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Smolders, Sven; Plancke, Yves; Bi, Qilong; Vanlede, Joris; Kolokythas, Gerasimos

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A Sand Transport Model for the Scheldt Estuary: The 3D Scaldis Sand Model

Sven Smolders, Yves Plancke, Qilong Bi, Joris Vanlede, Gerasimos Kolokythas
Department of Mobility and Public Works, Flemish Government
Flanders Hydraulics Research
Antwerp, Belgium
sven.smolders@mow.vlaanderen.be

Abstract—A sand transport model for the Scheldt estuary, located in the Netherlands and Belgium, based on the hydrodynamic 3D Scaldis model is presented in this paper. The objective is to model only non-cohesive sediment transport. The model is validated using field measurements performed with a Delft bottle at different locations along the estuary. Asymmetry of the cross sectionally averaged flow velocity is used to understand the results of the sand model in terms of net sand transport direction.

I. INTRODUCTION

In Western Europe the implementation of the Seine-Scheldt connection will improve the European waterway network in order to meet the growing demands of modern logistics in a more effective manner [1]. This will result in increased shipping traffic between France and Flanders (Belgium) and the Flemish Government will improve the navigability of the upper part of the Scheldt estuary in order to allow class Va ships to pass. At the moment, the upstream part of the Upper Sea Scheldt (Figure 1) is a Class IV fairway (ships up to 85 m long and 9.5 m wide) and forms a bottleneck in the European network.

Therefore, an integrated plan is being developed, in which navigability, safety and nature are the key elements. The questions that are to be answered within this 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 110 m long and 11.4 m wide and 3.5 m draught), taking into account the other functions of the estuary, like safety, nature and recreation.

The outcome of a feasibility study was that with relatively small measures a balance between cost and benefit can be found, but allowing navigability up to Class Va while increasing safety for ships of class IV and lower. The integrated plan aims at further developing the conclusions from this feasibility study towards Class Va shipping. It is of the utmost importance that the design of this enlargement leads to a multifunctional Scheldt estuary with assets for navigability, guarantees for protection against flooding and a sustainable natural system.

In the framework of the study “Integrated Plan Upper Sea Scheldt”, a set of models are improved or developed by the different project partners. The output of one model can be input for another and as such a model train is used to evaluate the effects of different alternatives (specified morphology of the

Scheldt river in a specific state and at a specific time) under different scenarios (a range of boundary conditions that take into account the climate change, sea level rise, increasing or decreasing tidal amplitude, high or low discharge).

Flanders Hydraulics Research developed a 3D high resolution model for hydrodynamics in the tidal Scheldt estuary, called Scaldis [2,3]. The hydrodynamic model was extended with a model for both cohesive [5] as non-cohesive [6] sediment transport. The University of Antwerp (UA) improves their 1D ecosystems model for primary production in the Scheldt estuary [7]. The Research Institute for Nature and Forest (INBO) builds ecotope and physiotope maps and models benthos, birds and migratory fish (twait shad) for the different alternatives.

This paper focusses on the setup and parameter sensitivity of the non-cohesive or sand transport model. The sand transport model will be described in detail and the results for the 2013 reference state of the model will be discussed.

II. THE SCHELDT ESTUARY

The Scheldt estuary is situated in Western Europe in the Netherlands and Belgium (Figure 1). The part of the estuary from the mouth till the Dutch/Belgian border (located at 67 km from the mouth, measured along the thalweg) is called Western Scheldt and is characterized by different ebb and flood channels surrounding large intertidal sand and mud flats. The part further upstream from the border till Ghent (located at 170 km from the mouth) is called Sea Scheldt and is characterized by a single channel bordered by much smaller intertidal flats and marshes. The part upstream from the tributary Rupel is called the Upper Sea Scheldt as shown in Figure 1.

The estuary mouth near Vlissingen (km 2) is approximately 5 km wide and flood enters twice a day with an average flood volume of 1.04 Gm³ [8]. The funnel shape of the estuary amplifies the tidal range, for mean spring and neap tides respectively, from 4.46 m and 2.97 m at the mouth to 5.93 m and 4.49 m near Hemiksem (km 104) (Figure 1). Further upstream friction dampens the tidal wave, which has still a mean tidal range of 2.24 m and 1.84 m for spring and neap tides respectively near Merelbeke (km 170), where the tide is stopped by a weir-lock construction. The total discharge of the Scheldt and tributaries (on average 120 m³/s) is very small compared to the tidal volume [9].

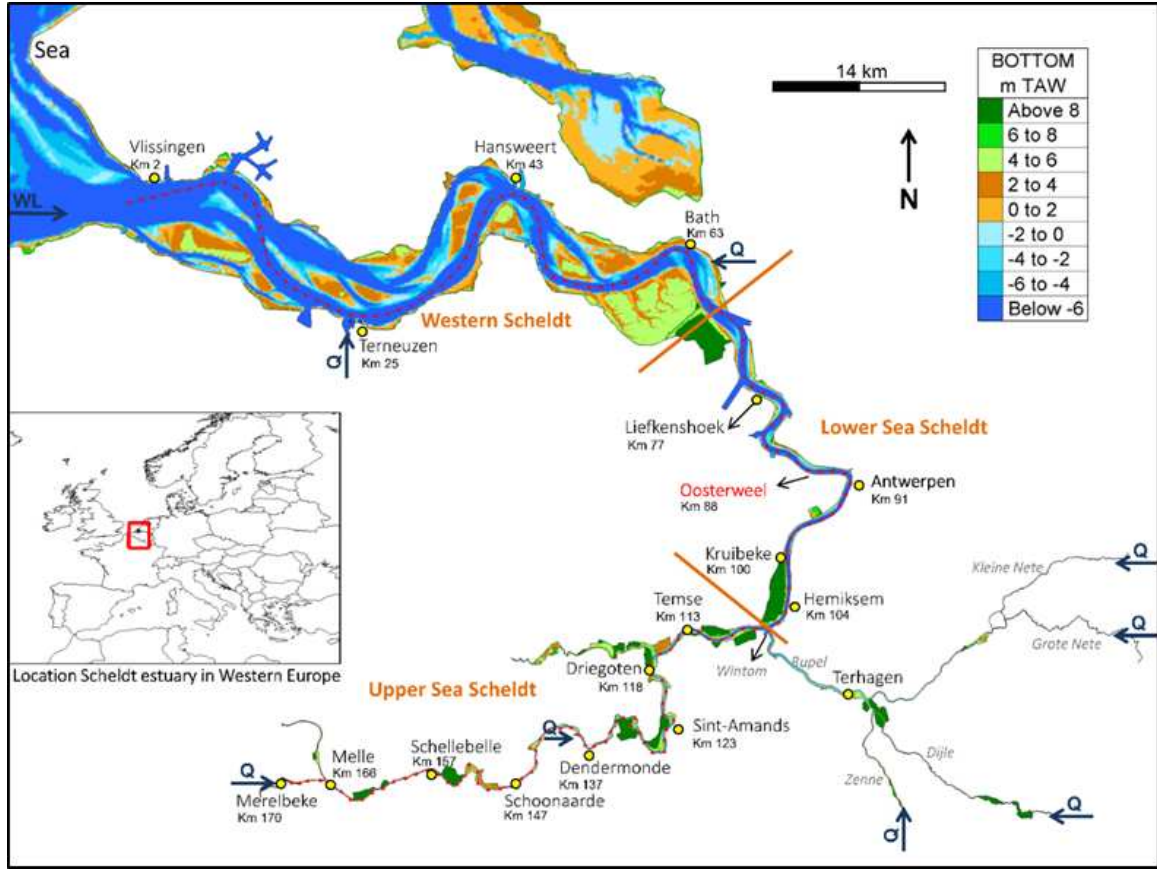


Figure 1 Introduction to the Scheldt estuary. Distances are measured from the estuary mouth

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

The hydrodynamic model, called Scaldis, is a TELEMAC-3D model. The model domain contains the full Scheldt estuary as it is shown in Figure 1 and also includes the Belgian coastal zone, extended to France in the South and The Netherlands in the north. The tributaries are included as far as the tidal influence reaches. Figure 1 shows a Q where eight daily averaged upstream discharges enters the model domain. Water level time series are imposed on the sea boundary. 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 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. 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 $0.026 \text{ s/m}^{1/3}$ in the downstream part and decreases to $0.014 \text{ s/m}^{1/3}$ 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. This model was calibrated using measured water levels, flow velocities and discharges over ADCP transects, and point measured flow velocities [3].

IV. SAND TRANSPORT MODEL: SCALDIS SAND

SISYPHE is coupled with TELEMAC-3D. No parameter changes were done in the hydrodynamic model. The coupling with the hydrodynamics is done every time step. Based on experience in previous projects and on a sensitivity study that is not shown here, the Engelund and Hansen (1967) total sand transport equation was chosen. This formula is derived for river flow [10]. The formula given by Engelund and Hansen estimates the total transport \vec{Q}_0 in the direction of the flow velocity \vec{v} :

$$|\vec{Q}_0| = \frac{0.05\alpha|v|^5}{\sqrt{g}s^2C^3d_{50}} \quad (1)$$

where $|\vec{Q}_0|$ is the magnitude of the total sand transport rate; α is a calibration coefficient (order 1); $|v| = \sqrt{u^2 + v^2}$ is the magnitude of the flow velocity [m/s] with u and v the flow velocity along the x and y axis; $s = (\rho_s - \rho) / \rho$ is the relative density with ρ_s and ρ the sediment and water density, respectively [-]; C is the Chézy friction coefficient [$\text{m}^{1/2}/\text{s}$]; and d_{50} is the

median grain size [m]. Furthermore, to account for the bed slope effects, the correction method of Flokstra and Koch [11] is available in SISYPHE (keyword: FORMULA FOR DEVIATION = 1) and multiplies the above equation by a factor:

$$|\vec{Q}| = |\vec{Q}_0| \left(1 - \beta \frac{\partial z_b}{\partial s}\right) \quad (2)$$

where β is a bed slope coefficient (keyword: BETA = 1.3); s is the coordinate in the flow direction and z_b is the bed level. This formula is implemented in SISYPHE in the subroutine bedload_engel.f. The formula is implemented as follows:

$$\Phi_b = C_{engel} \sqrt{(C_1 \times TOB)^5 / \max(CF, 1.E - 6)} \quad (3)$$

with

$$C_{engel} = 0.1 \sqrt{s \times g \times d^3} \quad (4)$$

and

$$C_1 = \frac{1}{(s \times \rho \times g \times d)} \quad (5)$$

and

$$CF = \frac{2n^2g}{h^{1/3}} \quad (6)$$

and

$$TOB = 0.5 \times \rho \times CF \times |v|^2 \quad (7)$$

where Φ_b is the dimensionless current induced sediment transport rate; TOB is the bed shear stress [Pa]; CF is the quadratic friction coefficient; g is the gravitational acceleration constant [m/s²]; d is the sediment grain size [m]; n is the Manning friction coefficient [s/m^{1/3}]; h is the water depth [m]; and ρ is the water density [kg/m³]. CF can have a different formula depending on the type of friction coefficient that was chosen in the model. For Scaldis a Manning bottom friction coefficient was chosen and the corresponding formula for CF is given here (equation 6).

Suspended load transport is not activated in SISYPHE because the Engelund and Hansen transport equation is a total load equation. The morphological factor is set to 1. The sediment grain size is equal to 150 μ m. Only a single sediment fraction is taken into account over the entire model domain. There is an unlimited amount of sediment available in the model (= 100 m of sediment layer thickness). The simulation will run for 15 days (a full spring-neap tidal cycle) and graphical output is written to a results file every half hour. the time step is four seconds. No sediment will enter the model domain through the boundaries. Sediment can leave the domain freely. To prevent the model from resulting into unwanted erosion at the inflow boundaries, a fixed bed elevation (zero evolution) was defined in the boundary conditions file (.cli). This can be achieved by

assigning LIEBOR=5 for the inflow nodes (8th column in .cli file).

The hydrodynamic model has two days to spin up. After these two days the model is started again from the last time step of the spin up simulation and the sediment module SISYPHE is coupled. A uniform sediment layer is available throughout the entire model domain.

In the hydrodynamic model a Manning bottom friction coefficient was spatially varied to calibrate the water levels and flow velocities in the model (Figure 2). By default the sediment module uses the bottom friction coefficient of the hydrodynamic module to calculate the bed shear stresses to estimate sediment motion. But during calibration of the hydrodynamic model the variation in bottom friction coefficient is used to compensate also for non-physical properties of the model, like numerical diffusion. Taking these values of the bottom friction coefficient would not be correct for sediment transport. Therefore a fixed value for the Manning bottom friction coefficient was used for the entire model domain for the sediment transport module. In the subroutine coefro_sisyphe.f a fixed value for the bottom friction coefficient was introduced. The Manning coefficient was set to 0.02 m/s^{1/3}. In the subroutine tob_sisyphe.f changes were made to make sure the fixed bottom friction coefficient was used in the calculations of the bed shear stress.

The difference in sand transport between using a fixed Manning value for the entire model domain or using the Manning coefficient spatially varying from the hydrodynamic model is part of the sensitivity analysis that follows.

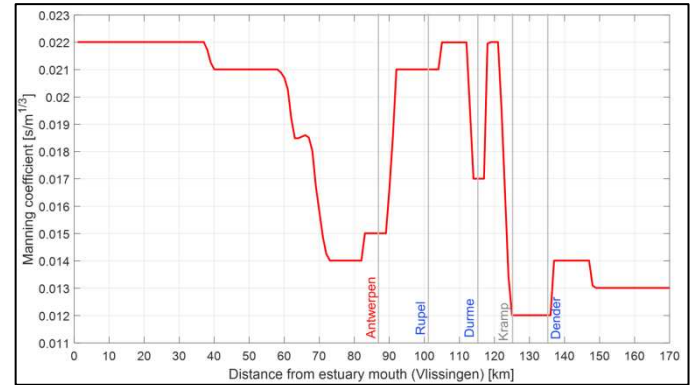


Figure 2 - Manning bottom roughness coefficient of Scaldis 3D 2013 along the estuary axis.

The sediment module calculates a certain sand transport and the related bottom changes. By default these bottom changes are updated in the bottom file of the hydrodynamic model every time step. As the focus of the sand transport model is on sand transport and not on morphology. Therefore the update of the bottom in the hydrodynamic model is switched off in the code. The mass balance and bottom changes are still recorded in the sediment module and are given as output, but the sand transport is always calculated based on the hydrodynamics with a fixed initial bathymetry.

V. MODEL VALIDATION

Delft bottle measurements

A simulation of 15 days with TELEMAC-3D coupled with SISYPHE was run. The downstream boundary is a forced water level combined with X and Y velocity components. A 15 day simulation makes sure a complete spring-neap tidal cycle is simulated. The upstream boundaries (8) have a constant discharge imposed. This is 23, 34.7, 11.1, 15.92, 34.6, 8.3, 10.4, 35, 0 m³/s for the Terneuzen, Merelbeke, Dender, Zenne, Dijle, Grote Nete, Kleine Nete and Bath discharge boundary respectively (Figure 1). The bathymetry of 2013 is used [3]. Model validation was done using Delft bottle (Figure 3) sand transport measurements of 13 hour (= full ebb and flood cycle) measurements campaigns at different locations along the Sea Scheldt [12]. Different measurements at different heights in the water column were used to estimate the total transport over the entire water column [12]. From the 15 day simulation a tide was chosen that came closest to the tide during the 13 hour measurement campaign at the specific location. The sand transport rate close to the location of the point measurement was extracted from the model and plotted together with the measured values for total sand transport. Good measurement results are available for six locations along the Sea Scheldt: Oosterweel, Kruikeke, Driegoten, Dendermonde, Schoonaarde, and Schellebelle (locations indicated in Figure 1).



Figure 3 – Delft bottle on frame to measure sand transport just above the bottom.

The comparison between modelled and measured sand transport for these locations is given in Figure 4 to Figure 9. Time in the x-axis is expressed relative to low water. Throughout the Sea Scheldt there is a low but longer sand transport during the ebb flow and a high but short peak during the flood flow. All locations except Driegoten gave a very good agreement between model and measurement for sand transport.

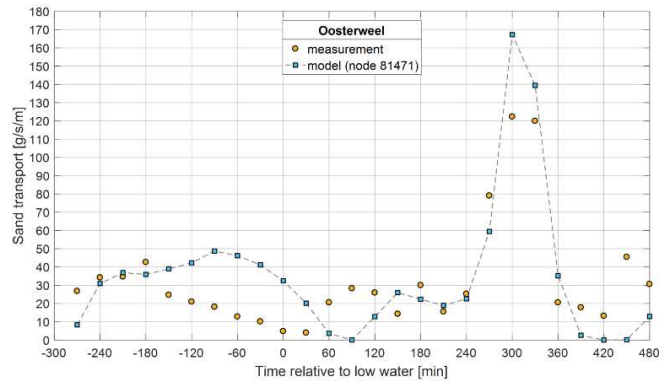


Figure 4 – Modelled and measured sand transport at Oosterweel (km 88)

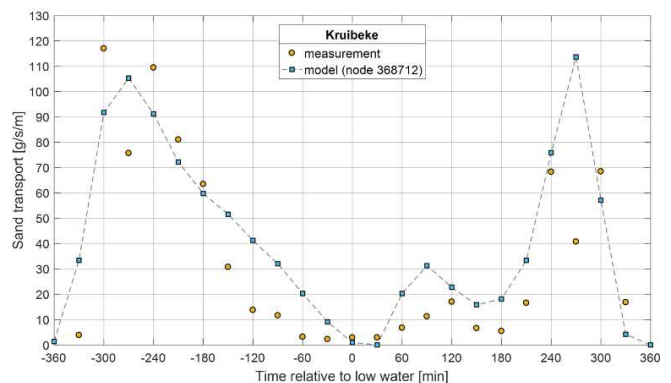


Figure 5 – Modelled and measured sand transport at Kruikeke (km 100)

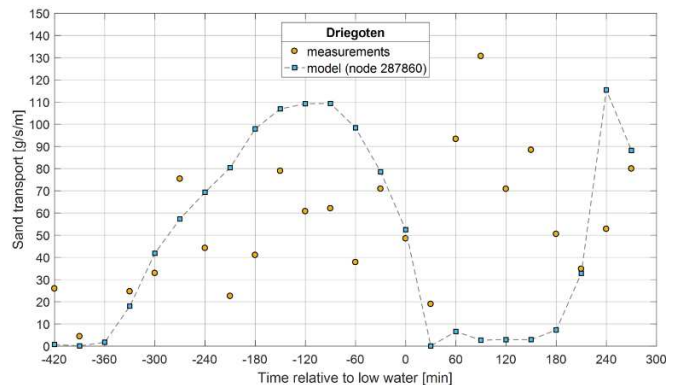


Figure 6 – Modelled and measured sand transport at Driegoten (km 118)

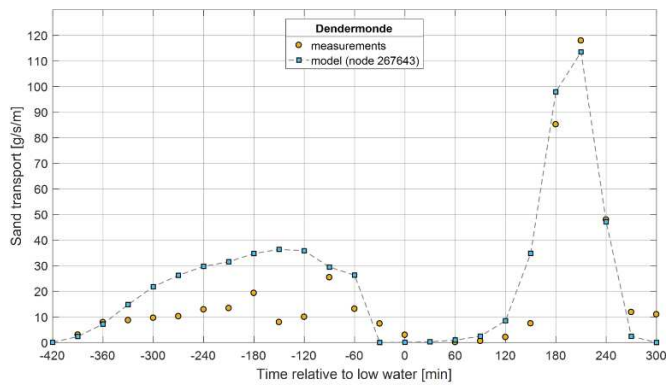


Figure 7 – Modelled and measured sand transport at Dendermonde (137)

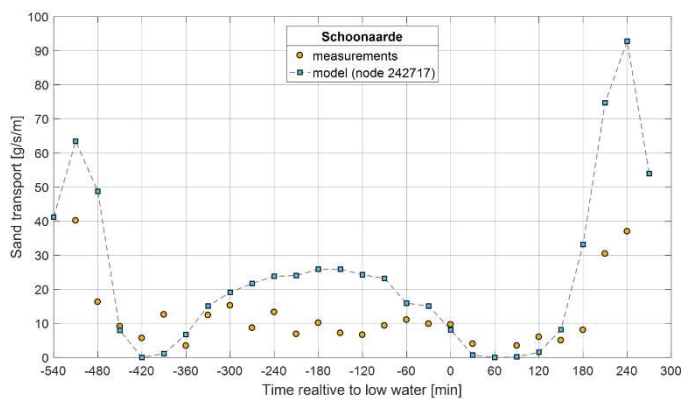


Figure 8 – Modelled and measured sand transport at Schoonaarde (km 147)

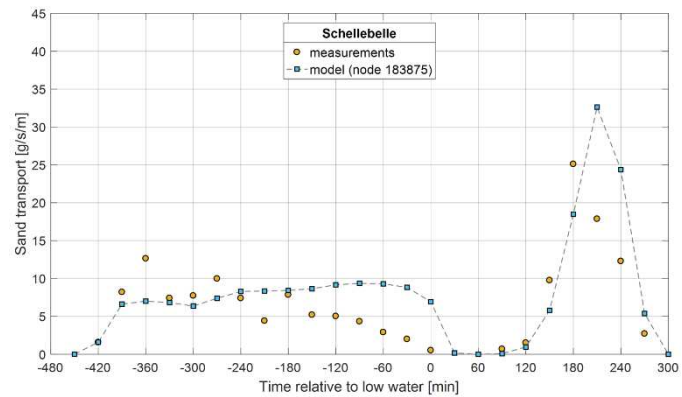


Figure 9 – Modelled and measured sand transport at Schellebelle (km 157)

Computed transport rates

In [13] sand transport rates over transects in the Sea Scheldt were calculated based on the difference in bathymetry data from 2001 and 2010, lithological information of the bottom and

data of the dredging and disposal works. These transport rates are compared to the model results and this is shown in Figure 11. The model results are scaled up from a net transport over a spring-neap tidal cycle (15 days) to a net transport over a period of 1 year. The calculated sand transport from [13] is scaled down from a transport over ten years to a transport number of one year and was then adjusted to take a bed porosity of 0.5 into account. For the Upper Sea Scheldt the model shows a very good agreement with the calculated sand transport, both in magnitude as in transport direction. The model tends to underestimate the sand transport a little, mainly in the Lower Sea Scheldt. For the tidal arm to Gentbrugge (box 19 in Figure 11), the model gives a net import, although very small, and the calculated sand transport gives a value 200 times larger. In the sand transport model the Durme (tributary, location shown in Figure 11) is importing sand like the calculated transport. The value given by the model is much smaller than the calculated import. For the Lower Sea Scheldt the model results give mainly ebb dominated sand transport, whereas the calculated transports are directed upstream. Transport rates are in the same order of magnitude, except for the three transects closest to the border (most downstream); there the model results are much smaller than the calculated results. Larger scale changes to the estuary like dredging and dumping and de-embankments are not included in a short model run, but it is unclear if this might give the difference seen in the sand transport numbers and directions in the Lower Sea Scheldt. In [14] a sand transport model (Delft3D) is used for the Scheldt estuary and on the Dutch/Belgian border the transport directions show also a net downstream transport direction.

VI. SAND TRANSPORT OVER TRANSECTS

The net sand transport over transects can be calculated for different type of tides: neap and spring tide or averaged over a spring/neap tidal cycle tide. Figure 10 shows that for an averaged spring/neap tidal cycle the sand transport in the Western Scheldt is directed upstream (negative value). Around the Dutch-Belgian border the direction of the transport changes to downstream. The sand transport increases a lot between km 90 and 100 in downstream direction with some peaks with upstream transport in between. In the Upper Sea Scheldt the transport direction is usually downstream with one exception around km 147 (around Schoonaarde). The transport rates during a neap or spring tide behave differently and are also plotted in Figure 10. Over most transects the transport rate increase during spring tide and decreases during neap tide, but in the Upper Sea Scheldt starting from km 132 the opposite trend is seen (Figure 10). Sometimes the net transport direction changes when going from a neap tide to a spring tide, like around km 100-115 (Figure 10).

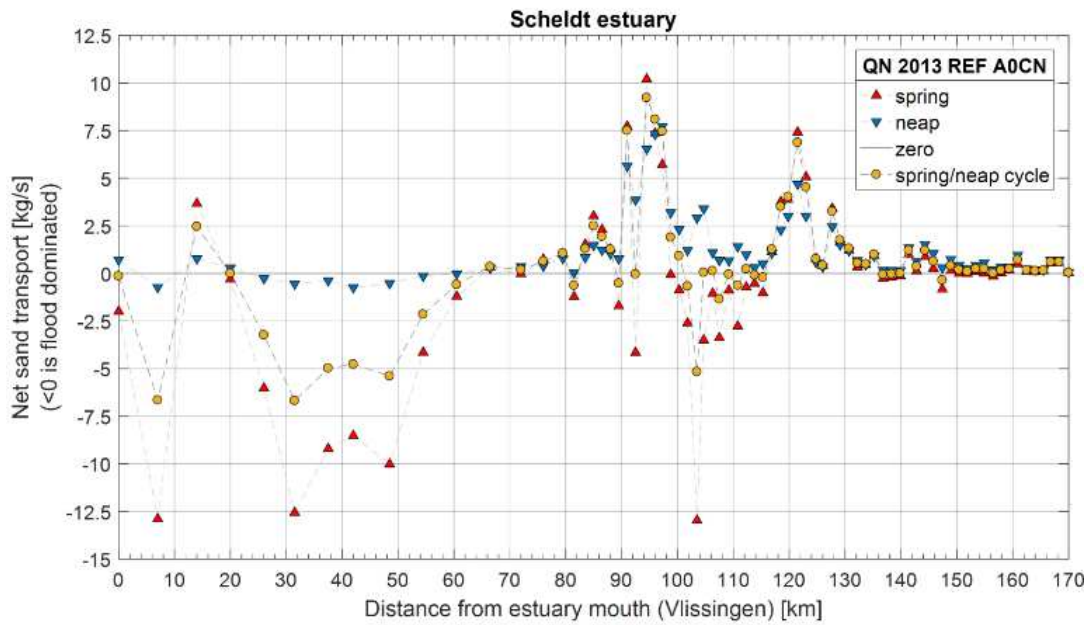


Figure 10 – Net sand transport over different cross sections along the Scheldt estuary calculated and plotted for a neap and spring tide, and averaged over a spring/neap tidal cycle. A positive value means transport in downstream direction.

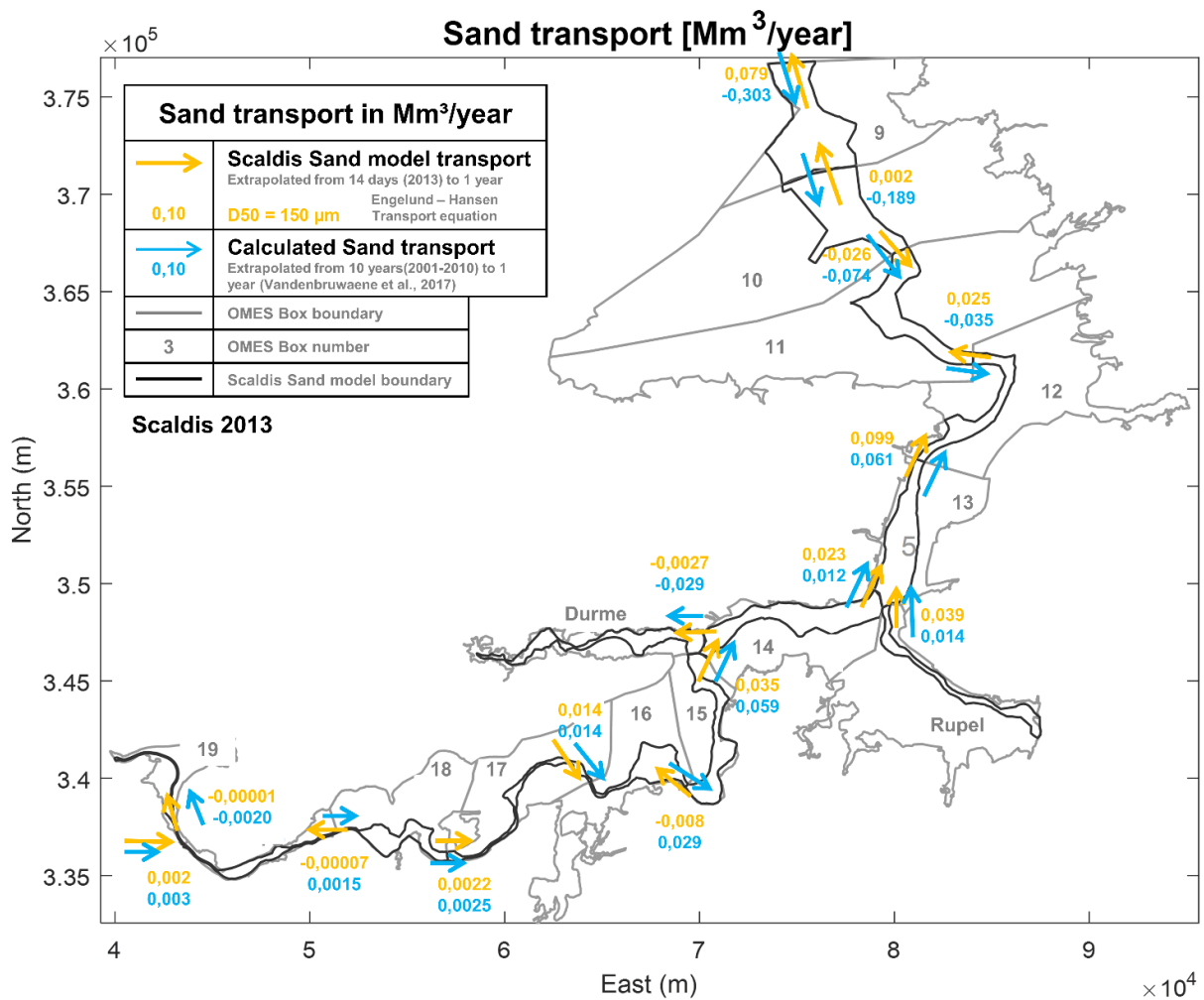


Figure 11 – Sand transport between different parts of the estuary. Model results are compared with calculated sand transport.

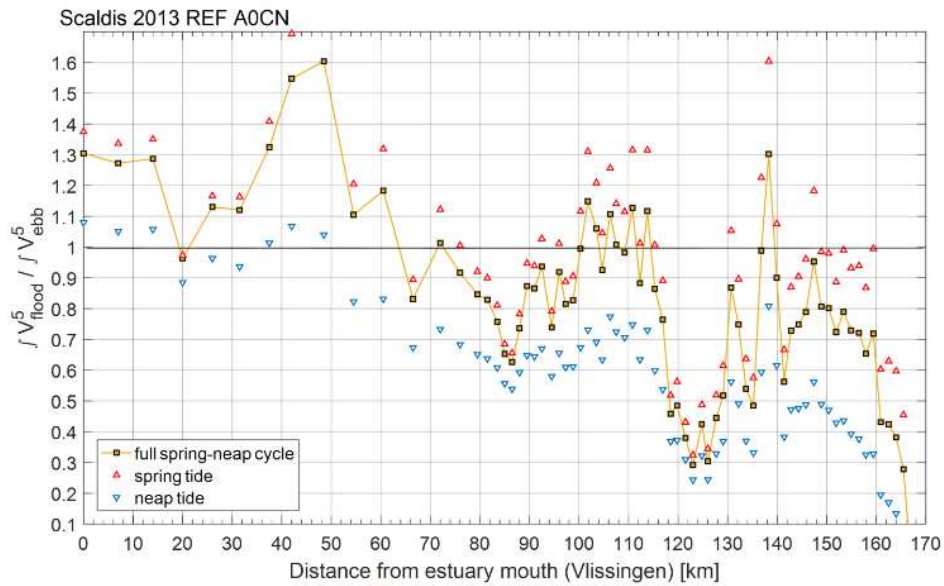


Figure 12 – Asymmetry between flood and ebb over time integrated cross sectional averaged flow velocity to the power five

VII. FLOW VELOCITY ASYMMETRY

The flow velocity is the largest driving force behind the Engelund and Hansen equation (see equation 1). Since there is no threshold for this velocity for incipient motion, an integration of both flood and ebb cross sectional averaged flow velocity to the power five can give more insight in why the net sand transport is going in up- or downstream direction. The asymmetry between the integrated cross sectional averaged flood and ebb velocity to the power five is shown in Figure 12. The asymmetry is shown for an integration over a full spring-neap tidal cycle and for an integration over two spring (to take diurnal inequality into account) and two neap tides separately. When the asymmetry is larger than 1 it means that the flow velocity to the power five is larger in the upstream direction and is thus flood dominated. If the asymmetry is smaller than 1 it is ebb dominated. Since cross sectional averaged flow velocities are used, the spatial variation along the transect is lost. Figure 12 shows that for the Western Scheldt the asymmetry is mostly larger than 1, which coincides with the upstream direction of the transport found in Figure 10. At approximately the Dutch-Belgian border (km 65) the asymmetry drops below 1, changing the direction of the transport to downstream. Between km 100 and 115 the transport direction changed again from downstream to upstream and this is also seen in Figure 12 where the asymmetry rises again above 1. In the Upper Sea Scheldt the asymmetry is mostly below 1 and the transport direction is ebb dominated. One peak in asymmetry above 1 can be seen around km 138 and this coincides with a reduced transport in the ebb direction, but the net sand transport does not change entirely to the upstream direction. The spring and neap tide markers show that asymmetry can change a lot between these two extremes in tides and can also change the dominance from ebb to flood or vice versa.

VIII. MASS BALANCE

The sand transport over the different transects along the Scheldt estuary was calculated for a full spring-neap tidal cycle. A mass balance is calculated for each polygon formed by a downstream and upstream transect. This sand mass balance is shown in Figure 13. This figure shows the areas in the Upper Sea Scheldt that are accumulating sand (in red) and other areas that are eroding and thus losing sand (in blue).

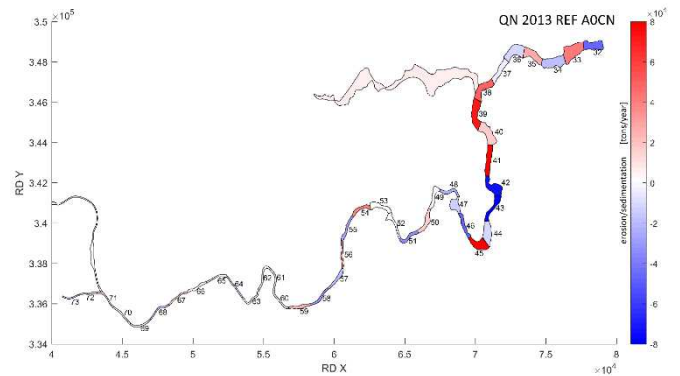


Figure 13 - A sand mass balance calculated after a full spring-neap tidal cycle and extrapolated to one year based on calculated transports over transects for run 2013 REF A0CN.

IX. SENSITIVITY: CONSTANT MANNING COEFFICIENT CORRECT?

The spatial varying Manning coefficient from the hydrodynamic model is the result of a calibration exercise. This coefficient takes also non-physical processes, like numerical diffusion, into account. Because of this, we think it is better to use a constant Manning bottom roughness coefficient for the sediment module SISYPHE separately. According to equations 6 and 7, the larger the Manning coefficient, the larger the

calculated bed shear stress will be. So the locations in the model domain where the constant Manning coefficient of $0.02 \text{ m/s}^{1/3}$ is larger than the coefficient given in the hydrodynamic module, will have larger sand transport rates and vice versa. This is shown in Figure 14 where the results of a simulation with a fixed Manning coefficient (equal to $0.02 \text{ s/m}^{1/3}$) over the entire domain and the results of a run where SISYPHE uses the Manning coefficient of the hydrodynamic model (spatially varying as seen in Figure 2). The Manning coefficient in the hydrodynamic model is lower than the constant value given for the sediment module for the region between km 70 and km 90 and upstream of km 123. The differences can be big and even result in a difference in net transport direction. This also means that choosing a different constant Manning coefficient could change the net transport magnitude and direction. Furthermore when comparing a sand transport model in TELEMAC and SISYPHE with a sand transport model in a less diffusive code (and thus with higher Manning coefficient values in the hydrodynamics and sediments) such as Delft3D, the latter will show higher sand transport rates. For a Manning coefficient varying from $0.012 \text{ s/m}^{1/3}$ to $0.022 \text{ s/m}^{1/3}$ the transport rate can be 10 time higher!

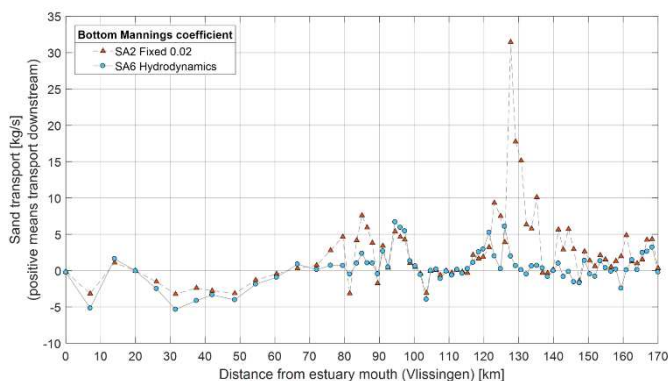


Figure 14 - Effect of choice of Manning coefficient on net sand transport over different transects along the Scheldt estuary. A positive net transport is transport in the downstream direction. A negative net transport is transport in the upstream direction.

X. CONCLUSIONS

This paper describes a new sand transport model for the Scheldt estuary. The Engelund and Hansen total load equation was chosen as transport equation. The hydrodynamic data was delivered by the 3D Scaldis model. When the model results are compared to point measurements for total sand transport most locations show a very good agreement. Comparing model results with calculated net sand transport rates based on the difference of bathymetry measurements between 2001 and 2010 showed that the model reproduces the sand transport rate and directions in the Upper Sea Scheldt well. Conversely, the model underestimates the transport rate in the Lower Sea Scheldt and finds opposite directions of transport close to the Dutch/Belgian border.

Transport rates over transects are shown for the entire estuary and most of the transport rates and directions can be explained by the integration over time of the cross sectional averaged flow velocity to the power five (as it is used in the Engelund and Hansen equation).

Finally, the sensitivity of the sand transport rate results to the choice of Manning bottom roughness coefficient are shown. Specific measurements are necessary to confirm the use of a different Manning coefficient in the sediment model compared to the coefficient in the hydrodynamic model.

REFERENCES

- [1] Bour, N. (2008) Seine-Nord Europe Canal: central segment of the Seine-Scheldt waterway link. On Course: PIANC magazine 132: 5-12.
- [2] Smolders, S.; Maximova, T.; Vanlede, J.; Teles, M.J. (2014). Implementation of controlled reduced tide and flooding areas in the TELEMAC 3D model of the Scheldt Estuary, in: Bertrand, O. et al. (Ed.) (2014). Proceedings of the 21st TELEMAC-MASCARET User Conference, 15th-17th October 2014, Grenoble – France. pp. 111-118
- [3] Smolders, S.; Maximova, T.; Vanlede, J.; Plancke, Y.; Verwaest, T.; Mostaert, F. (2016). Integraal plan Boven-Zeeschelde: Subreport 1. SCALDIS: a 3D Hydrodynamic model for the Scheldt Estuary. Version 5.0. WL Rapporten, 13_131. Flanders Hydraulics Research: Antwerp. XXVIII, 246 + 228 p. bijl. pp.
- [4] Smolders, S., Bi, Q., Maximova, T., & Vanlede, J. (2018). Modelling Cohesive Sediments in the Scheldt Estuary (Belgium) with SEDI-3D. In Proceedings of the XXVth TELEMAC-MASCARET User Conference, 9th to 11th October 2018, Norwich (pp. 53-60).
- [5] Smolders, S.; Maximova, T.; Vanlede, J.; Plancke, Y.; Verwaest, T.; Mostaert, F. (2016). Integraal Plan Boven-Zeeschelde: Subreport 1 – SCALDIS: a 3D Hydrodynamic Model for the Scheldt Estuary. Version 5.0. WL Rapporten, 13_131. Flanders Hydraulics Research: Antwerp, Belgium.
- [6] Smolders, S.; Plancke, Y.; Vanlede, J.; Mostaert, F. (2019). Integraal Plan Boven-Zeeschelde: Sub report 10 – Scaldis Sand: a sand transport model for the Scheldt estuary. Version 4.0. FHR Reports, 13_131_10. Flanders Hydraulics Research: Antwerp.
- [7] Van Engeland T., T.J.S. Cox, K. Buis, S. Van Damme, P. Meire (2018). 1D Ecosystem model of the Schelde estuary: model calibration and validation. Report 018-R217.
- [8] Baeyens, W., van Eck, B., Lambert, C., Wollast, R., and Goeyens, L. General description of the Scheldt estuary. *Hydrobiologia* 34:83-107, 1998.
- [9] Meire, P., Ysebaert, T., Van Damme, S., Van den Bergh, E., Maris, T., and Struyf, E., (2005). The Scheldt estuary: a description of a changing ecosystem. *Hydrobiologia* 540:1-11, 2005.
- [10] Engelund, F. and Hansen, E., (1967). A Monograph on Sediment Transport in Alluvial Streams. Teknisk Forlag, Copenhagen, Denmark.
- [11] Flokstra, C.; Koch, F. (1981). Numerical aspects of bed level predictions for alluvial river bends. Delft Hydraulics Laboratory. Netherlands, Publication 258
- [12] Plancke, Y.; Smolders, S.; Mostaert, F. (2018). Sedimenttransport in het Schelde-estuarium: deelrapport 1. Bepalen van het aandeel zandtransport uit metingen met de Delftse fles. Versie 3.0. WL Rapporten, 16_001_1. Waterbouwkundig Laboratorium: Antwerpen. VI, 13 + 22 p. bijl. pp
- [13] Vandenbruwaene, W.; Levy, Y.; Plancke, Y.; Vanlede, J.; Verwaest, T.; Mostaert, F. (2017). Integraal plan Boven-Zeeschelde: Deelrapport 8 – Sedimentbalans Zeeschelde, Rupel en Durme. Versie 4.0. WL Rapporten, 13_131_8. Waterbouwkundig Laboratorium: Antwerpen.
- [14] Coen, L.; Plancke, Y.; De Maerschalck, B.; Mostaert, F. (2018). Agenda voor de Toekomst Morfologie Mesoschaal: Deelrapport 13 – Scenario's morfologisch beheer. Versie 4.0. WL Rapporten, 14_024_13. Waterbouwkundig Laboratorium: Antwerpen.