling velocities representing micro- and macroflocs. These settings are now common in neighbouring models of the Scheldt mouth, North Sea and Wadden Sea. The addition of a larger settling fraction is expected to increase SPM levels and siltation.
- The (vertical) exchange between the water column and seabed is poorly known. The LTV2015a settings represent a low exchange of sediments between the water column and the bed, whereas the LTV2015b settings have a medium to high exchange of

sediments. This difference gives insight into dominant processes for residual sediment transport. If water column processes such as estuarine circulation are dominant, a lower water-bed exchange will enhance residual transport and ETM formation. However, mechanisms related to water-bed exchange (such as deposition or erosion lag) are dominant, a lower water-bed exchange will reduce residual transport and ETM formation.

- The LTV2015c settings are intended to investigate the effect of a third large (and fast settling) sediment fraction on SPM levels and siltation. Up to a certain level, a higher settling velocity will result on a stronger residual transport, as both water column and water-bed exchange sediment residual transport processes against the concentration gradient act much more effective on faster settling fractions. However, very fast settling fractions have a strongly reduced likelihood on being in suspension, so also experience little transport. It is therefore interesting to investigate how a 4 mm/s settling fraction behaves compared to a 2 mm/s settling fraction.

Table 3.4 Parameter settings tested. The old and new reference runs are shown in bold.

Run ID	τ_{crit1} (Pa)	M_1 (d^{-1})	τ_{crit2} (Pa)	M_2 ($kg\ m^{-2}s^{-1}$)	P_{sedmin}	Z_{res} ($*10^3$)	α	w_s (mm/s) (per fraction)
LTV2008	0.1[1])	2	0.5[1])	$3.5\ 10^{-7}$	-	8.64	0.1	2/2
LTV2009	0.1	2	0.5	$3.5\ 10^{-7}$	0.1	8.64	0.1	1/0.2
LTV2010	**0.1**	**1**	**0.5**	$\mathbf{1.75\ 10^{-7}}$	**0.1**	**86.4**	**0.1**	**1/1**
LTV2015a	0.1	0.02	1	$3.5\ 10^{-7}$	0.01	17.28	0.1	2/0.5
LTV2015b	**0.2**	**2**	**1**	$\mathbf{3.5\ 10^{-6}}$	**0.1**	**86.4**	**0.1**	**2/0.5**
LTV2015c	0.05	0.2	1	$3.5\ 10^{-7}$	0.1	86.4	0.1	2/0.5/4
LTV hydro 2014	**0.2**	**2**	**1**	$\mathbf{3.5\ 10^{-6}}$	**0.1**	**86.4**	**0.1**	**2/0.5**

[1] 10 in the harbour

4 Results

In this chapter the result of older model settings and new model alternatives are compared to suspended sediment concentration data collected near the bed and mid-water column at Boei84 and WZ buoy (not all data stations were available as output for some of the older simulations). The siltation rates in the harbours and flats were also used to assess model performance.

4.1 SPM concentrations

As described in Chapter 3, data and model results are compared relative to the time from high water (with model concentrations in g/l in red and the data concentrations in blue). The standard deviation around the mean for both data and model are also shown in the blue and red shaded bands respectively.

In addition, figures showing the time-averaged spatial SPM concentration in the near surface model layer and near bed model layer show the changes that the model settings have on the mean surface SPM concentration and on the extent of the turbidity maximum.

4.1.1 Previous simulations

In order to assess the development of this model over time, a comparison is first made with the previous LTV simulations from 2008, 2009 and 2010. Figure 4.1 - Figure 4.6 show the results at Boei 84 for the LTV 2008, LTV 2009 and LTV 2010 mud models respectively.

The essential difference between the LTV 2008 model and LTV 2009-LTV 2010 models is that the 2008 model did not yet include a dredging and dumping module. This means that sediment loads from harbour maintenance dredging were user-defined inputs rather than linked to the actual harbour sedimentation rates computed by the model. So no closed mass balance between dredging and dumping existed in the LTV 2008 simulations. The computed sedimentation volumes were substantially smaller than the user-defined sediment loads. To solve this problem, a dredging and dumping module was developed in Delwaq that was first applied in the LTV 2009 simulation. The inclusion of this module produces satisfactory results of sediment concentrations and sedimentation rates in the short term, as long as the system is initialised with the proper sediment mass on the seabed. However, as sediment was not sufficiently retained in the turbidity maximum in this application, and therefore not in the sediment bed, on the long term (i.e. after multiple years of spin-up to attain a dynamic steady state independent from initial conditions) far too low sediment concentrations and sedimentation rates were computed. This problem was solved by the inclusion of a deposition efficiency which decoupled the settling flux and the deposition flux. This enhanced near-bed concentrations and the effect of estuarine circulation on residual fine sediment transport. Another difference between the LTV 2008 model and LTV 2009/2010 model is that in the 2008 model there were only 5 layers. The LTV 2009 and LTV 2010 models have six layers in the vertical. For the LTV 2008 model hydrodynamic results of the complete year 2006 were used (run G06). For the LTV 2009 model only (updated) hydrodynamic results of Q4 2006 were used (run G19). For the LTV 2010 model updated hydrodynamic results of the complete year 2006 were used (run G34). For a discussion on the performance of these hydrodynamic simulations see the LTV 2008 – 2010 reports.

The only difference between the LTV 2009 and LTV 2010 models is the hydrodynamic and wave forcing. Settings of the mud model remained the same. Nevertheless computed concentration levels near Antwerp are substantially lower in the LTV 2010 model than in the LTV 2009 model. This is explained by the different spin-up period. The LTV 2009 model represents a repetition of Q4 2006. The LTV 2010 model simulates the complete year 2006. On average, the estuarine circulation is stronger (due to higher freshwater discharge) in Q4 2006 than in 2006 as a whole. Also the LTV 2009 model had not yet reached a complete dynamic equilibrium, which was achieved in the LTV 2010 model.

Boei 84 was the only station that was present in all previous versions of the model. In addition due to limited outputs from the older simulations (LTV 2008 and LTV 2009) only the mean surface and near-bed SPM field plots were produced for the LTV 2010 model. In general suspended sediment concentrations, both near the bed and mid water column remained too low, notably in the LTV 2010 model near Antwerp. When the model is compared to the data on a different scale (Figure 4.4) then variability in the SPM dynamics is more visible, however variability is still lower than in the data. Figure 4.5-Figure 4.6 show that the low modelled concentrations are present throughout the estuary, also in the estuarine turbidity maximum (although present).

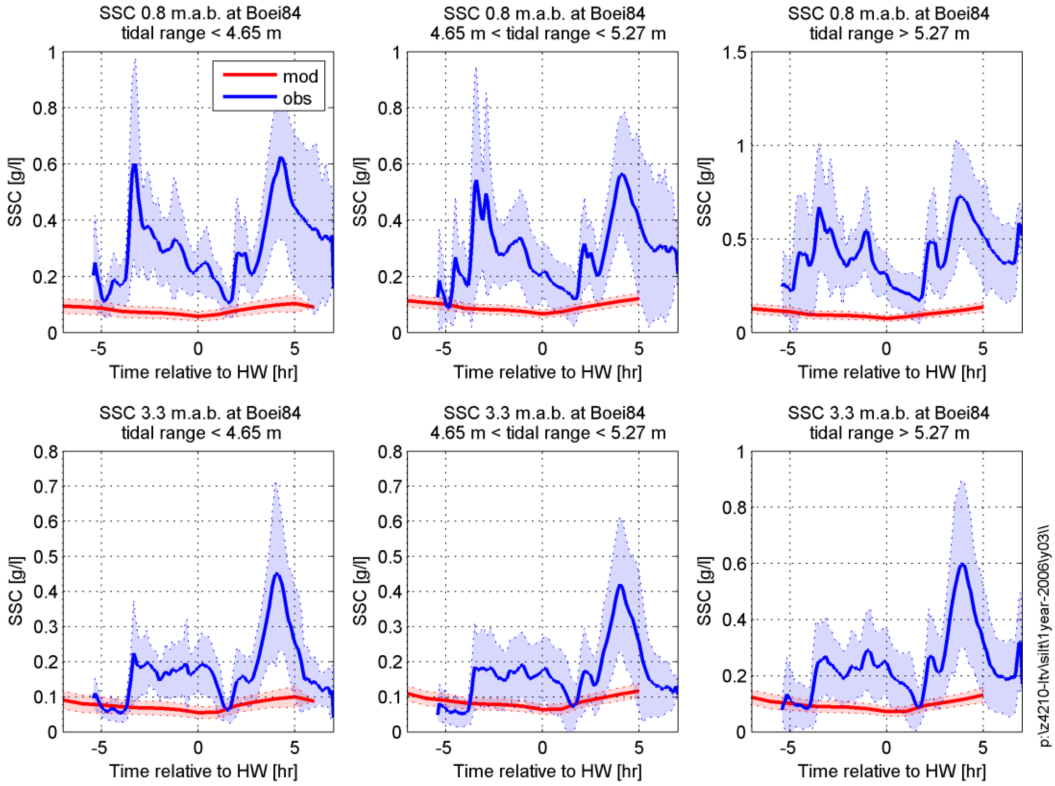

Figure 4.1 Suspended sediment concentrations near bed and mid water column for LTV 2008 at station Boei 84 for the entire year of 2008.

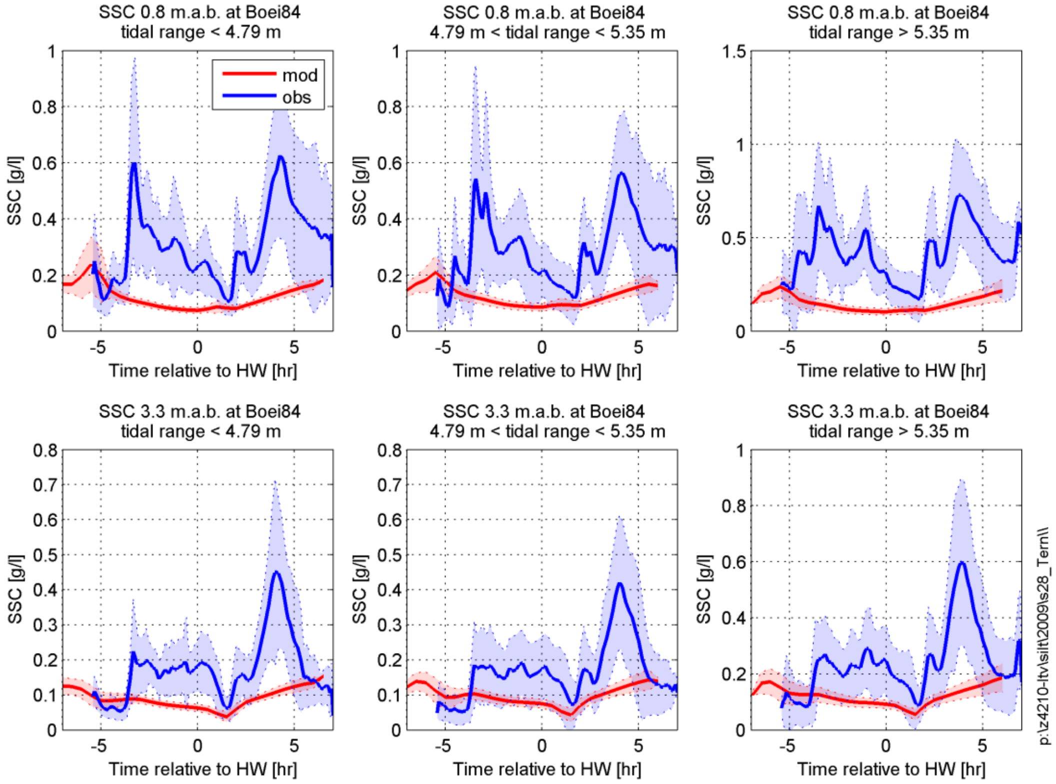

Figure 4.2 Suspended sediment concentrations near bed and mid water column for LTV 2009 at station Boei 84 for the last quarter of 2009.

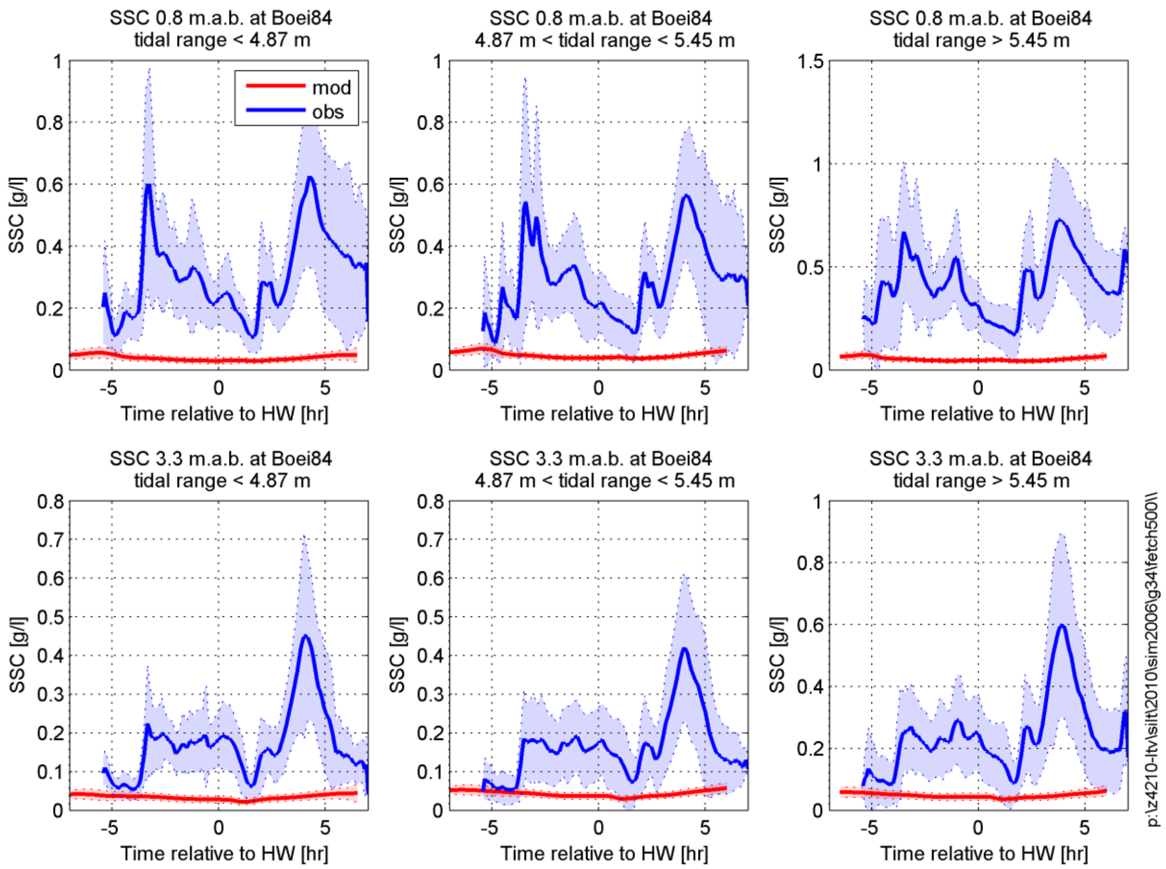

Figure 4.3 Suspended sediment concentrations near bed and mid water column for LTV 2010 at station Boei 84 for the entire year of 2010.

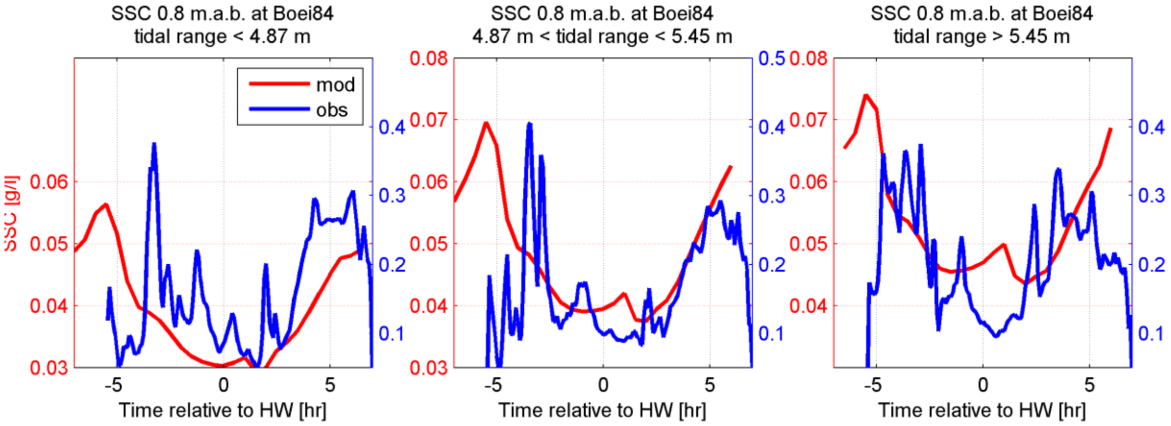

Figure 4.4 Suspended sediment concentrations near the bed for LTV 2010 at station Boei 84, showing model and observations on different scales

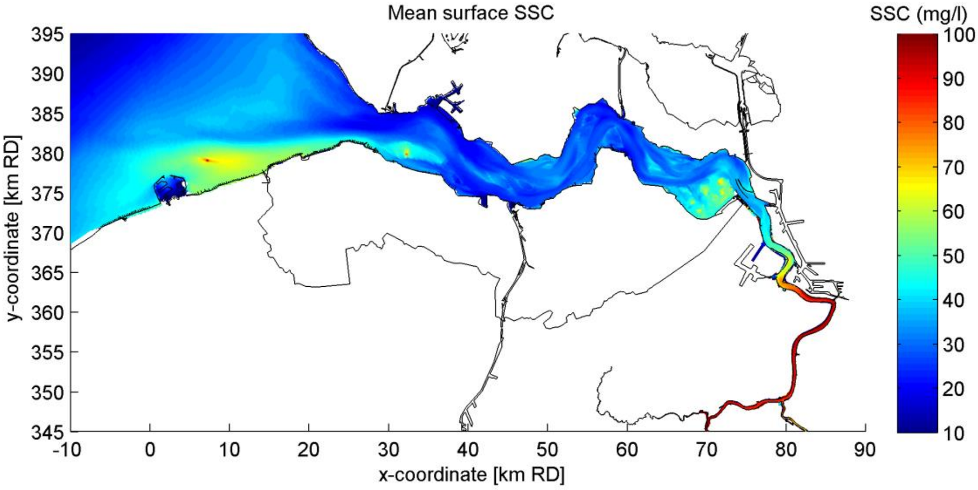

Figure 4.5 Near surface annual mean SPM concentrations for the LTV 2010 mud model

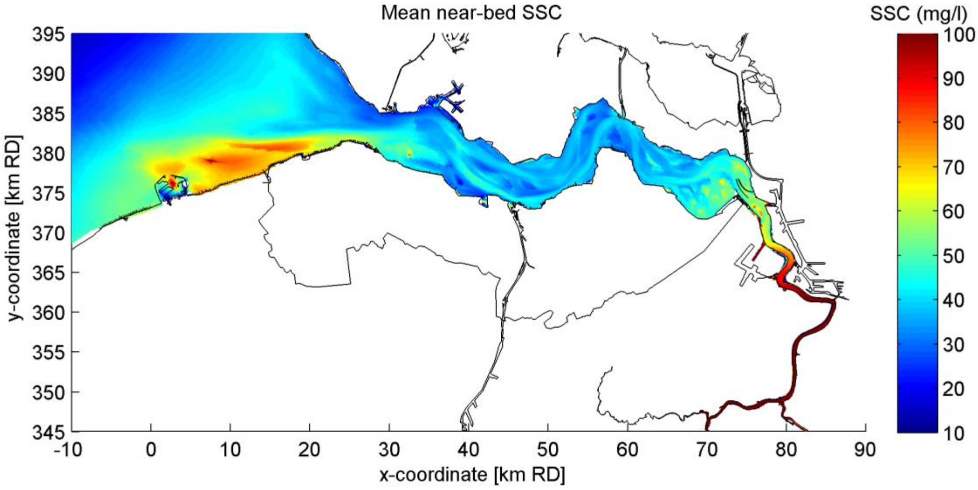

Figure 4.6 Near bed annual mean SPM concentrations for the LTV 2010 mud model

4.1.2 LTV 2015 simulations

As can be seen from Figure 4.3-Figure 4.6, the concentration of SPM within the estuary, at Boei 84, is still far too low for the LTV 2010 model compared to the data. A series of new sensitivity tests were carried out in order to improve the concentration levels both up estuary and offshore using different parameter settings and testing the addition of a third (finer) fraction.

Results show that adjusting setting velocity of the sediment fractions in combination with a larger erosion parameter and a reduced deposition efficiency parameter has a large influence on results. Comparing LTV2015a; Figure 4.7) with LTV 2010 (Figure 4.3) reveals that doubling the settling velocity for the marine/coarser fraction (fraction 1) has a large influence on the concentrations levels. A reduction in the settling velocity of the riverine fraction (0.5 instead of 1 mm/s) improved the simulation of mid-depth sediment concentrations, although near-bed concentrations are now overestimated. A larger erosion parameter for both fractions and a reduced deposition efficiency mean that more sediment is eroded from the bed and more sediment also remains in the lower water column before re-depositing. Figure 4.8-Figure 4.9 show the much higher suspended sediment concentrations in the water column. The yearly averaged concentrations near the bed are much higher up-estuary and also along the coast near Zeebrugge.

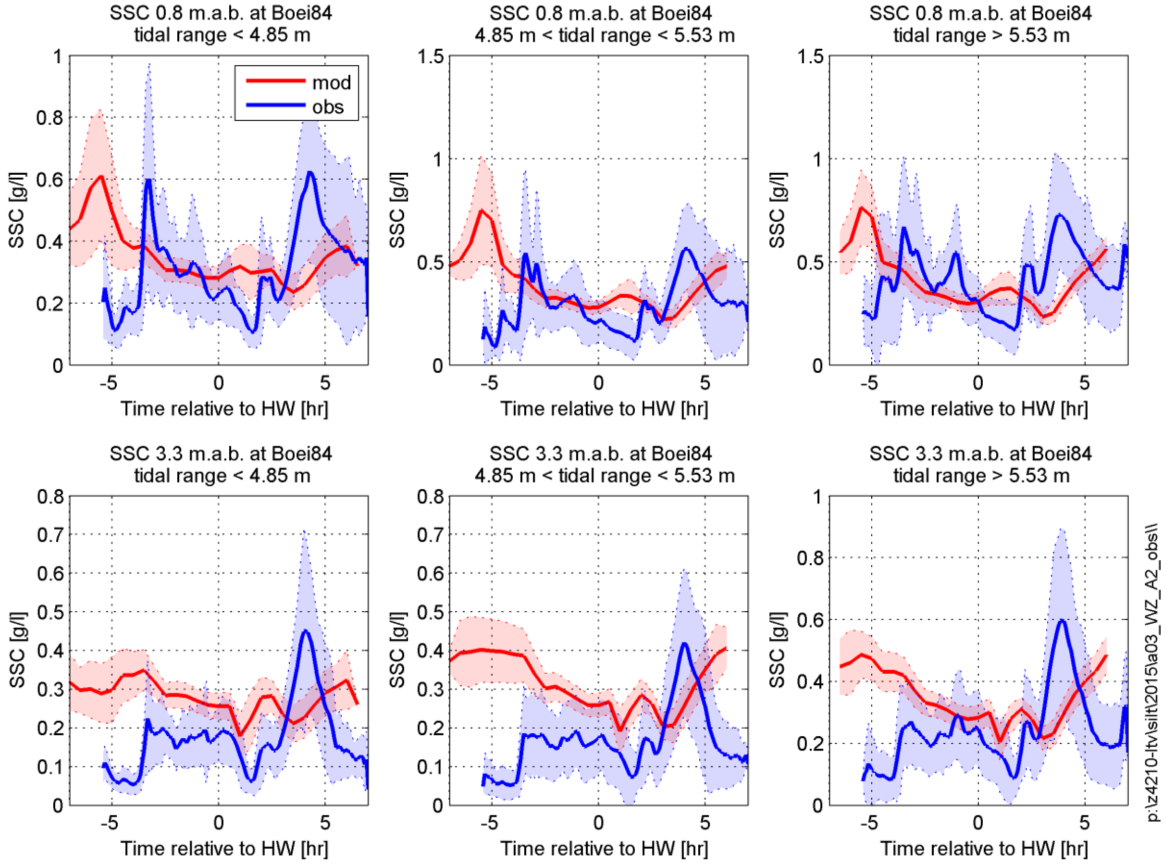

Figure 4.7 Suspended sediment concentrations near the bed and mid water column for LTV 2015a at station Boei 84.

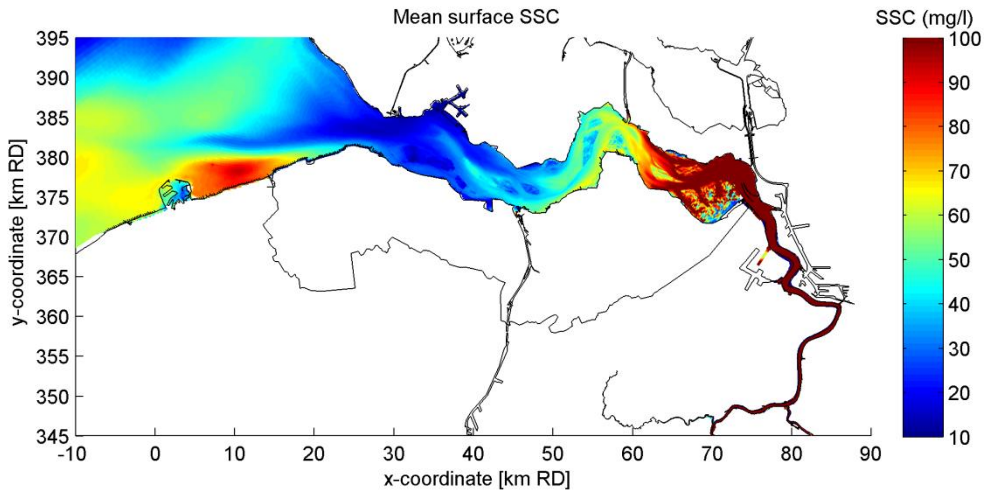

Figure 4.8 Near surface annual mean SPM concentrations for the LTV 2015a mud model

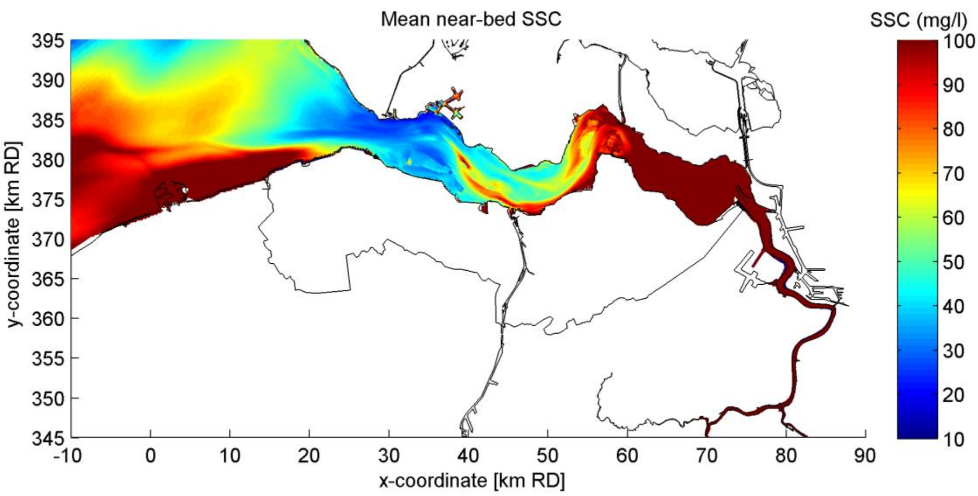

Figure 4.9 Near bed annual mean SPM concentrations for the LTV 2015a mud model

Despite the update of several parameter settings to produce the SPM concentrations in Figure 4.7 (LTV2015a), the phasing of the SPM peaks with water levels needed to be further improved.

A slight improvement was achieved using settings similar to the Vlaamse Baaien model (Vroom et al., 2016) as shown in Figure 4.10 below, by increasing the critical shear stress for erosion and the erosion parameters further (LTV2015b). The concentrations near the bed were also reduced and are now closer to the data. The variability of the model is also improved compared to the 2008 – 2010 simulations (see Fig. 4.1 – 4.3). Alternatively the addition of a third fraction coarser fraction, whilst maintaining a lower critical shear stress for erosion resulted in good average suspended sediment concentrations near the bed (Figure 4.13) for settings applied in LTV2015c and an improved phase match. Also higher concentrations occur along the coast near the bed.

Even with these new improved settings, the sediment concentrations offshore are too low (although higher than computed with LTV2015a). Also the intra-tidal variability is underestimated. Table 4.1 shows the mean, median, 10 and 90 percentile for the full timeseries of modelled (Q1 2006) near bed suspended sediment concentrations and the corresponding measured near bed suspended sediment concentrations. The mean and median concentrations for the first quarter are similar and the 10 percentile is identical. The higher concentrations however are not captured by the model as can be seen from the difference in the 90 percentile.

Table 4.1 Statistical parameters for the full timeseries of SSC in Q1 for the LTV2015c model and measurements at Boei 84 (near bed).

Statistic	LTV 2015c	Boei 84
Mean	0.22 g/l	0.32 g/l
Median	0.20 g/l	0.29 g/l
10 percentile	0.14 g/l	0.14 g/l
90 percentile	0.30 g/l	0.55 g/l

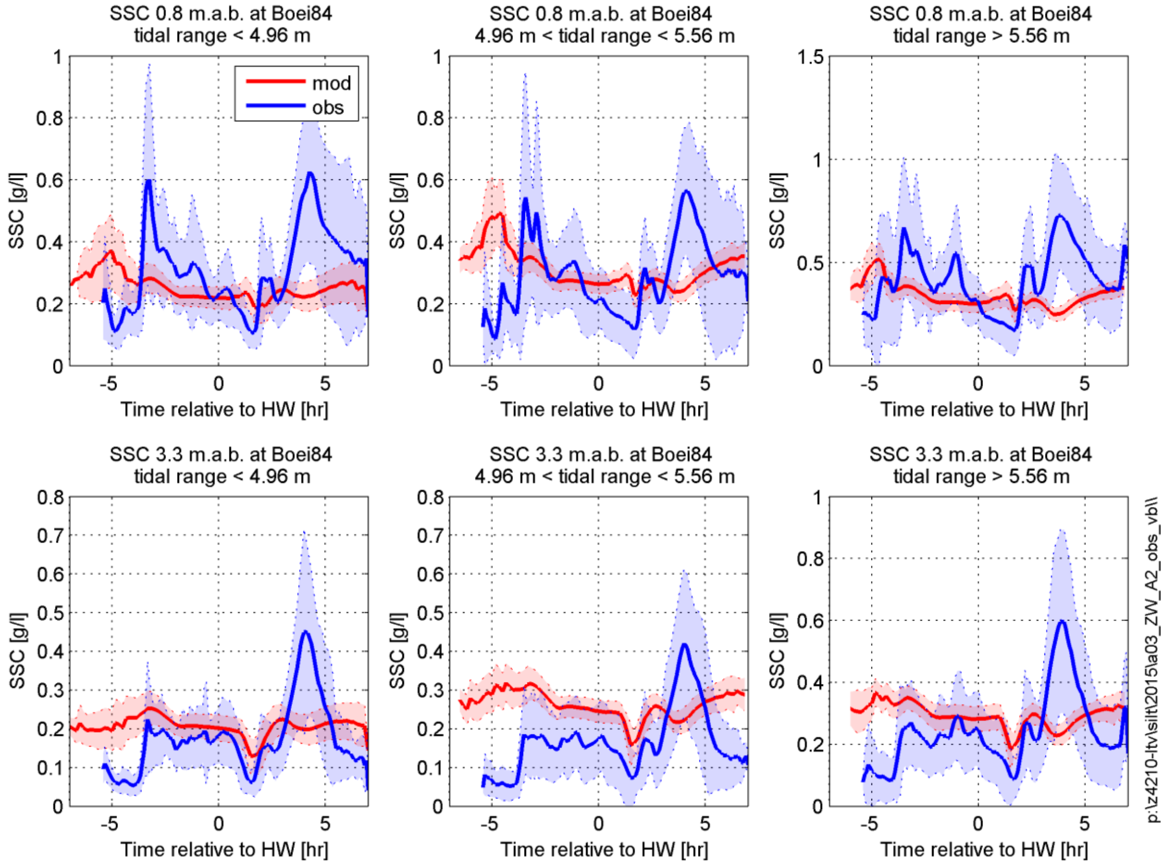

Figure 4.10 Suspended sediment concentrations near the bed and mid water column for LTV 2015b at station Boei 84.

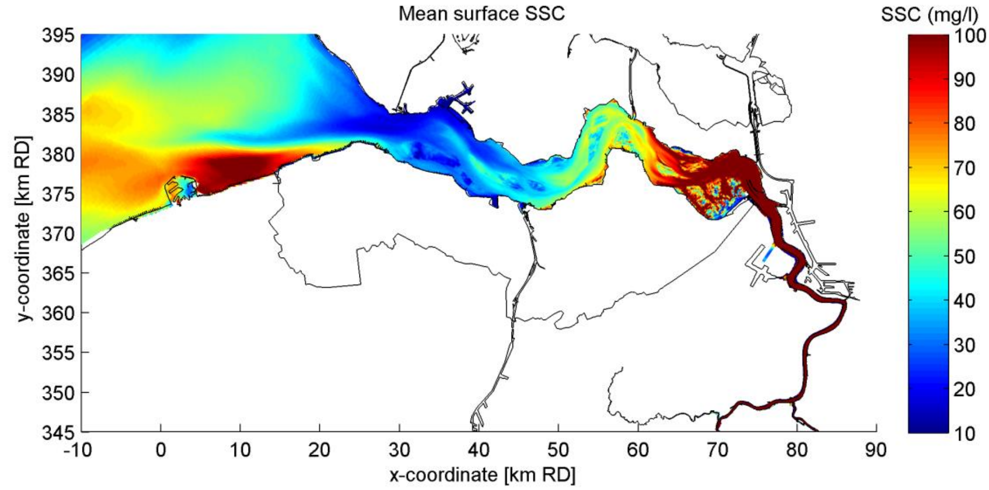

Figure 4.11 Near surface annual mean SPM concentrations for the LTV 2015b mud model

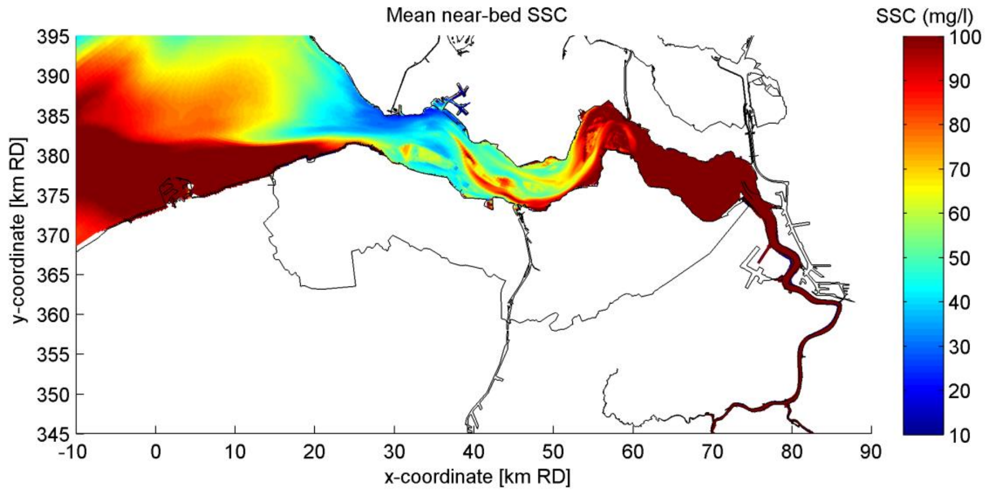

Figure 4.12 Near bed annual mean SPM concentrations for the LTV 2015b mud model

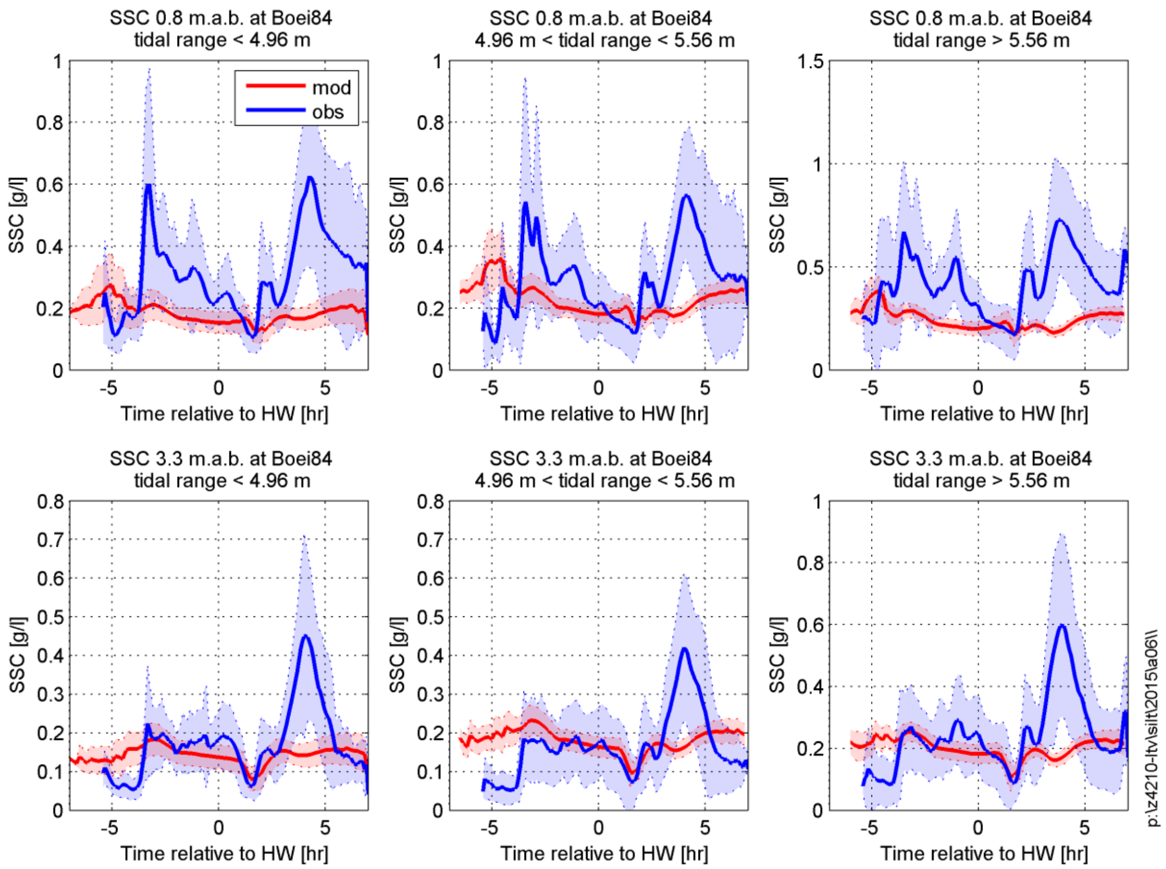

Figure 4.13 Suspended sediment concentrations near the bed and mid water column for LTV 2015c at station Boei 84.

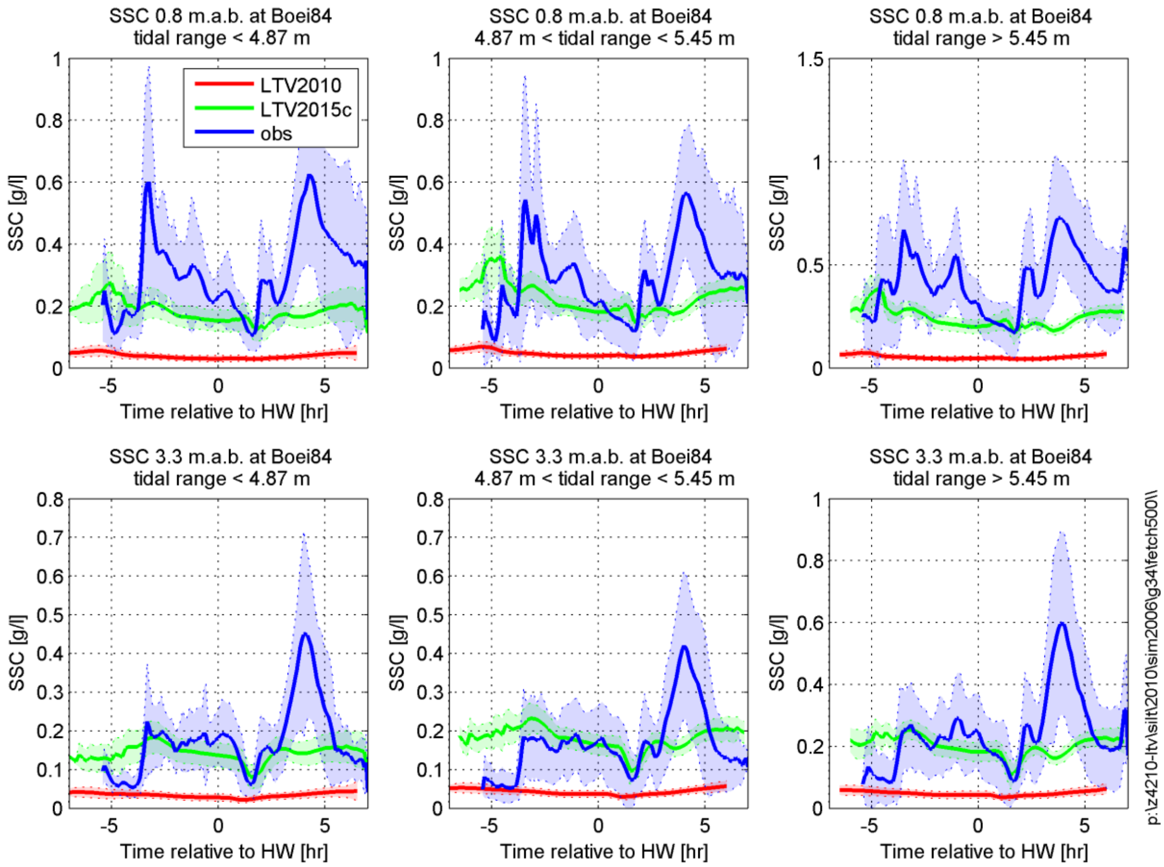

Figure 4.14 Suspended sediment concentrations near the bed and mid water column for LTV 2015c at station Boei 84 compared to LTV2010.

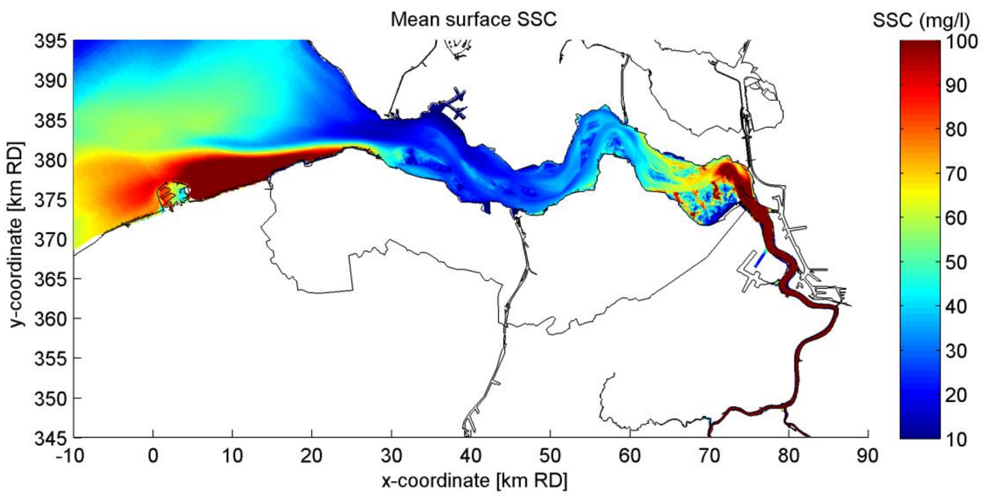

Figure 4.15 Near surface annual mean SPM concentrations for the LTV 2015c mud model

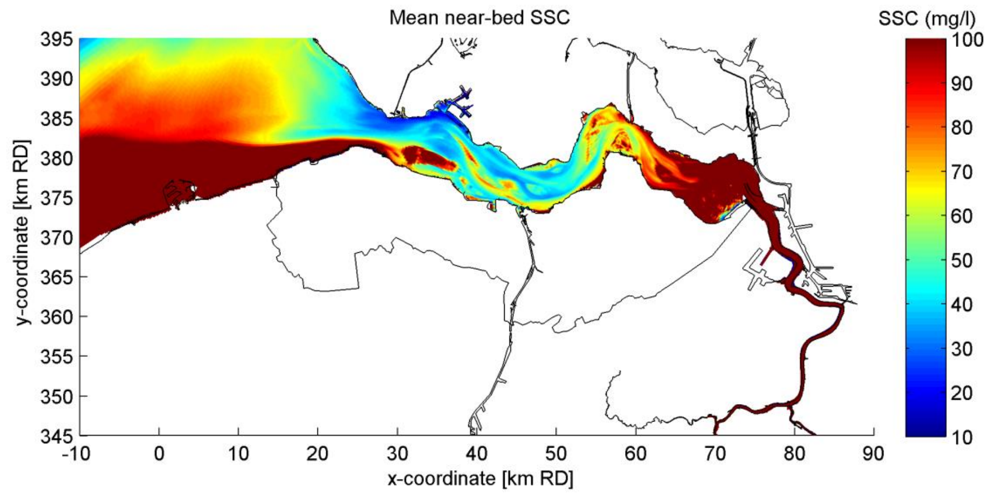

Figure 4.16 Near bed annual mean SPM concentrations for the LTV 2015c mud model

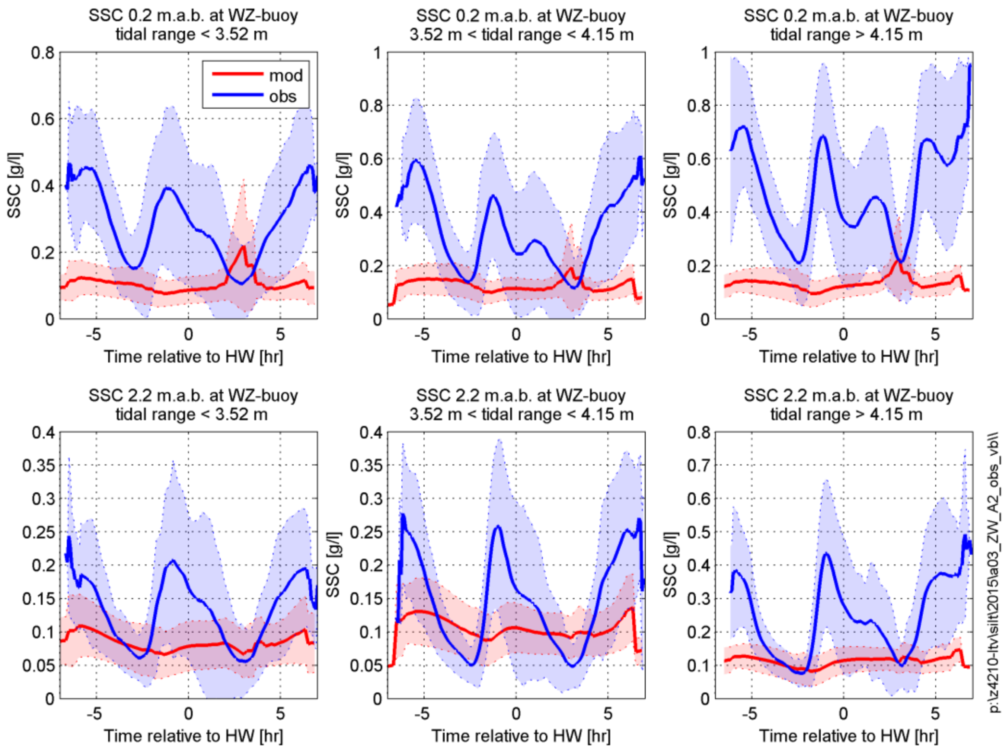

Figure 4.17 Suspended sediment concentrations near the bed and mid water column for LTV 2015b at station WZ buoy just offshore of Zeebrugge

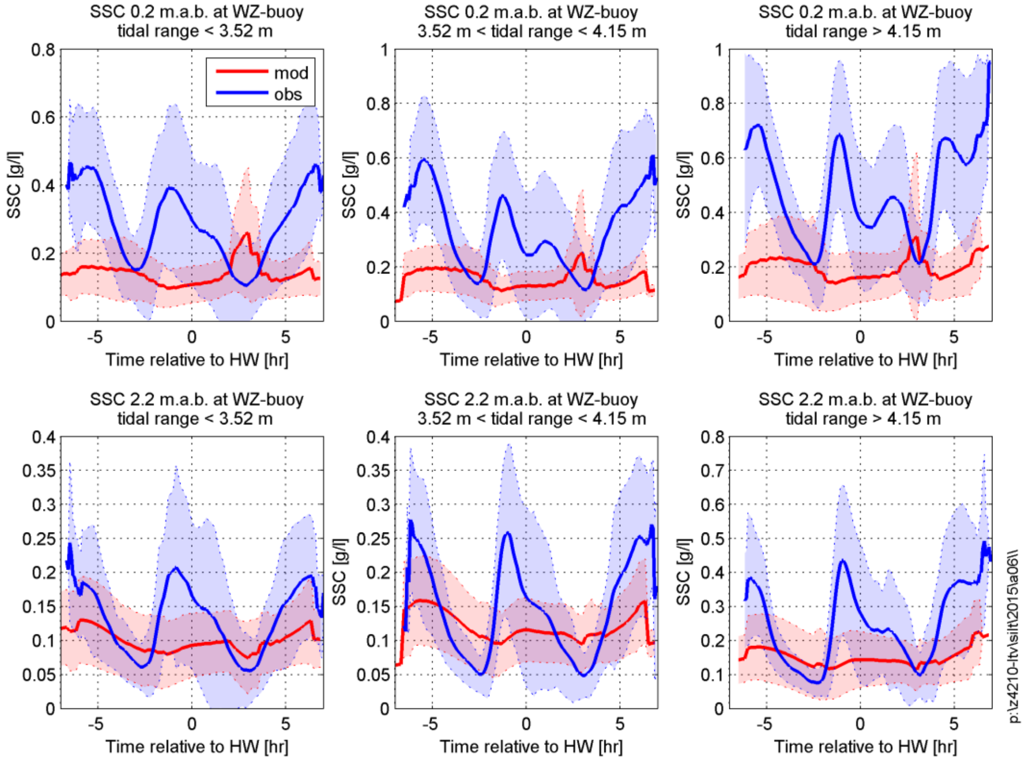

Figure 4.18 Suspended sediment concentrations near the bed and mid water column for LTV 2015c at station WZ buoy just offshore of Zeebrugge

4.2 Mass balances

Figure 4.19 and Figure 4.20 show sediment exchanges (net and gross) in ktons/year between the different areas (i.e. between North Sea and the Western Scheldt, the Western Scheldt and the Sea Scheldt etc.) of the estuary for LTV 2010 and LTV2015c respectively. The balances show a net export from the Schelde to the Sea Scheldt, the Sea Scheldt to the Westerschelde and on to the North Sea for both LTV2010 and LTV2015b. The main difference between both mass balances is the strong increase in the gross exchanges between Western Scheldt, Sea Scheldt and Scheldt river explained by the computed higher sediment concentration levels near Antwerp for LTV2015c.

Figures 4.19 and Figure 4.20 show a small divergence of residual transport in the Western Scheldt and Sea Scheldt (order 100 – 400 kton/year). This suggest that the computations have not yet completely reached a dynamic equilibrium, as in that case a convergence equal to the net sedimentation is expected. However, the concentration level differences between two subsequent computations remains very small, so the simulations are close to equilibrium.

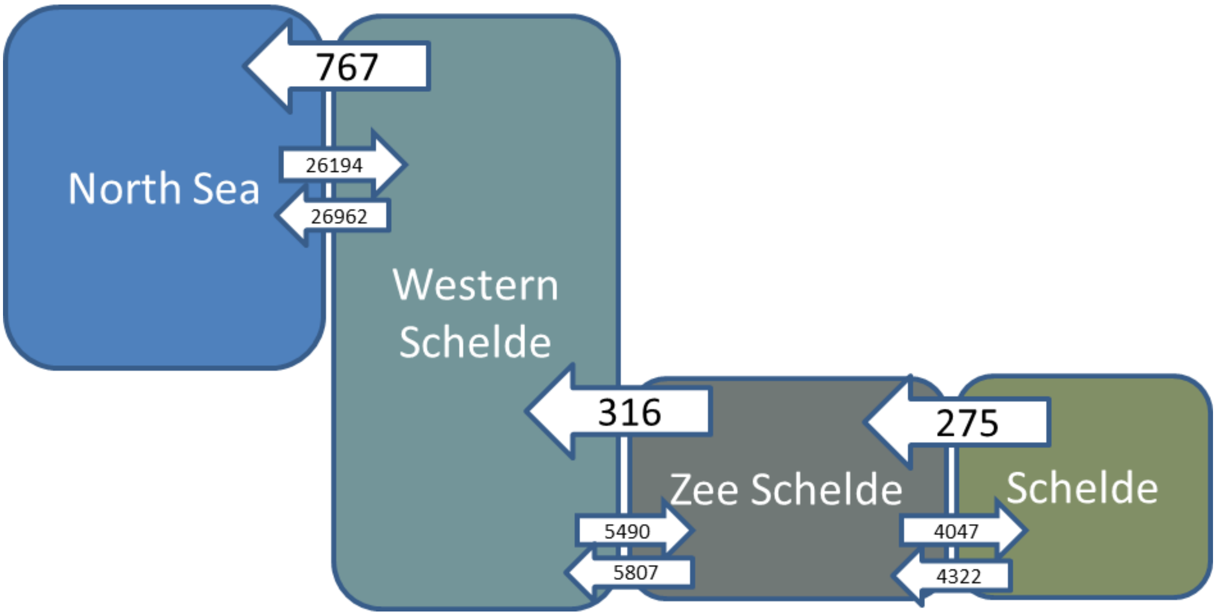

Figure 4.19 Sediment exchange in ktons/year (net and gross) for LTV 2010

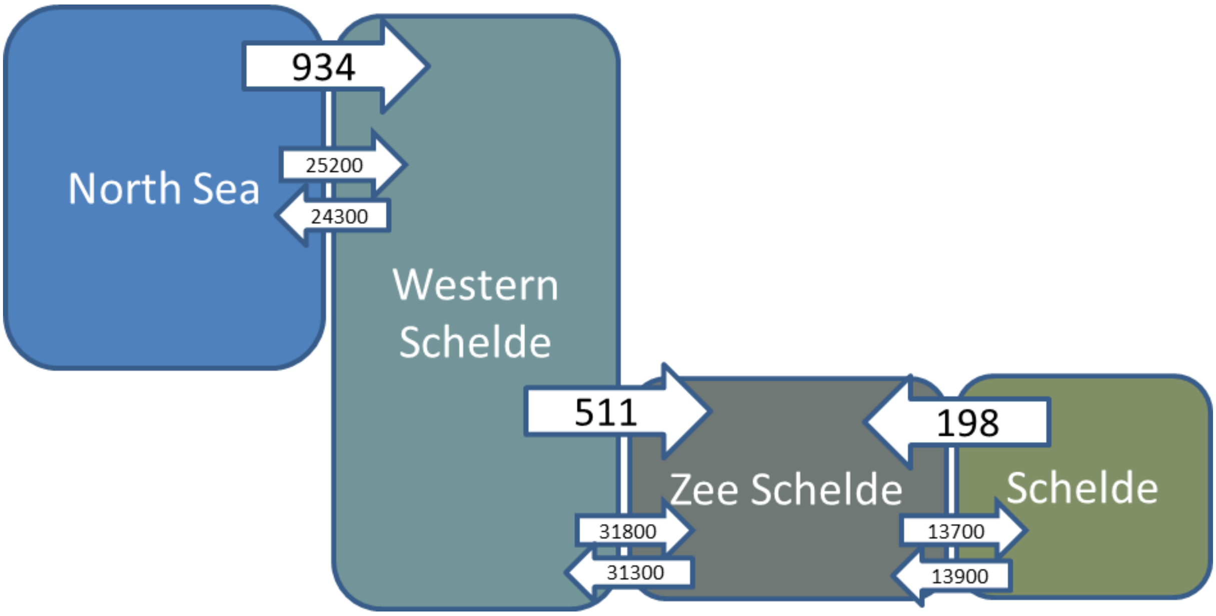

Figure 4.20 Sediment exchange in ktons/year (net and gross) for LTV 2015c

4.3 Siltation in the harbours and flats

Another indicator of model performance is the amount of siltation occurring in the habours and docks of Terneuzen, Zeebruge, Deurganckdok and Vlissingen and the intertidal mudflats of Hansweert in The Netherlands and the Zeeschelde mudflats in Belgium. Table 4.2 and Figure 4.21 shows the amount of siltation at different harbours/docks in megatons per year for each simulation compared to estimates based on actual or permitted disposal volumes. Table 4.3 shows the same values for the intertidal flats. It should be noted that the model simulations were only 3 months long (January-April) and so these yearly siltation rates were estimated by simply multiplying the modelled siltation rates by four and so are not exactly representative of yearly forcing conditions, however provide an indication whether the model is reproducing siltation rates in the right order of magnitude. Sitation rates are well represented at some locations (e.g. Deurganckdok and Terneuzen) but underestimated at other locations such as Braakman and Zeebrugge.

Table 4.2 Yearly siltation (megatons per year) in the harbours for additional model simulations.

Model Run	Braakman	DGD	Kallo	Sloeh	Terneuzen	Zandvliet	Zeebrugge
Estimates	0.8	2	-	0.6	0.25	-	3.1
LTV2010	0.2	0.1	0.4	0.03	0.12	0.12	1.5
LTV2015a	0.1	2.7	0.8	0.1	0.2	0.3	0.5
LTV2015b	0.2	2.6	1.	0.2	0.3	0.9	1.2
LTV2015c	0.1	1.8	0.7	0.2	0.2	0.8	1.0

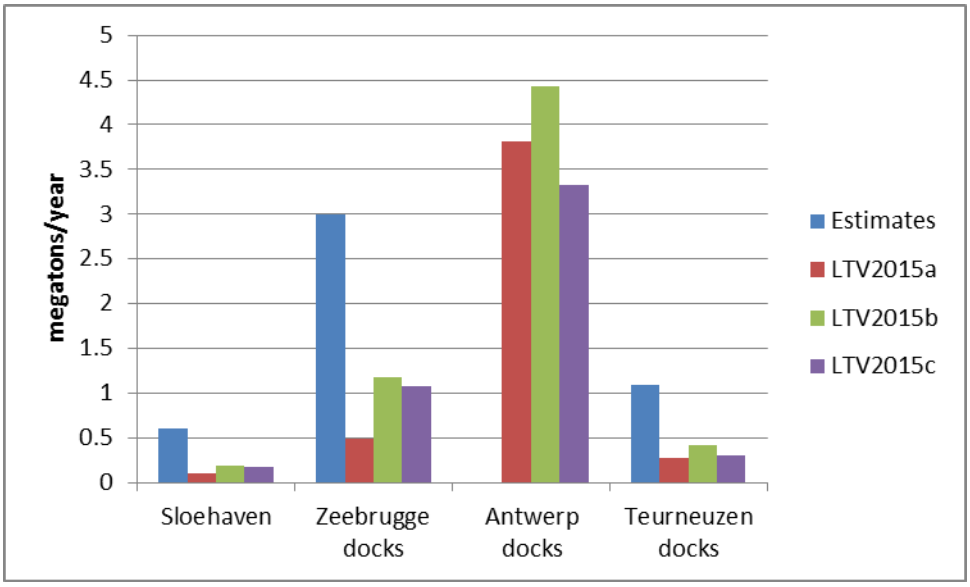

Figure 4.21 Yearly siltation (in megatons per year) for selected harbours compared to estimates

Table 4.3 Yearly siltation rates (megatons per year) on the intertidal flats for additional model simulations

Model Run	**Western Scheldt**	**Sea Scheldt**	**Combined**
Estimates	0.2	0.1	0.3
LTV2010	0.13	0.12	0.25
LTV2015a	0.01	0.8	0.8
LTV2015b	0.07	1.5	1.6
LTV2015c	0.05	1.04	1.1

Model Run	**Western Scheldt**	**Sea Scheldt**	**Combined**
Estimates	0.2	0.1	0.3
LTV2015a	-0.01	0.04	0.03
LTV2015b	-0.06	-0.05	-0.11
LTV2015c	-0.07	0.01	-0.06

Yearly siltation on mudflats of the Western Scheldt is estimated at 0.5 – 2 cm/yr (2 – 10 kg/m^2/yr) (Van Kessel et al., 2008). Computed siltation rates on the tidal flats are somewhat underestimated in the Western Scheldt and overestimated in the Sea Scheldt.

5 Update of LTV model with hydrodynamics 2014

5.1 Input hydrodynamics 2014

The hydrodynamics simulations of 2014 were performed at Flanders Hydraulics Research, as reported by Chu, *et al*. (2017). The SIMONA model was updated for 2014 inputs of bathymetry, initial salinity field, river discharge boundary conditions and wind forcing. The North Sea water level and salinity boundary conditions were corrected based on analysis of model output from the ZUNO model (reference). The results of the updated model were then compared to measurements of instantaneous water level, velocity and salinity.
Water levels are well reproduced by the model from downstream (station Vlakte van de Raan) to upstream (station Kallo). The stationary velocity at Buoy 84 and Oosterweel were also well reproduced (RMSE of velocity magnitude in general less than 0.2 m/s). The velocity magnitude further upstream at Driegoten was substantially overestimated by about 0.4 m/s, due to the positioning of the station closer to the deep tidal channel (Chu, *et al*. 2017). Salinity is generally well reproduced by the model.

For the purpose of understanding the impact of updated bathymetry, river discharge and to a lesser extent, wind forcing, on sediment transport in the modelled scenarios, the bathymetries, discharge time series and wind regime for both the 2014 simulations and the 2006 simulations were analysed.

The difference in bathymetry was computed by subtracting the 2006 depth from the 2014 depth (both defined positive downwards), see Figure 5.1. Red colours indicate areas that are deeper in 2014 and blue colours indicate areas that are shallower in 2014. The largest differences are in the order of ±10 m and are located at sea and in the navigation channel. Differences at sea are mainly caused by bar migration, which is not expected to have a large effect on the model results. Differences at the navigation channel may have been caused by changes in the dredging activities and will have an important effect on the behaviour of suspended sediment around Antwerp harbour.

The river discharge is mainly dominated by the upper Scheldt river discharge at Merelbeke. Table 5.1 shows the average discharge of the upper Scheldt River at Merelbeke per year and per quarter for the 2006 and 2014 hydrodynamics simulations. On average the discharge in 2014 was 37.7 m^3/s, which is significantly higher than the average discharge of 27.6 m^3/s in 2006. Moreover, the seasonal distribution of the discharge over the year has shifted. Observations in 2014 showed a higher maximum discharge in Q1 and a higher minimum discharge in Q3 than in 2006 (Q2 and Q4 are more in the same order of magnitude as in 2006).

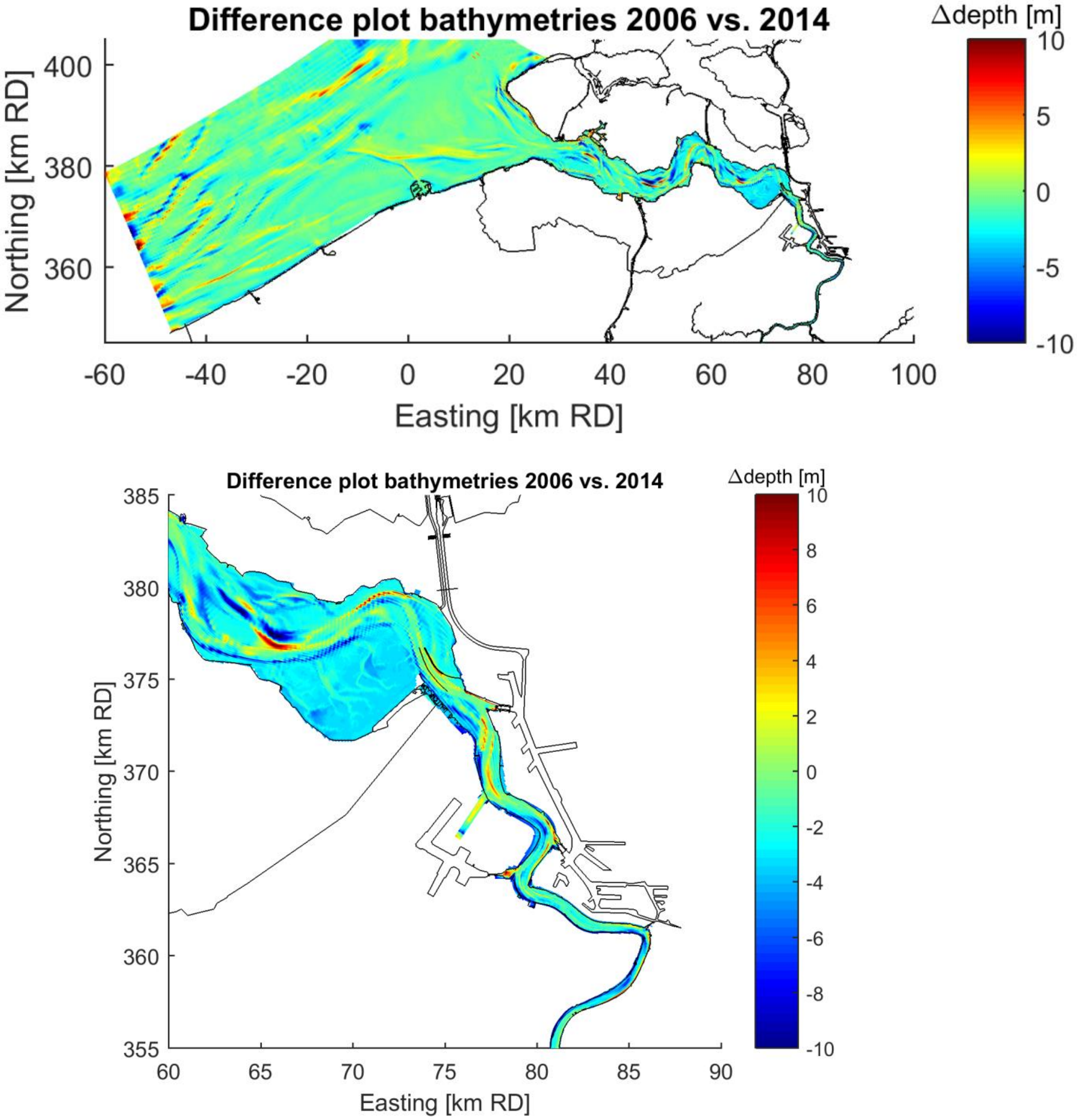

Figure 5.1 Comparison plot of bathymetry [m] 2006 and 2014: over the domain (upper panel) and zoomed at Antwerp harbour (lower panel). Red and blue colours respectively indicate areas that are deeper and shallower in 2014.

Table 5.1 Average discharge of the upper Scheldt river per year and per quarter for 2006 and 2014 hydrodynamics

Average discharge	**Yearly average** [m^3/s]	**Average Q1** [m^3/s]	**Average Q2** [m^3/s]	**Average Q3** [m^3/s]	**Average Q4** [m^3/s]
2006	27.6	44.3	30.8	13.4	22.0
2014	37.7	71.5	25.6	24.2	29.6

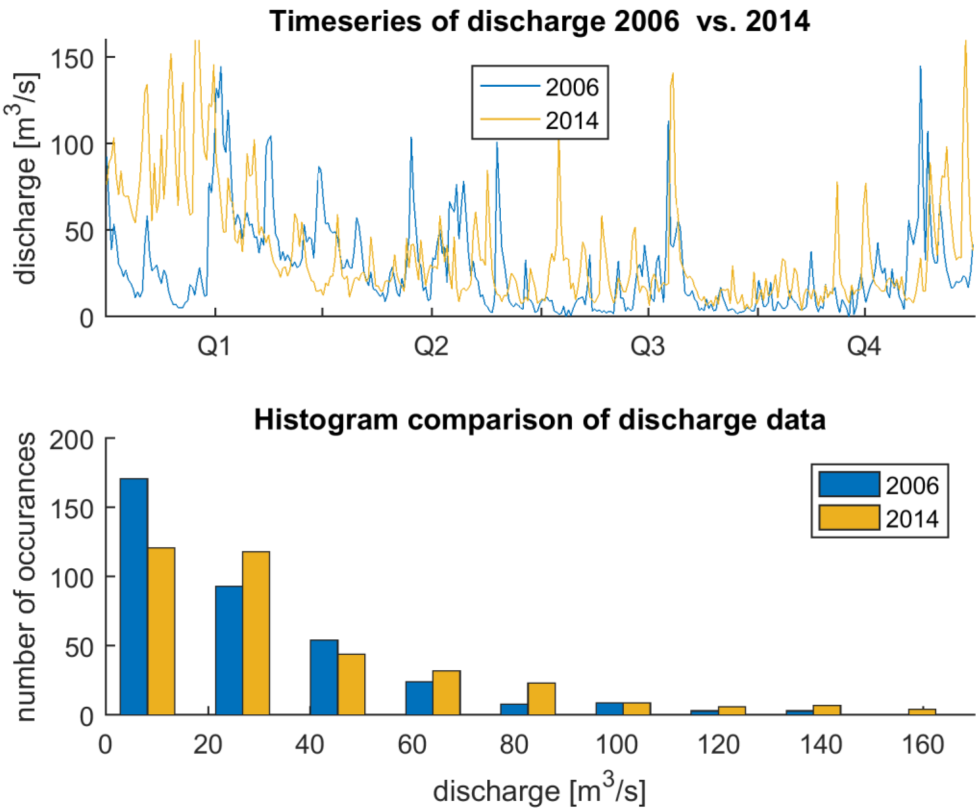

Figure 5.2 Comparison plots of discharge between 2006 and 2014: (a) as time series in the upper panel and (b) as histogram in the lower panel

The wind forcing in the LTV model was also updated for 2014 values, using the same hourly-average wind speed at station Vlissingen (station 310) as was used for 2006 data. The average wind speed was slightly larger in 2014 and fluctuations in wind speed were stronger, as can be seen from Figure 5.. The average wind speed throughout 2014 was 6.2 m/s with a standard deviation of 3.3 m/s (compared to an average of 5.9 m/s with a standard deviation of 2.9 m/s in 2006). Especially during the first quarter the wind speed was a lot higher with an average of 7.6 m/s in 2014 (compared to 6.1 m/s in 2006). This may result in more frequent strong winds that can have an important effect on the suspended sediment concentrations due to larger bed shear stresses (predominantly during the first quarter, which is the period simulated for LTV2015b model).

Table 5.3: Average discharge of the upper Scheldt river per year and per quarter for 2006 and 2014 hydrodynamics

Average wind speed	**Annual mean** [m/s]	**Average Q1** [m/s]	**Average Q2** [m/s]	**Average Q3** [m/s]	**Average Q4** [m/s]
2006	5.88	6.13	5.31	4.99	7.08
2014	6.18	7.59	5.07	5.12	6.93

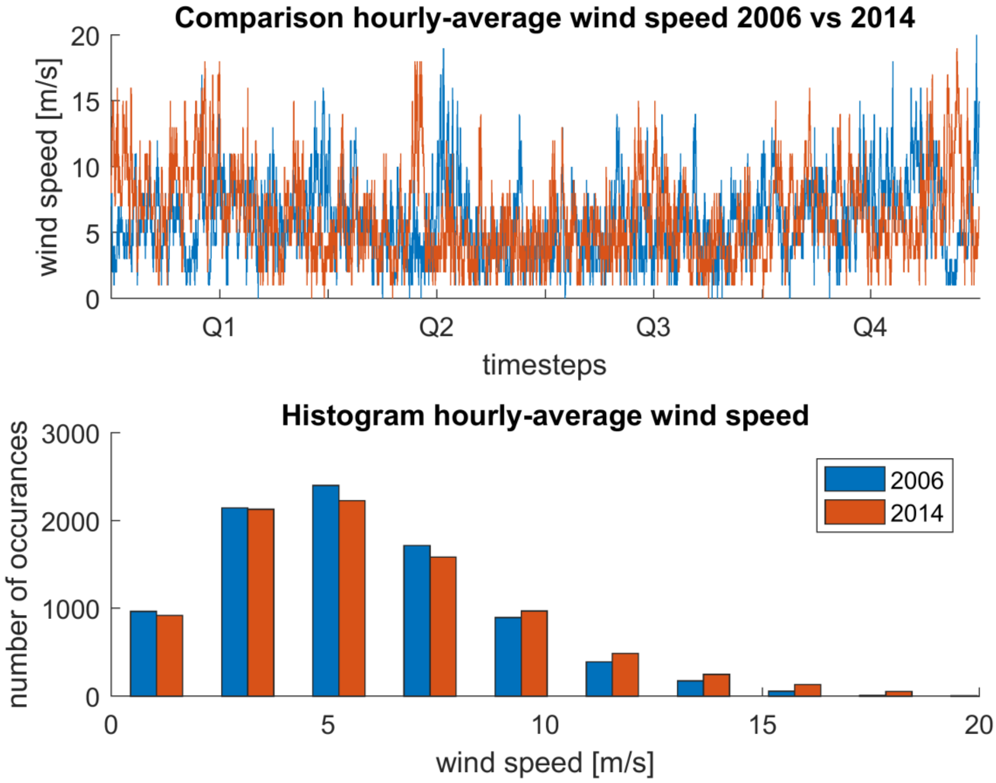

Figure 5.2 Comparison plots of wind speed between 2006 and 2014: (a) as time series in the upper panel and (b) as histogram in the lower panel

The abovementioned updates of the bathymetry, river discharge and the wind forcing have important consequences for the bed shear stress fields. The larger river discharge and increased wind forcing will cause an increase in bed shear stresses throughout the estuary and changes in the bathymetry may also locally affect the bed shear stress. The resulting difference between the annual mean bed shear stress is shown as a difference map plot in Figure 5.3. Blue colours indicate that the shear stress was larger for 2006 hydrodynamics, whereas red colours indicate larger shear stresses for 2014 hydrodynamics.

In general, it can be said that the shear stresses were larger for 2014 hydrodynamics as a result of the combination of the updated bathymetry, larger discharge and stronger winds. The biggest increases were found on the tidal flats in the Western Scheldt estuary and along the coast. However, for a few areas the shear stresses were smaller in 2014. This is the case at some locations in Antwerp harbour (amongst others near Deurganckdok harbour basin), where significant differences occurred in bed shear stresses (of ±1 Pa) for 2014 hydrodynamics. The updated bathymetry may be causing this change in bed shear stress around the harbour area, as the navigation channel was maintained for harbour activities. In general it can be said that the bed shear stress mostly decreased at locations that are deeper in 2014, whereas at locations that are shallower in 2014 the bed shear stress mostly increased.

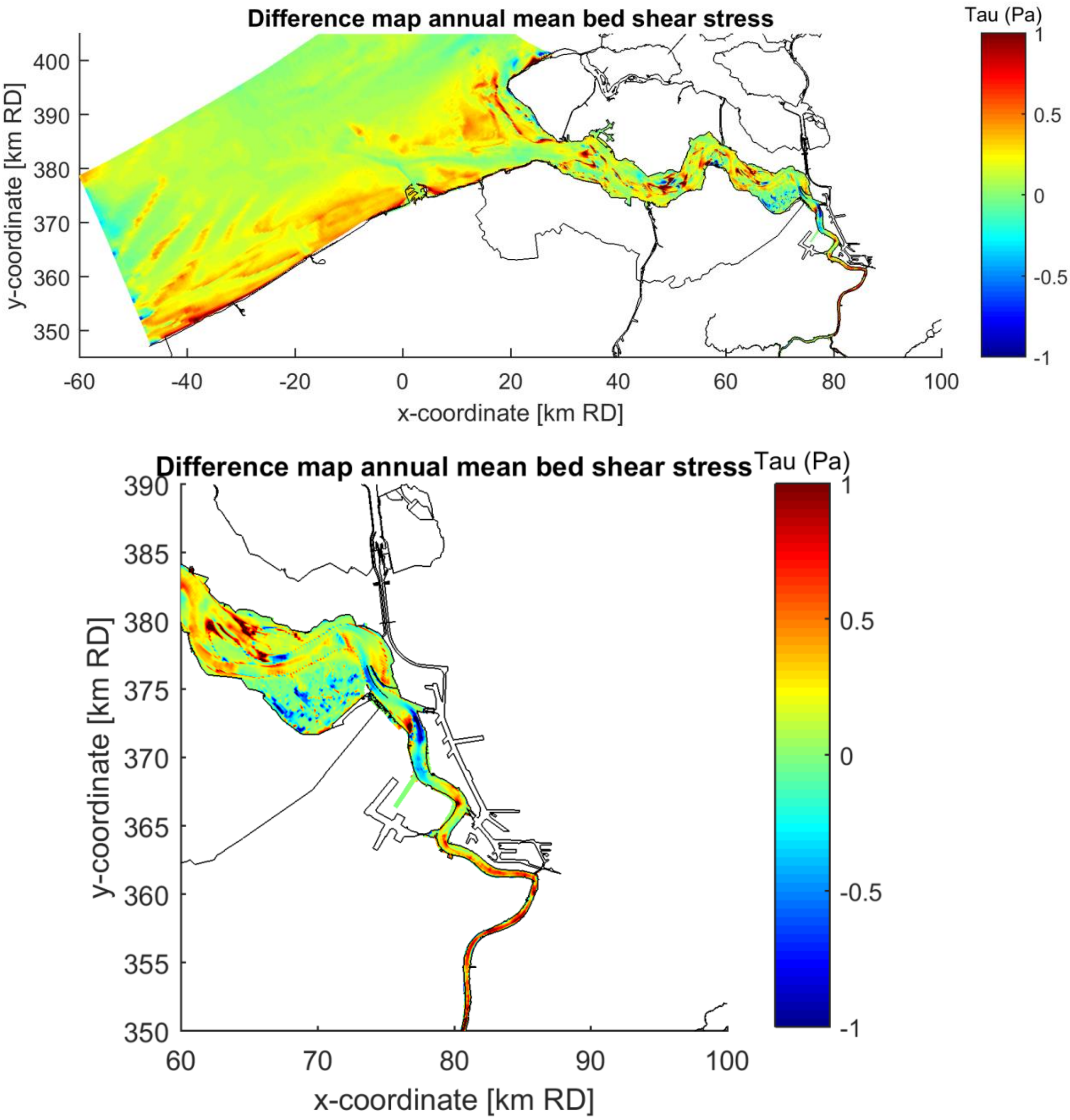

Figure 5.3 Comparison plot of annual mean bed shear stresses [Pa] as a difference map (bed shear stress 2014 – bed shear stress 2006) over the domain (upper panel) and zoomed at Antwerp harbour (lower panel). Red and blue colours respectively indicate areas with larger and smaller bed shear stress in 2014.

5.2 SPM concentrations

The following sections describe the results of the LTV model with settings of 2015b using the hydrodynamics of 2014. As there are no observations from 2014, these results are compared to observations from 2006 and to the previous model results (where the hydrodynamics of 2006 were used). Firstly, the SPM concentrations are described in this section. Figure 5.4 shows a comparison between the suspended sediment concentration observed in 2006 at station Boei 84 and modelled using hydrodynamics of 2014 (update of Figure 4.10). Over the tidal cycle the concentrations are mostly in the same order of magnitude, although near bed concentrations are slightly underestimated. The modelled peak in SPM that occurred two hours after HW does not correspond to the 2006 observations.. Note that this difference may be caused by the different years under consideration. Near the surface, on the other hand, the peak that was observed in 2006 is not found in the model (neither when using 2006 hydrodynamics, nor when using 2014 hydrodynamics). Also, the observed tidal asymmetry in SPM is not well reproduced by the model. According to the model ebb and flood concentrations are similar, whereas according to observations peak ebb concentrations are clearly higher than peak flood concentrations. This may be due to a lack of grid resolution, as in local models the asymmetry is better captured (Van Maren et al., 2011).

A comparison between the concentrations observed in 2013 at station WZ buoy just offshore of Zeebrugge and modelled using hydrodynamics of 2014 is given in Figure 5.5 (update of Figure 4.17). The model results for 2014 hydrodynamics (red line) are more in the same order of magnitude with the observed concentrations in 2013 than for the hydrodynamics of 2006 (green line), although the model results seem out of phase. Moreover, the statistical deviations (visualized by the coloured surface around the mean value) show that the model results have a lot more fluctuations over the tidal cycle than before.

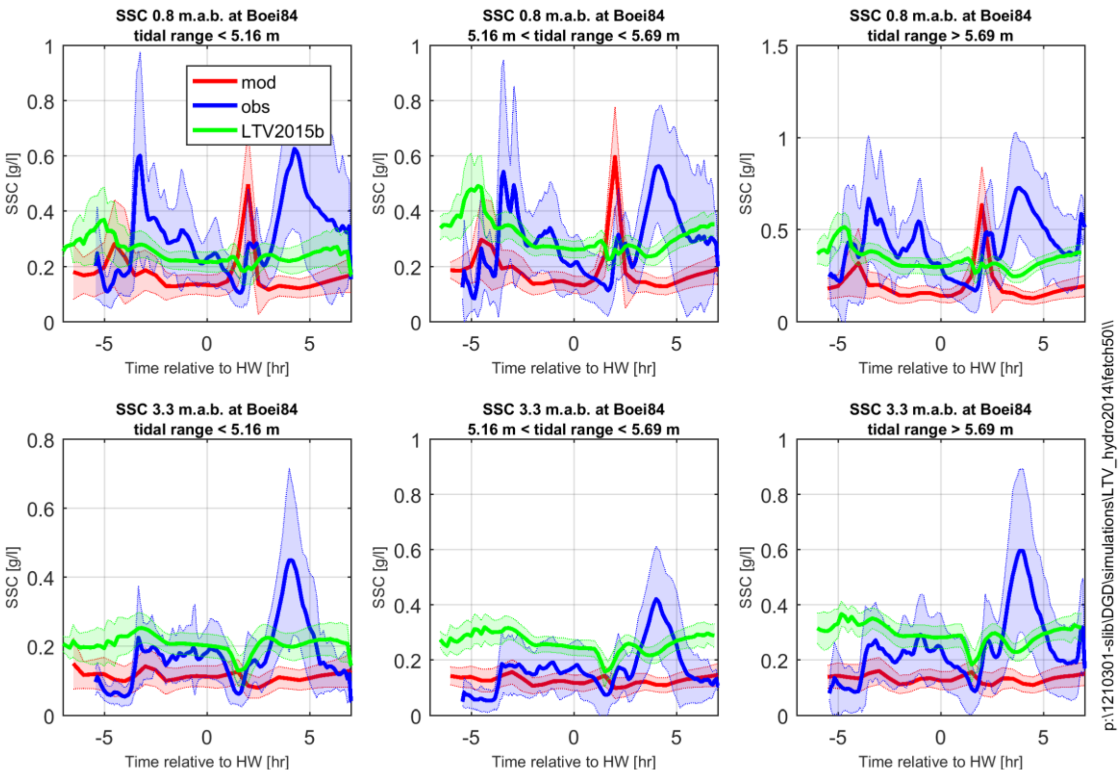

Figure 5.4 Suspended sediment concentrations at 0.8 m and 3.3 m above bed at station Boei 84: observed in 2006 (blue) and modelled using LTV model with 2014 and 2006 hydrodynamics (red and green respectively)

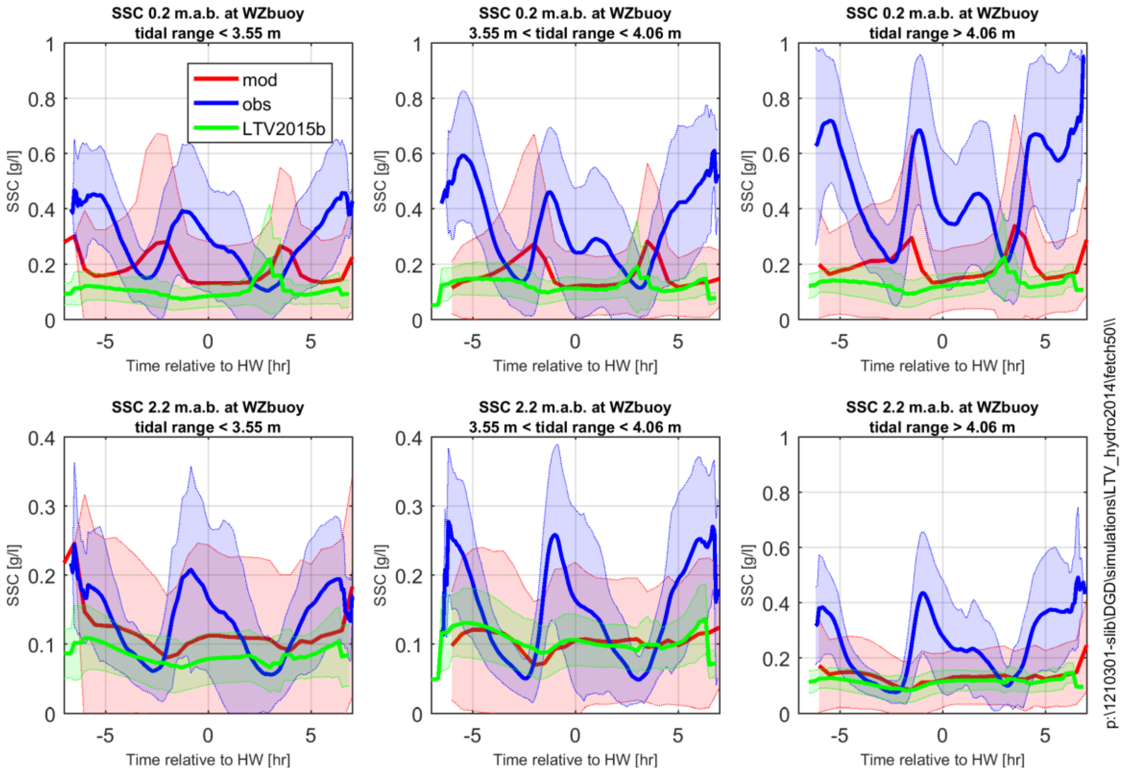

Figure 5.5 Suspended sediment concentrations at 0.2 m and 2.2 m above bed at station WZ buoy (just offshore of Zeebrugge): observed in 2013 (blue) and modelled using LTV model with 2014 and 2006 hydrodynamics (respectively red and green)

Figure 5.6 and Figure 5.7 show the annual mean concentration near the surface and near the bed (respectively). These can be compared to the results of LTV2015b model in Figure 4.11 and Figure 4.12 Table 5.1 summarizes representative concentrations for some important locations. Upstream the concentrations decreased slightly to around 110-130 mg/L at the surface and around 150-180 mg/L near the bed in 2014. Around Deurganckdok the surface concentrations decreased strongly to about 110-130 mg/L (instead of 240-280 mg/L for hydro 2006). Near-bed concentrations are also lower around 200-300 mg/L.

In the Westerschelde estuary the average surface concentration was slightly larger (55-65 mg/L) and near-bed concentration increased significantly from 50-90 mg/L (hydro 2006) to 120-190 mg/L (hydro 2014). The spatial gradients between the channel and the tidal flats are now much more pronounced. In the mouth the concentration has increased slightly, especially near the bed (110-140 mg/L).

Table 5.1 Comparison of concentrations in LTV model with hydrodynamics of 2006 and hydrodynamics of 2014. All concentrations are denoted in mg/L

Jaar	Depth	Mouth	Tidal flats	Near DGD	Upstream river
2006	Surface	40 – 60	40 – 55	240 – 280	160 – 200
	Near-bed	60 – 80	50 – 90	~300	200 – 250
2014	Surface	60 – 80	55 – 65	110 – 130	110 – 130
	Near-bed	110 – 140	120 – 190	200 – 300	150 – 180

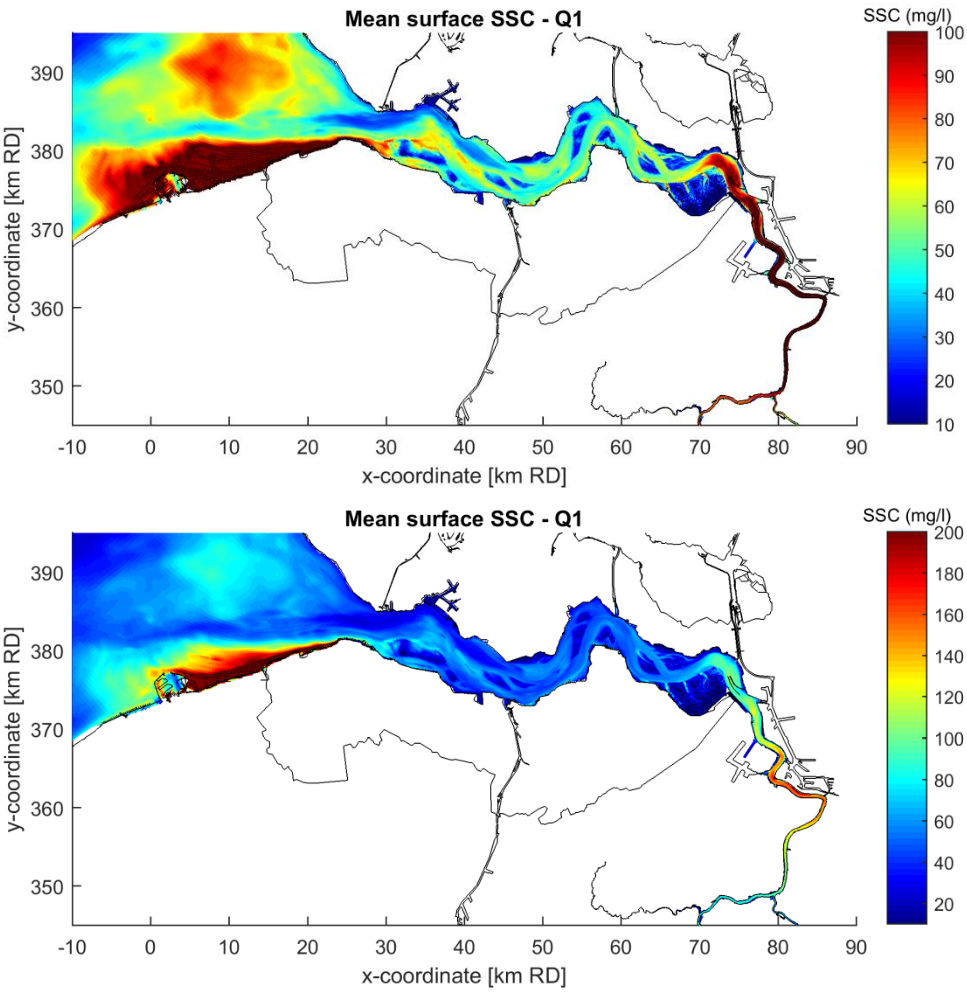

Figure 5.6 Near surface annual mean SPM concentrations for the LTV mud model with 2014 hydrodynamics (upper figure with colour scale 0-100 mg/L; lower figure with colour scale 0-200 mg/L)

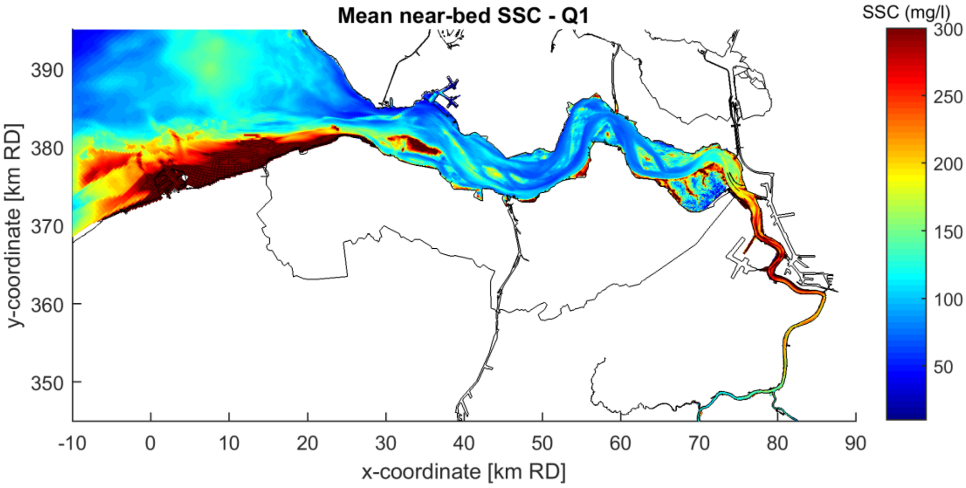

Figure 5.7 Near bed annual mean SPM concentrations for the LTV mud model with 2014 hydrodynamics with colour scale 0-300 mg/L

These differences in suspended sediment concentrations can largely be explained by the differences in bed shear stresses (as an effect of the stronger wind in 2014). At locations where the shear stress was larger (i.e. on the tidal flats in the Western Scheldt estuary and along the coast), the concentration increased. At locations where the shear stress was smaller (e.g. around the Antwerp harbour) the concentration decreased. Moreover, the discharge was larger, thus the Sea Scheldt is flushed. Hence, suspended sediment concentrations went down in the Sea Scheldt and up in the Western Scheldt.

In general, the resulting suspended sediment concentration has a smaller up-estuary gradient in horizontal direction. The vertical sediment concentration gradient, i.e. the difference between surface and near-bed concentration, increased throughout the estuary.

5.3 Mass balances

Figure 5.8 shows sediment exchanges (net and gross) in ktons/year between the different areas for hydrodynamics of 2014 similar to Figure 4.19 and Figure 4.20 in section 4.2. The balances show a net export from the Schelde to the Zeeschelde, the Zeeschelde to the Westerschelde and on to the North Sea, as for both LTV2010 and LTV2015b. The main difference between the mass balances is the strong decrease in the gross exchanges between Westerschelde, Zeeschelde and Schelde, due to the computed lower sediment concentration levels near Antwerp for hydrodynamics of 2014. Note that the gross exchange between North Sea and Western Scheldt have increased, which is caused by the higher sediment concentration levels near the river mouth for hydrodynamics of 2014.

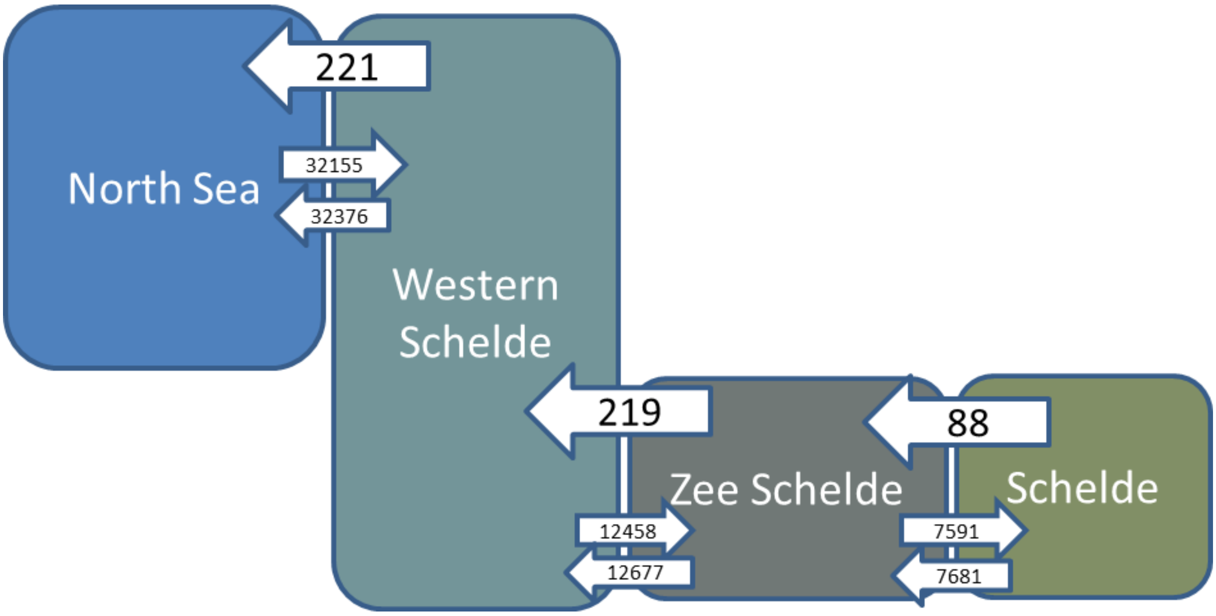

Figure 5.8 Sediment exchange in ktons/year (net and gross) for hydrodynamics of 2014

5.4 Siltation in harbours and ports

Another indicator of model performance is the amount of siltation occurring in the harbours and docks of Terneuzen, Zeebrugge, Deurganckdok and Vlissingen and the intertidal mudflats of Hansweert in The Netherlands and the Zeeschelde mudflats in Belgium. Table 4.2 shows the amount of siltation at different harbours/docks in megatons per year for each simulation compared to estimates based on actual or permitted disposal volumes. It should be noted that the model simulations of LTV2010 and LTV2015 were only 3 months long (January-April), so these yearly siltation rates were extrapolated (they are not exactly representative of yearly forcing conditions, but provide an indication whether the model is reproducing siltation rates in the right order of magnitude). Siltation rates for hydrodynamics 2014 are in the right order of magnitude at some locations (e.g. Braakman) but underestimated at other locations such as DGD and Zeebrugge.

Table 5.2 Yearly siltation (megatons per year) in the harbours for additional model simulations.

Model Run	Braakman	DGD	Kallo	Sloeh	Terneuzen	Zandvliet	Zeebrugge
Estimates	0.8	2	-	0.6	0.25	-	3.1
LTV2010	0.2	0.1	0.4	0.03	0.12	0.12	1.5
LTV2015a	0.1	2.7	0.8	0.1	0.2	0.3	0.5
LTV2015b	0.2	2.6	1.	0.2	0.3	0.9	1.2
LTV2015c	0.1	1.8	0.7	0.2	0.2	0.8	1.0
Hydro 2014	**0.8**	**0.68**	**0.32**	**0.1**	**0.09**	**0.44**	**1.1**

Table 4.3 shows the same yearly siltation parameter on the intertidal flats. The siltation rate on the intertidal flats of the Western Scheldt has decreased quite significantly. Note, once again, that for LTV2010 and LTV 2015 models the yearly siltation was extrapolated based on the first quarter of the year, whereas for hydrodynamics of 2014 the entire year was modelled. Also note that the model removes all sedimentation on mud flats exceeding a mass per unit area of 184 kg/m2 (which is equivalent to a thickness of about 0.2 to 0.4 m depending on the assumed density of the deposits), placing it back elsewhere in the model to prevent excessive accumulation of sediments within one segment. Therefore the amount of sediment that was moved by this criterion should be added to the total sedimentation found in the model results to obtain the amount of sediment that actually deposited on the tidal flats throughout the simulation.

Table 5.3 Yearly accretion rates (megatons per year) on the intertidal flats for additional model simulations

Run	Western Scheldt	Sea Scheldt	Combined
Estimates	0.2	0.1	0.3
LTV2010	0.13	0.12	0.25
LTV2015a	0.01	0.8	0.8
LTV2015b	0.07	0.42	0.49
LTV2015c	0.05	1.04	1.1
Hydro 2014	**0.0005**	**0.22**	**0.22**

6 Discussion and Conclusions

The LTV mud model was developed over the period 2006-2010 and used to test several scenarios for dredging and dumping studies, including the relocation of several dump sites and changes in discharge scenarios. However, no further developments on the LTV mud model have been carried out since 2010 and since then there has been knowledge development, new suspended sediment data collected and the development of other models covering similar domains.

The work reported here described an update of the LTV mud model with the objective to align the model settings with SPM model developments and improvements in the Western Scheldt mouth, North Sea and Wadden-Ems area since 2010. The second objective was to compare the model results with recent measurements and if possible improve the suspended sediment concentrations, their intra-tide variability and siltation rates in intertidal areas with respect to the 2010 version of the model. The updated settings lead to an improvement in the simulation of sediment dynamics both offshore and in the Scheldt estuary.

The updates implemented focussed on the sediment transport model (Delft3D-WAQ) model only. The hydrodynamic forcing of these simulations remained the same as for the LTV2010 model. This update includes both grid and hydrodynamic improvements in the Upper Sea Scheldt and an update of the bathymetry and boundaries to 2014 conditions. Several sensitivity tests were performed and parameters such as the settling velocity, critical shear stress for erosion and erosion parameters were modified in order to a) increase the levels of suspended sediment near the bed and in the water column, b) improve the intra-tidal variability in suspended sediment concentrations and c) to improve the sedimentation rate over the intertidal flats.

The new settings and the addition of one or even two coarser fractions resulted in improved levels of suspended sediment concentrations both up estuary near the estuary mouth (Zeebrugge) but intra-tidal variability, though improved, is still less than seen in the measurements.

Siltation rates in the harbours and docks are also in the right order of magnitude and the sedimentation rates on the intertidal flats show a mixed picture: underestimated in the Western Scheldt and overestimation in the Sea Scheldt.

The essential differences between the update model and the 2010 model are:

1. Switching from a single-fraction to multiple-fraction model including faster settling particles. This enhanced turbidity levels near the bed and in local turbidity maxima;
2. Enhancing the (gross) vertical sediment exchange between the water column and the seabed. This enhanced the influence of settling and erosion lag effects on residual transport.

It is noticed that the process formulations did not change.

It is recommended to study (both in-situ and with the SPM-model) the residence time of mud in the estuary and the mud stock on the bed (both in the channels and on the flats) available for resuspension as a function of time (e.g. neap-spring cycle, during low and high river discharge, seasonal and annual trends).

Update to 2014 hydrodynamics
When updating the model with 2014 hydrodynamics the concentrations around the Antwerp harbour decreased, whereas concentrations in the river mouth increased. This results in a weaker up-estuary sediment concentration gradient.

The sediment concentration is a result of the equilibrium between several forcings and processes. The most important ones that play a role here are the hydrodynamic forcings (tides, waves and river discharge) and the human interventions (dredging and dumping). For 2014 hydrodynamics:

- the bathymetry was updated: the entrance channel of the Antwerp harbour was deepened by dredging activities, leading to a decrease in bed shear stress and hence lower suspended sediment concentration;
- the (fresh) river discharge increased significantly, pushing the estuarine turbidity maximum further towards the river mouth (as well as causing a stronger vertical concentration gradient);
- the wave forcing increased, which causes more resuspension of sediments, particularly near the river mouth;

The combined influence of these hydrodynamic forcings results in a weaker up-estuary sediment concentration gradient in horizontal direction, as well as a downstream shift of the estuarine turbidity maximum.

Note that the parameter settings for dredging and dumping were the same for 2006 and 2014 hydrodynamics, but that does not mean the influence of these interventions is identical (for example all sediment that deposits in harbour basins is placed back in the model domain).

Since the model has been updated to hydrodynamics of 2014, it is recommended to make a direct comparison between computed and observed SPM levels for the year 2014.

7 References

Arentz L., V. Harezlak, T. van Kessel, T. van der Kaaij (2012). Kalibratie slibtransport- en GEM-model. Deltares report 1205620, Delft, The Netherlands.

Cronin, C. and M. Blaas (2013). MoS2-II Deterministic Model Calibration: Updates of the ZUNO-DD Hydrodynamic and SPM model. Deltares report 1204561-000-ZKS-0025, Delft, The Netherlands.

Chu, K.; Vanlede, J. Decrop, B.; Verwilligen, J.; Mostaert, F. (2017). Update snelheidsvelden Zeeschelde en Sluistoegangen: Technical Report. Version 2.0. FHR Reports, 00_081_1. Flanders Hydraulics Research: Antwerp.

Duren L.A. van; T. van Kessel; A.G. Brinkman; A. de Kluijver; F. Fey; C.A. Schmidt (2015). Verkenning Slibhuishouding Waddenzee: een samenvatting van twee jaar modelleren en kennis verwerven. Deltares en IMARES Wageningen UR.

Kessel, T. van, J. Vanlede, M.A. Eleveld, D. van der Wal (2008). Mud transport model for the Scheldt estuary in the framework of LTV. Deltares report Z4594, Delft, The Netherlands.

Kessel, T. van, J. Vanlede (2009). Impact of harbour basins on mud dynamics Scheldt estuary in the framework of LTV. Deltares & FHR report 1200253, Delft, The Netherlands.

Kessel, T. van, J. Vanlede, M.A. Eleveld, D. van der Wal, B. De Maerschalck (2010). Validation and Application of Mud Model Scheldt Estuary in the framework of LTV. Deltares & FHR report 1202021, Delft, The Netherlands.

Kessel, T. van, J. Vanlede, J.M. de Kok (2011). Development of a mud transport model for the Scheldt estuary. Continental Shelf Research 31 S165–S181 DOI: 10.1016/j.csr.2010.12.006.

Maren, D. S. van, J. C. Winterwerp, Z. B. Wang, B. Decrop, and J. Vanlede (2011). Predicting the effect of a Current Deflecting Wall on harbour siltation. Cont. Shelf Res. 31, S182–S198.

Maren D.S. van; J. Vroom; L. Sittoni; T. van Kessel; K. Cronin; L. Arentz (2014). Mud dynamics in the Ems-Dollard, phase 2: setup sediment transport models. Deltares report no. 1205711, Delft, The Netherlands.

Vroom J., D.S. van Maren, J. van der Werf, A. van Rooijen (2016). Zand-slib modellering voor het mondingsgebied van het Schelde-estuarium. Deltares report 1210301-002, Delft, The Netherlands.