Modelling Cohesive Sediments in the Scheldt Estuary (Belgium) with SEDI-3D

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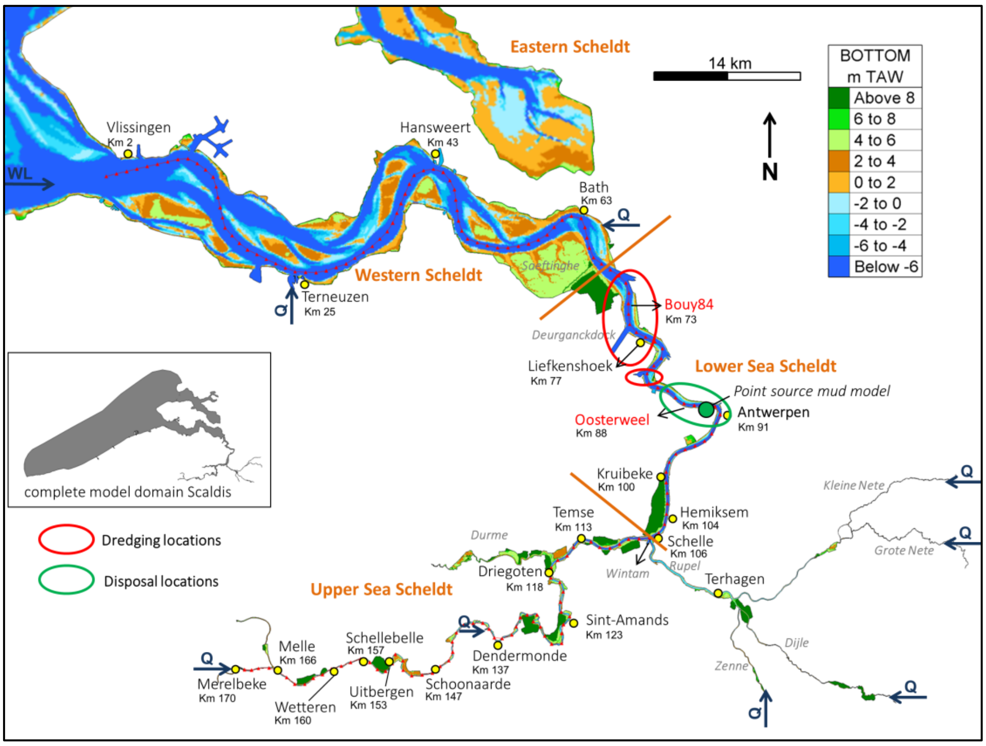

Figure 1- general overview of model domain and Scheldt estuary

***Abstract*—A new cohesive sediment transport model for the Scheldt Estuary is presented in this paper. The model is built in SEDI-3D, which itself is part of the TELEMAC-3D code. The 3D hydrodynamic Scheldt model, Scaldis, was used for hydrodynamics. One fraction of fine sediments is modelled as a tracer. The results show good agreement with point measurements and with estimated transport rates and directions. However the local turbidity maximum is dependent on a local sediment source and a fix for excessive deposition of mud in shallow areas needs a more elegant solution.**

I. Introduction

The implementation of the Seine-Scheldt connection will result in increased shipping traffic between France and Flanders. The Flemish Government wants to improve the navigability of the Upper Sea Scheldt. Within this framework, an integrated plan is being developed, in which navigability, safety and nature are the key elements.

At the moment, the upstream part of the Upper Sea Scheldt is a Class IV fairway (ships up to 85m long and 9.5m wide) and forms a bottleneck in the European network. The questions that need to be answered within the integrated plan pertain to the measures that need to be taken to upgrade the Upper Sea Scheldt to a Class Va fairway suitable for ships up to 2250 tons (ships up to 110m long and 11.4m wide), with respect for the other functions (safety, nature and recreation). It is of the utmost importance that the design of the morphological changes in the Upper Sea Scheldt leads to a multifunctional Scheldt Estuary with assets for navigability, guarantees for protection against flooding and a sustainable natural system.

A chain of models will be used to evaluate the different morphological scenarios. The mud model described in this paper is a part of that model chain. Cohesive sediments play a key role in aquatic ecosystems like the Scheldt estuary. They determine light penetration into the water column and hence affect the primary production. They determine the layers of the bed supporting benthic life and the sediment's organic content forms food supply to filter feeders. Therefore the behavior of these cohesive sediments is important in the assessment of the impact of changes in bathymetry or management of the estuary and for this project, the Upper Sea Scheldt in particular. Results of the mud model will be used as input for models of project partners, e.g. cohesive sediment concentrations affect light penetration and this will affect algae growth, which is modeled in an ecosystem model of the University of Antwerp [1].

An existing mud model for the Scheldt Estuary was already developed in the framework of the Long Term Vision for the Scheldt estuary. This model was developed in DELWAQ [2, 3, 4, 5]. This model runs autonomous, but gets a spring/neap tidal cycle from a hydrodynamic model (SIMONA) as input and this input is repeated the longer the simulation time is set.

Within the integrated Plan Upper Sea Scheldt a 3D hydrodynamic model of the Scheldt Estuary was developed, named "Scaldis", in TELEMAC-3D. The model is described in detail in [6, 7, 8]. When coupling the hydrodynamics of this TELEMAC-3D model with DELWAQ it was not possible to simplify the model grid and decrease the number of computational nodes of the hydrodynamic model (which is possible in linking a SIMONA model with DELWAQ). This resulted in serious time constraints for running a simulation because DELWAQ could not run on multiple processors at that time and therefore a new mud model was made using SEDI-3D code that was already present within the TELEMAC-3D code.

In developing a new mud model in SEDI-3D some goals were set to reach a good quality model. The mud model should represent:

- the observed global spatial suspended sediment concentration (SSC) distribution, like the location of an estuarine turbidity maximum (ETM);
- a good intra-tidal SSC variation;
- a good spring/neap SSC variation;
- an overall mass balance in equilibrium;
- a good response to higher river discharges;
- good siltation rates of intertidal areas and salt marshes in the order of 1-2 cm/year, and siltation rates of harbor and docks according to dredging volumes.

II. TELEMAC-3D HYDRODYNAMIC MODEL: SCALDIS 3D

This chapter will briefly describe the TELEMAC-3D model, Scaldis 3D, which is presented in full detail in [6]. The model domain contains the Belgian coastal zone, extended to France in the South and The Netherlands in the north, the Eastern and the Western Scheldt in the Netherlands and the Sea Scheldt with its tributaries as far as the tidal influence reaches. The mesh resolution increases from 500 meters in the coastal zone to 120 meters in the Western Scheldt, to 60 meters in the Sea Scheldt further increasing upstream towards 5 meters at the upstream discharge boundaries. The horizontal grid contains 459,692 nodes. In the vertical there are five layers following a sigma transformation (0, 0.12, 0.30, 0.60 and 1). The bathymetry is interpolated from multi-beam measurements and lidar data for the shallow areas. Water level time series are imposed on the sea boundary and daily averaged discharges are imposed on 8 upstream liquid boundaries. Wind is assumed to be incorporated into the water level boundary downstream and is not taken into account further. The model was calibrated using a spatial varying Manning bottom friction coefficient. The friction coefficient varies from 0.026 $s/m^{1/3}$ in the downstream part and decreases to 0.014 $s/m^{1/3}$ in the upstream river part. Salinity is present as an active tracer and density effects are taken into account. The mixing length model of Nezu and Nakagawa is used for the vertical turbulence modelling. The horizontal turbulence model is the Smagorinski model. Tidal flats are present and equations are solved and corrected on tidal flats. Coriolis is taken into account.

III. SEDI-3D MUD MODEL: SCALDIS MUD

A. Theoretical background

Cohesive sediment transport occurs in water through the combination of advection and diffusion. In SEDI-3D, a 3D advection-diffusion equation is solved by considering the cohesive sediment particles moving at the same velocity as the fluid:

$$\frac{\partial C}{\partial t} + U_j \frac{\partial C}{\partial x_j} = \frac{\partial}{\partial x_i}\left(\frac{\nu_t}{\sigma_t}\frac{\partial C}{\partial x_i} + w_s C \delta_{i3}\right) \qquad (1)$$

In this equation U is the mean flow velocity [m/s], t is the time [s], x_j represents the components of the coordinate vector [m], ν_t is the eddy viscosity [m2/s], σ_t is the turbulent Prandtl-Schmidt number (i.e. the ratio of ν_t to the eddy diffusivity of the sediment particles), C is the sediment concentration [g/L or kg/m³], w_s is the representative mean settling velocity [m/s], and δ_{ij} is the Kronecker delta.

At the interface between the water column and the bed layer, erosion processes happen due to the shear motion of the flow. The erosion flux is computed with the Partheniades formula. The erosion flux is the product of an erosion rate multiplied with a probability factor as a function of the shear stress in excess of a critical erosion shear stress:

$$E = \begin{cases} M\left(\frac{\tau_b}{\tau_{ce}} - 1\right) & if\ \tau_b > \tau_{ce} \\ 0 & otherwise \end{cases} \qquad (2)$$

with M the Krone-Partheniades erosion constant [kg/m²/s], τ_b the bed shear stress and τ_{ce} the critical bed shear stress for erosion. So erosion only occurs when the bed shear stress is higher than the critical bed shear stress for erosion set by the user. The erosion constant M determines the intensity of the erosion. A larger value will mean more erosion if erosion occurs. The bed shear stress is given by:

$$\tau_b = \rho_w u_* |u_*| \tag{3}$$

with ρ_w the density of the water and u_* the friction velocity. In SEDI-3D, a quadratic friction law is used with a drag coefficient C_D to compute τ_b in a rough regime. When a Manning coefficient is used the equations look as follows:

$$\tau_b = \frac{1}{2}\rho_w C_D \overline{U}|\overline{U}| \tag{4}$$

With:

$$C_D = 2n^2 \frac{g}{h^{1/3}} \tag{5}$$

Where $\overline{U}$ is the depth-averaged velocity (which is also calculated in SEDI-3D), n is the Manning coefficient, g is gravitational constant and h is the water depth. After the calculation of this shear stress, the shear velocity is calculated and is then imposed at the bottom as a boundary condition for solving the momentum conservation equations of the flow.

The empirical deposition law from Krone is implemented in SEDI-3D to estimate sediment deposition. Here the deposition flux is approximated by the product of local sediment concentration with the settling velocity, multiplied with a deposition probability:

$$D = \begin{cases} w_s C\left(1 - \frac{\tau_b}{\tau_{cd}}\right) & if\ \tau_b < \tau_{cd} \\ 0 & otherwise \end{cases} \tag{6}$$

Where τ_{cd} is the critical shear stress for mud deposition , w_s is the settling velocity [m/s], and C is the sediment concentration in suspension [g/L] or [kg/m³]. If the bottom shear stress is smaller than the critical bottom shear stress for deposition, sediment is settling. Within this project the choice was made to model deposition D as a shear stress independent flux, following [10] and [11]. This is also in line with recent applications in modelling cohesive sediment transport [12, 13]. This is done by setting τ_{cd} to a large value of 1 000 Pa. The formula for the deposition flux, equation 6, then simplifies to:

$$D = w_s C \tag{7}$$

The bed evolution in SEDI-3D is calculated via the Exner equation:

$$(1-\lambda)\frac{\partial z_b}{\partial t} + (E - D) = 0 \tag{8}$$

where λ is the bed porosity and z_b is the bed level.

B. Parameter choices

In this version of SEDI-3D (V7P2r1) only one fraction of cohesive sediment can be modelled. Based on [14, 15, 16] a characteristic mud particle diameter of 50 µm and a settling velocity of 0.5 mm/s was chosen. The sediment density was set to 2650 kg/m³. Flocculation and hindered settling were not taken into account. Only one bed layer was chosen and this bed layer is initially empty. If mud deposits in this layer, the mud layer density was set to 500 kg/m³. The critical shear stress for erosion was set to 0.05 Pa and the erosion coefficient was set to 1.0E-4 kg/m²/s. These last two parameters are calibration parameters.

C. Boundary conditions

A simulation period of 42 days was chosen: two days for the hydrodynamic spin-up, 20 days for sediment spin-up and 20 days actual sediment run. The downstream water level boundary represents measured water levels from 29/07/2013 - 07/09/2013. The upstream discharges are kept constant with a long yearly averaged value and an rain event of five days, represented in the discharge time series as an event with a return period of 1/6.

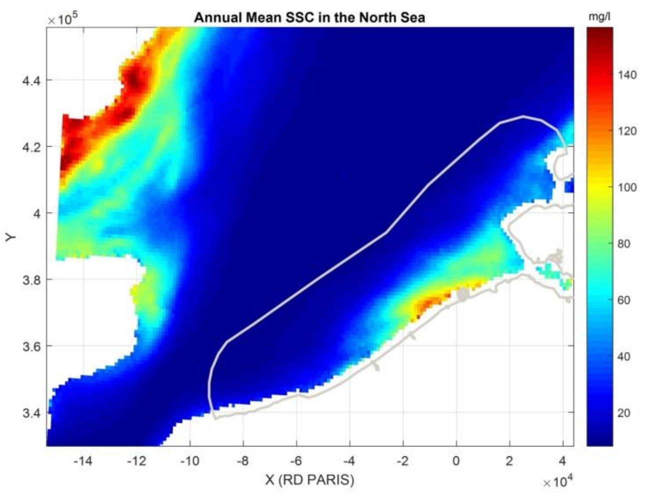

Figure 2 - Annual mean SSC in the North sea with the location of the Scaldis model sea boundary (source: KBIN – OD Natuur)

A constant sediment concentration is given to every liquid boundary. This concentration for the discharge boundaries represents the average annual total sediment load for the period 1971-2009 calculated by [17]. The order of magnitude of the contribution at each boundary varies between 0.04 g/L for the smallest tributary and 0.1 g/L for one of the larger upstream tributaries. For the downstream boundary satellite images were used from [18] (see Figure 2). The concentrations vary in space along the boundary, but one value was chosen, i.e. 0.013 g/L, for the entire downstream boundary because this boundary is far from the zone of interest of the project, i.e the Upper Sea Scheldt (see Figure 1).

The bottom layer is empty. The Bottom friction coefficient has a direct effect on the calculated shear stresses (equation 4). Normally the bottom friction coefficient of the hydrodynamic model is used for the calculations of the shear stresses for SEDI-3D, but since the spatial varying Manning bottom friction coefficient is the result of a calibration process and when calibrating it corrects more than only a different bottom friction in different parts of the estuary. In the Scaldis model unnaturally low Manning bottom friction values (see Figure 3) had to be used to get the water motion correct in most upstream locations of the model. Therefore the subroutine clsedi.f was changed so that for the sediment model only a constant Manning bottom friction coefficient of 0.02 s/m$^{1/3}$ was used.

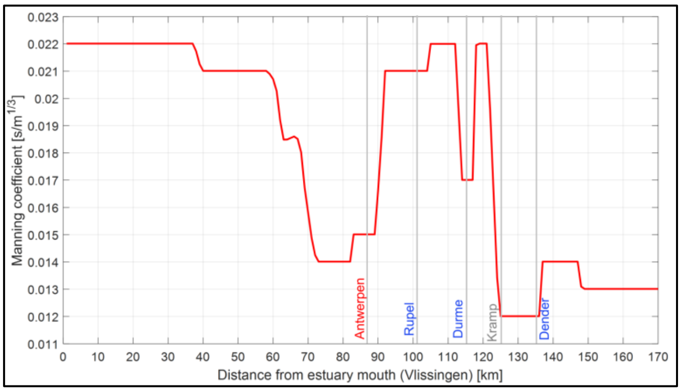

Figure 3 - Manning bottom roughness coefficient of Scaldis 3D 2013 along the estuary axis.

D. Initial conditions

A model simulation of two days is used to spin-up the hydrodynamics. This previous computation file is used to start a new 40 day simulation with sediment. The bed layer is empty at the start. Cohesive sediment is initiated in the water column as a concentration of 0.5 g/L. A sensitivity analysis showed that initialising a simulation with the same amount of sediment on the bed will give a similar result in an equilibrium situation. Putting an unlimited supply of sediment on the bed (bed layer with thickness of 100 m as default) gave much better results for SSC, but the erosion rates on the bottom were unrealistically high. Therefore it was chosen to initiate sediment in the water column as a concentration.

E. No feedback to hydrodynamic model

To keep the parallel with DELWAQ, the sediment module does not update the bottom of the hydrodynamics part. In the subroutine fonvas.f this update is commented. Also the effect of SSC on the water density is turned off in the subroutine drsurr.f by eliminating the sediment contribution to the relative density.

F. Reduced settling velocity in shallow areas using a logistic function

When the critical deposition shear stress is very high equation 6 becomes equation 7 and settling velocity is constant over the entire model domain. The first simulations showed that a lot of sediment is captured in shallow areas. In these areas deposition occurs, but the shear stresses are too low to bring sediment back into suspension, making these shallow areas sediment traps. Therefore a logistic function was added to equation 7 under the form of an alpha:

$$D = \alpha\, w_s\, C \tag{9}$$

with

$$\alpha = \frac{1}{1+e^{-k(d-d_0)}} \tag{10}$$

Where d is the water depth, d_0 is the water depth below which a significant reduction will take place and k determines the steepness of the slope in reducing alpha from 1 to 0. With k = 5 and d_0 = 1.5 m and 3.0 m two example are given in Figure 4.

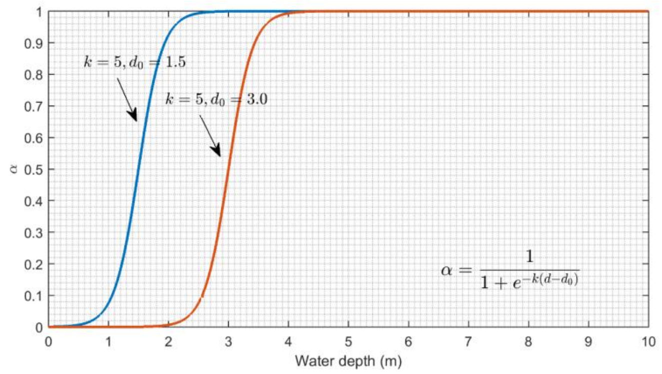

Figure 4 - sigmoid (logistic) curve alpha α in function of water depth.

For the mud model d_0 = 1.5 m proved to be very successful in keeping shallow areas becoming sediment traps. This alpha was added to the settling velocity calculated in the subroutine vitchu.f.

G. Dredging and disposal flux

As a first approximation of dredging and disposal of sediment, the total disposal flux of sediment is added as a point source of sediment to the simulation. The magnitude of the sediment concentration of this point source is determined based on reported disposals in recent years (2007-2015) [19]. On average 4.5 million tons dry solids (TDS) are deposited back in the estuary each year. In the Scaldis model a point source is added with coordinates (RD Paris): x=83430 m and y=361424 m The sediment is released with a discharge of 0.1 m³/s and a concentration of 1441.53 g/L at -6 m TAW (Belgian reference level, where 0 m TAW corresponds to low water at the sea at the Belgian coast). This corresponds to a release of 4.5 million tons TDS per year. Because the bottom is not update to the hydrodynamics, no effort is done to dredge sediment from the estuary. The point source is located near the actual disposal sites in the estuary (big green dot in Figure 1).

IV. RESULTS

A. Spin-up time sediment

Using pure S2 harmonic boundary conditions for the water levels (programmed in subroutine sl3.f as SL3 = 1.89D0 * SIN(AT * (2.D0 * PI/43200.D0) + (PI/2)) + 2.68D0) and constant discharges upstream the sediment was initialised in the model on the bed for one simulation and the same amount of sediment was initialised in the water column as a concentration in another identical simulation. The mass balance is plotted in Figure 5. The results show that both simulations tend to go the same solution and that after two days already both solutions come together. After 20 days the sediment in both simulations reaches a kind of equilibrium condition. This setup also shows that the closer to the final solution a simulation is started, the shorter the spin-up time needs to be.

B. Ensemble analysis

At three locations in the estuary SSC continuous point measurements are done. The measured values are compared with model results by performing an ensemble analysis. Every tide separately within a 14 day period is analysed for water level and SSC and time is expressed as hours relative to high water level. For every hour before and after (relative) high water average SSC concentrations with an uncertainty band are determined and plotted. This is done for the measured time series and the model results. In this way the time period of the measurement does not to coincide with the time period of the simulation. The three locations are called Bouy 84, Oosterweel and Driegoten. The three locations are situated at km 73, 89 and 118 from the estuary mouth at Vlissingen respectively. For Bouy 84 and Oosterweel measurements were done both near the surface and near the bottom (0.8 m and 3.3 m above the bottom). For both locations the results are very satisfying as can be seen in Figure 6 and Figure 7.

At Driegoten however the model showed no intra-tidal variation in SSC (figure not shown).

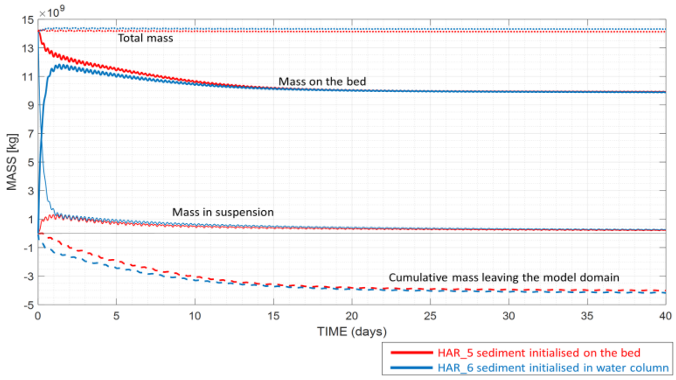

Figure 5 – Mass balance plot for simulation with sediment initialised on the bed and in the water column.

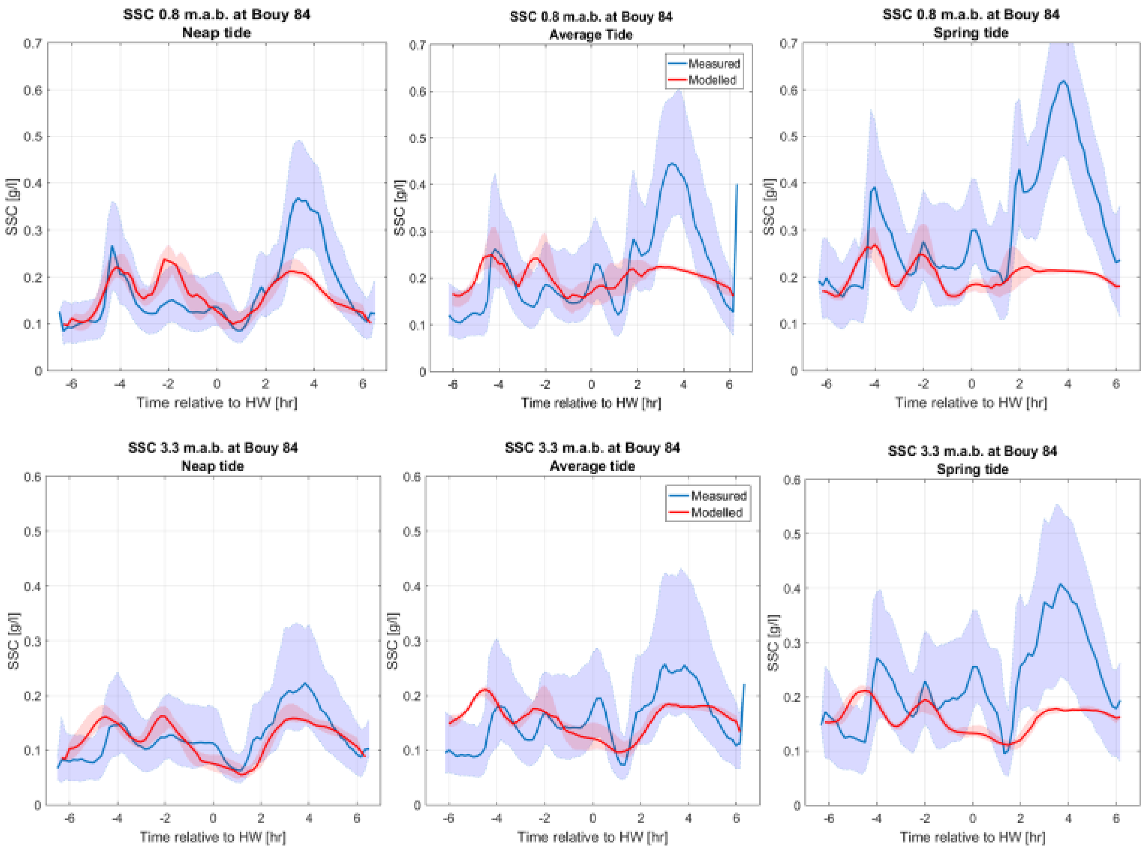

Figure 6 – Ensemble analysis results from model and measurements at Bouy 84

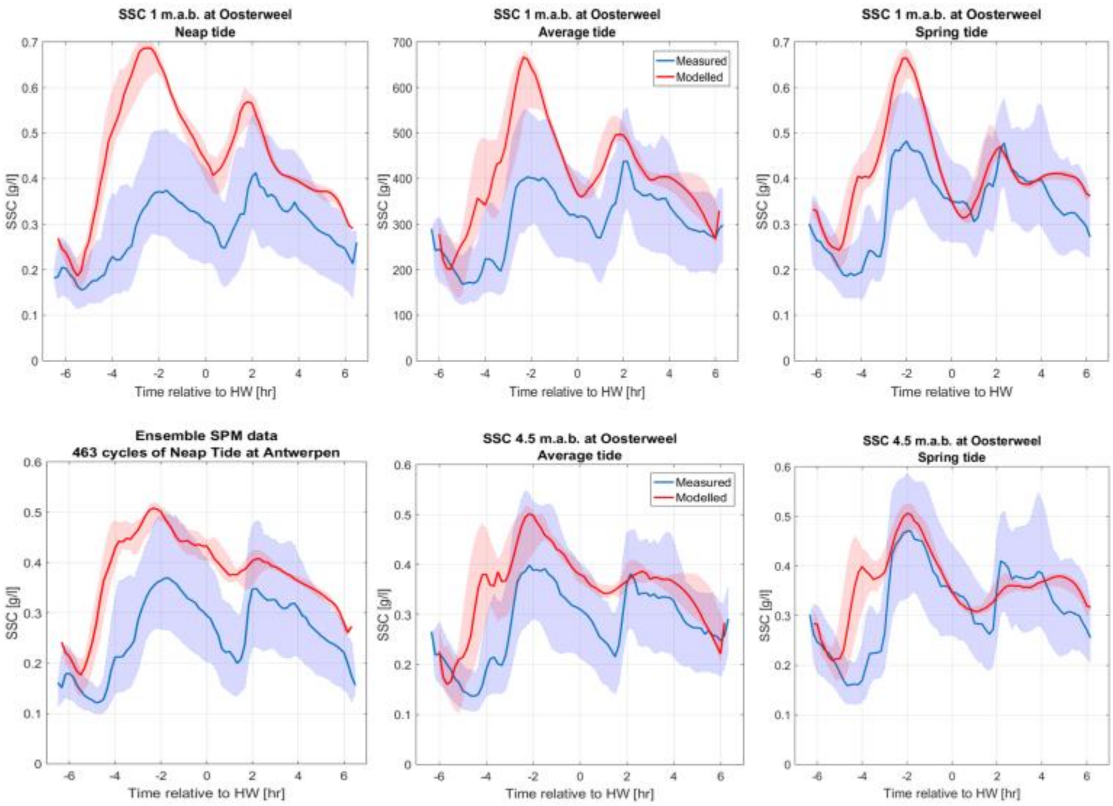

Figure 7 - Ensemble analysis results from model and measurements at Oosterweel

C. *Estuarine turbidity maximum*

When the results for SSC of the last 20 days of the simulation are averaged over time and over different cross sections and ETM is showing around Antwerp (km 80-90) (Figure 8). Depending on discharge events this location can be associated with higher SSC values in the real estuary.

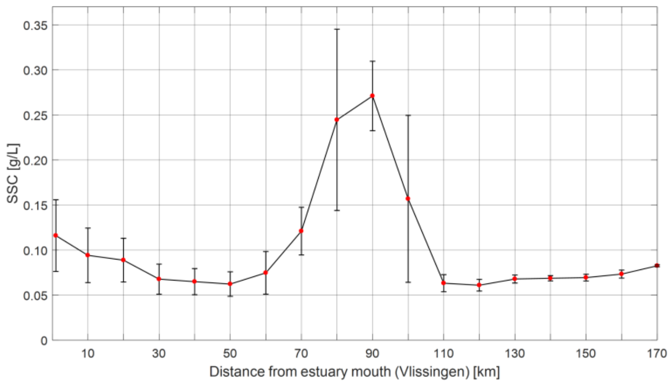

Figure 8 – cross sectional and time averaged SSC values along the Scheldt estuary showing an ETM

Figure 9 shows the same information as Figure 8 but with a higher spatial resolutions and for the different time steps of the simulation in the x-axis. This figure also shows the tide averaged location of the ETM and how it reacts on higher upstream discharge. In the lowest panel of the figure the tides on the boundary are given and the discharge over time of the most important discharge boundary upstream. The ETM moves a little downstream when the discharge upstream is increased.

D. *Mass transfer map*

Mud and sand transport over specific transect in the Sea Scheldt was estimated by [20] based on bathymetric surveys, lithological information of the bottom and dredging and dumping information. The estimated transports are values over a ten year period and here brought back to a one year averaged value. For the same transects the mud transport was calculated from the model results, i.e. for a full spring-neap tidal cycle. These results were then extrapolated to a one year period. Figure 10 shows the Sea Scheldt (Belgian part of the Scheldt Estuary) with the model results in yellow and transport directions over the transects indicated by yellow arrows. The grey values are the estimated values by [20]. For both the model and the estimated transport the directions over the specific transect was the same. But for most transects the model tends to overestimate the transport.

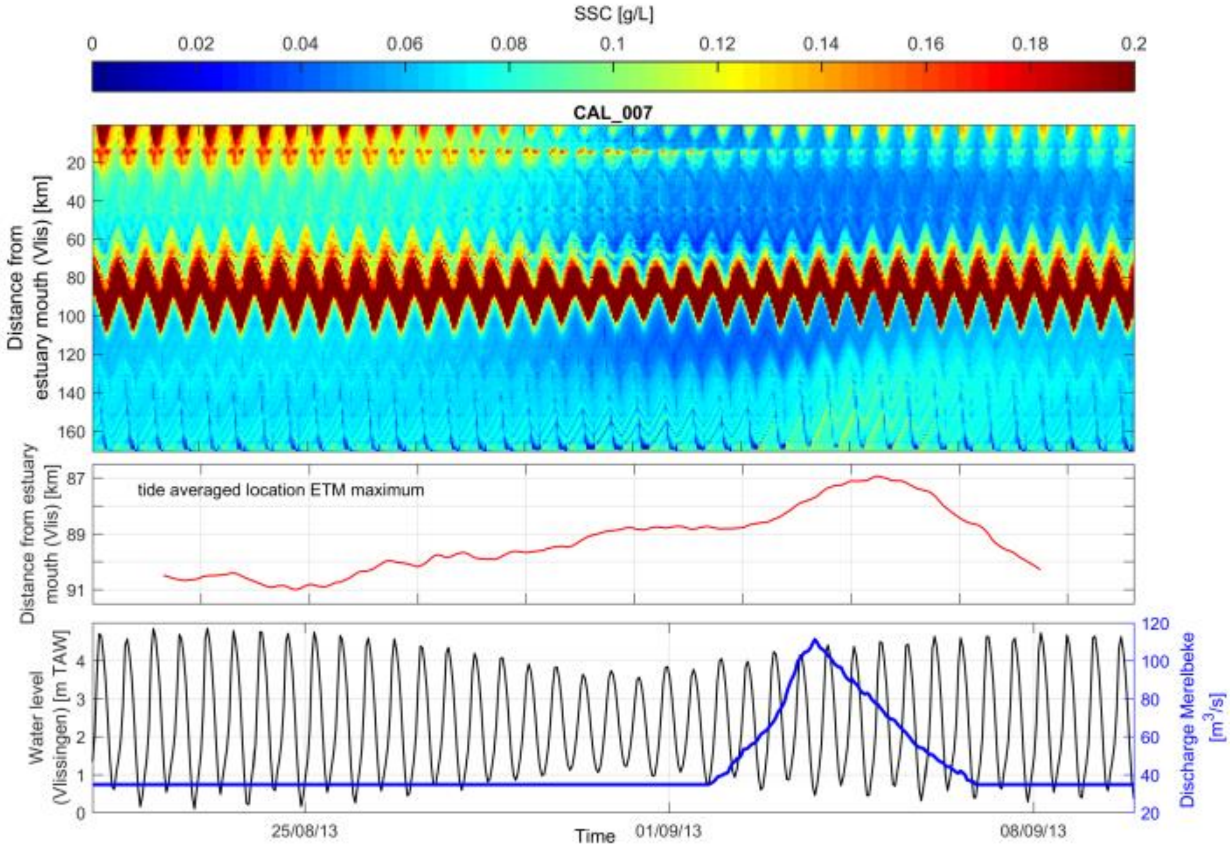

Figure 9 – Variation of SSC along the estuary in time.

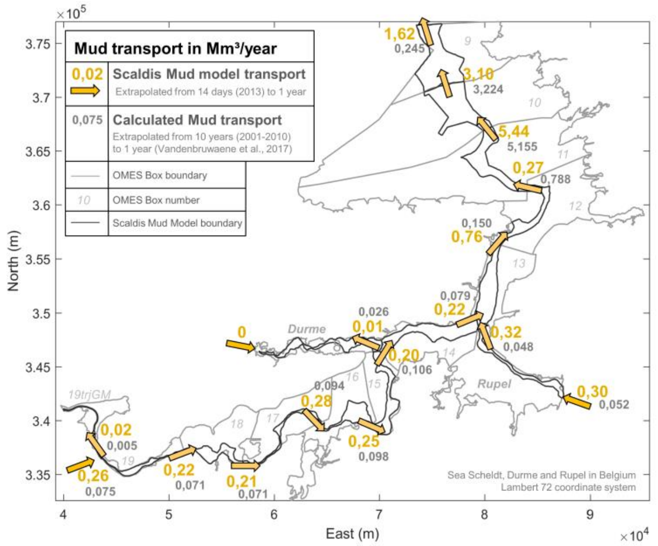

Figure 10 – Mud transport over specified transect in Mm³/year. Model results compared with estimated transports by [20]

E. Dredging and dumping number in the model

The model was able to reproduce similar amounts of sediments near lock entrances and tidal docks as dredged in reality.

V. Discussion

A. Natural ETM

At first the results of the model look very good, but a sensitivity simulation without the sediment source (to compensate for dumping of dredged material) showed that the ETM is entirely dependent on this sediment source. Without this source the sediment coming in the estuary at the upstream boundaries is flushed out of the estuary. The local sediment source is also responsible for the weak response of this ETM on the increased discharge upstream. More work is needed to solve this issue. Probably the low settling velocity is the cause and maybe a second fraction of cohesive sediments with a higher settling velocity can improve the model. However higher settling velocities will increase the problem of excessive sedimentation in shallow areas.

B. Excessive sedimentation in shallow areas

In shallow areas the shear stress is too low to bring enough sediment back into suspension, resulting in excessive rate of deposition of sediment. using a sigmoid function to reduce the settling velocity in shallow areas fixed the problem of excessive deposition of cohesive sediment. The word “fixed” is deliberately used here, because it is not a solution to the problem, but a fix. The d_0 value in equation 10 is a modeller’s choice and reduces settling velocity in water depths smaller than this d_0 value. However if circumstances change in the model, e.g. the concentrations increase a lot, excessive deposition flux can be noticed in those location that have water depths just above d_0. In the existing mud model in DELWAQ this problem arose too and was fixed by adding extra shear stress caused by wind [2]. This shear stress is very high in shallow water and has less effect in the deep channel. More work is needed to find an correct solution for this problem.

VI. CONCLUSIONS

A first attempt was made to create a new cohesive sediment transport model for the Scheldt Estuary. The first results show good intra-tidal variation for some locations and almost no variation for other locations. An ETM was formed, but this was dependent on a local sediment source. The ETM had also a weak reaction on higher upstream discharges. Mud transport rates and transport directions over transect along the estuary is in agreement with earlier estimates. A problem with higher deposition than erosion flux in shallow areas was fixed by reducing the settling velocity in these areas. Further work is needed to find a more elegant solution for this problem.

For larger resolution and better figures the authors refer to [21], the report describing this mud model in full length and detail.

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