



THE UNSTRUCTURED SCALDIS MODEL: A NEW 3D HIGH RESOLUTION MODEL FOR HYDRODYNAMICS AND SEDIMENT TRANSPORT IN THE TIDAL SCHELDT

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ABSTRACT

In the framework of the projects "Integral Plan for the Upper Sea Scheldt" and "Agenda for the Future", the SCALDIS model, a new unstructured high resolution model of the tidal Scheldt is developed in TELEMAC 3D (Telemac-Mascaret software platform). Starting from the stated model purpose, a weighted dimensionless cost function is set up that attributes equal weight to the vertical and the horizontal tide. By adapting the bottom roughness, the cost function is minimized during model calibration. Quantification of the model skill and cost function calculation is done using the VIMM toolbox which is developed and maintained at Flanders Hydraulics Research. The quantified model skill of the SCALDIS model shows that the model is well suited to assess the effects of changing the bathymetry and geometry of the Scheldt river on water levels, velocities, tracer dispersion and residence times, and that the hydrodynamics can be used as the basis for sediment transport calculations (both cohesive and non-cohesive).

Keywords: Scheldt Estuary, numerical model, VIMM toolbox

1. INTRODUCTION

Within the framework of the project "Integrated Plan Upper Sea Scheldt" commissioned by the Sea Scheldt division of Waterwegen & Zeekanaal NV, it is investigated how navigability can be improved in the upper part of the Sea Scheldt, without negative effects to nature and safety against flooding.

Within the Flemish-Dutch Long Term Vision for the Schelde-estuary, a 4 year (2014-2017) research programme was defined ("Agenda for the Future"), in which 8 topics will be dealt with (e.g. tidal penetration, risk for regime shift, sediment strategies, valuing ecology).

Within these two aforementioned programmes the need was identified to have a hydrodynamics and sediment transport model that covers the entire tidally influenced zone of the Scheldt Estuary and the mouth area, and that has sufficient resolution in the upstream part. The existing NEVLA schematization (Vanlede et al., 2015) that was built and maintained since 2006 at Flanders Hydraulics Research has the needed spatial coverage. Being implemented on a structured grid however, the resolution can only vary smoothly; more specifically from 300m in the North Sea over 65m around Antwerp to 20m at the upstream end. This upstream resolution is not sufficient to accurately describe the hydrodynamics and sediment transport there, taking into account that the river width decreases to 40m around Ghent.

In order to increase the resolution in the upstream part while keeping one model domain for practical reasons (so no nesting or domain decomposition) and with an acceptable computational cost, the natural choice was made to move to an unstructured grid.

2. MODEL PURPOSE

In the framework of the study "Integrated Plan Upper Sea Scheldt", a set of models are improved or developed by the different project partners.

These models will be used to evaluate the effects of different alternatives (specified morphology of the Scheldt river in a specific state and at a specific time), possible variants (modest changes to an alternative), 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 develops a new 3D high resolution model for hydrodynamics in the tidal Scheldt estuary (this paper). In a later stage, the hydrodynamics model will be extended to also include sediment transport (both non-cohesive and cohesive). The University of Antwerp (UA) improve on their ecosystems model for primary production in the Scheldt estuary. The Research Institute for Nature and Forest (INBO) builds ecotope and fysiotope maps and models benthos, birds and migratory fish (twaitshad) for the different alternatives.

The alternatives include the current state (2013-2014), a reference state (autonomous development between 2013 and 2050 including the sustainable management plan for class IV inland shipping and decided policy) and states including the future accommodation and maintenance of the fairway.

The different models that are to be used in this project are intricately intertwined. Tracer experiments will be carried out in the 3D hydrodynamic model in order to provide tracer concentration timeseries for calibration of the dispersion coefficient in the 1D model. For this purpose, the 3D model will be spiked with passive tracers, initialised in polygons that correspond to the boxes in the 1D OMES model. This is a similar method as used by Soetaert and Herman (1995) when they calibrated their 1D MOSES model to the SAWES water quality model for the Western Scheldt. The 1D model in turn will be used to calculate initial longitudinal salinity distributions for the 3D model calculations. For the ecotope maps and habitat modelling of INBO, areal coverage of low water 30% and high water 85% exceedance frequency, percentiles of immersion duration, current velocity maps and shear stress maps are derived from runs of the 3D hydrodynamic model.

SPM values from the ensuing sediment transport calculations in the 3D model provide an important input in the 1D ecosystem model of UA, because primary production in the Scheldt estuary is largely limited by light availability. SPM values are also an input in the migratory fish model of INBO. Effects of different alternatives on sand transport give an indication of what morphological changes to expect.

3. MODEL SCHEMATISATION

For the development of this new unstructured schematization, the open source numerical platform TELEMAC-MASCARET was chosen. TELEMAC-MASCARET was originally developed by EDF R&D and it includes the three-dimensional circulation model TELEMAC-3D. The model is based on the finite elements method. Assuming the hydrostatic hypothesis, TELEMAC-3D solves the three-dimensional Reynolds Averaged Navier Stokes (RANS) equations (Hervouet, 2007):

$$\frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} + \frac{\partial W}{\partial z} = 0 \quad [1]$$

$$\frac{\partial U}{\partial t} + U \frac{\partial U}{\partial x} + V \frac{\partial U}{\partial y} + W \frac{\partial U}{\partial z} = -g \frac{\partial \eta}{\partial x} + \nu \Delta(U) + F_x \quad [2]$$

$$\frac{\partial V}{\partial t} + U \frac{\partial V}{\partial x} + V \frac{\partial V}{\partial y} + W \frac{\partial V}{\partial z} = -g \frac{\partial \eta}{\partial y} + \nu \Delta(V) + F_y \quad [3]$$

$$\frac{\partial h}{\partial t} + \frac{\partial(uh)}{\partial x} + \frac{\partial(vh)}{\partial y} = 0 \quad [4]$$

(U, V, W) are the three components of the flow velocity, (u,v) the depth integrated flow velocities, ν the diffusion coefficient, g the gravitational constant and (F_x , F_y) the source and sink terms of the momentum equations ([2] and [3]). The set of equations is closed using the k- ϵ turbulence model.

TELEMAC provides the possibility of taking into account passive or active tracers in the model domain. The following equation describing the evolution of tracer concentration (T) is solved:

$$\frac{\partial T}{\partial t} + U \frac{\partial T}{\partial x} + V \frac{\partial T}{\partial y} + W \frac{\partial T}{\partial z} = \nu_t \Delta(T) + Q' \quad [5]$$

The tracer diffusion coefficient is given by ν_t and Q' represents the source terms for tracers.

3.1 Model Grid and Resolution

The model domain (pictured in figure 1) covers the entire tidal Scheldt estuary, including the mouth area and the Belgian Coastal Zone from Dunkerque (France), until Goeree (The Netherlands), including the Eastern Scheldt. Upstream the model extends to the limits of the tidal intrusion. All tributaries of the Scheldt are included.

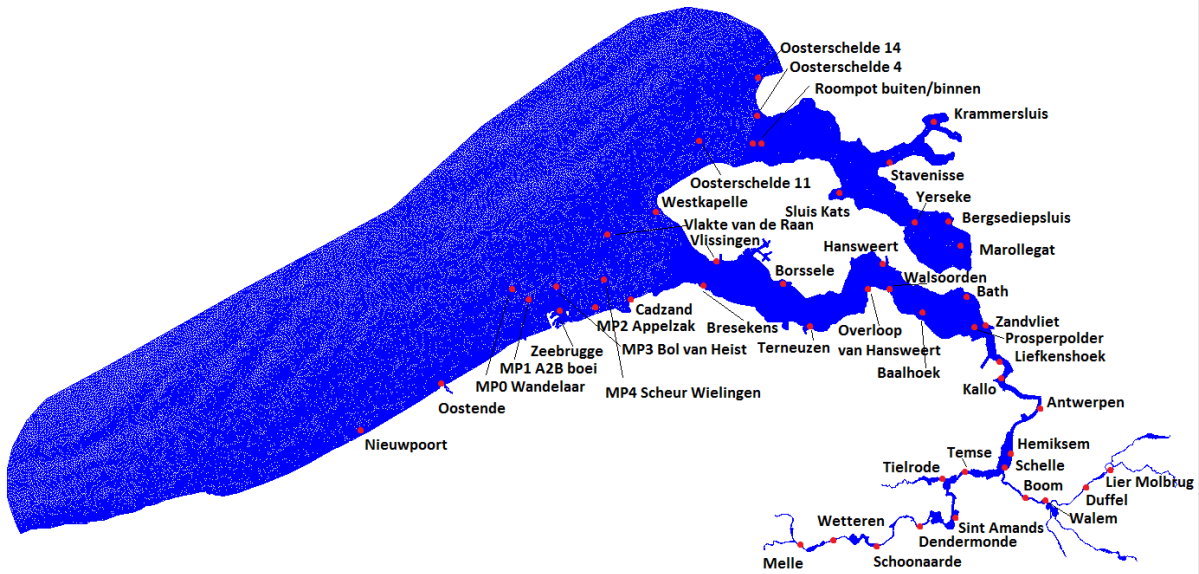


Figure 1: Model domain and output points

Using an unstructured grid allows to combine a large model extent with a high resolution upstream. The grid resolution varies from 7-9m in the Upper Sea Scheldt to 500m at the offshore boundaries.

The model grid consists of +460 000 nodes in the horizontal. The model is 3D with 5 sigma planes over the vertical, which gives a total of +2 300 000 of nodes. The resolution in the coastal area varies from 200 to 500 m depending on waterdepth. The resolution in the Eastern Scheldt is 200 m. In the Western Scheldt the resolution is 120 m. In the Sea Scheldt the resolution increases slowly to 30m near Antwerp and 10m in the Upper Sea Scheldt. Upstream the tributaries the resolution can reach 4m.

3.2 Bathymetry

Figure 2 shows the bathymetry of the SCALDIS model. It was built out of a patchwork of different data sources. The Belgian Continental Shelf and the Belgian coastal zone was measured in 2007-2009 by MDK-aKust. The bathymetry of the Dutch coast (mostly 2010-2012) was measured by Rijkswaterstaat and downloaded from Open Earth. The harbor of Zeebrugge is put at maintenance depth. The bathymetry of the Western Scheldt (2013) and the Eastern Scheldt (2010) was measured by Rijkswaterstaat. For the lower Sea Scheldt, bathymetric data of 2011 was provided by Maritime Access division. Bathymetric data for the Upper Sea Scheldt and Rupel basin (2014) was completed with data for the Dijle and Lower Nete (2010-2013) and for the Zenne and Grote and Kleine Nete (2001) which was provided by W&Z, Sea Scheldt division. For the Flood Control Areas along the river, the topographic data is derived from the Mercator Database.

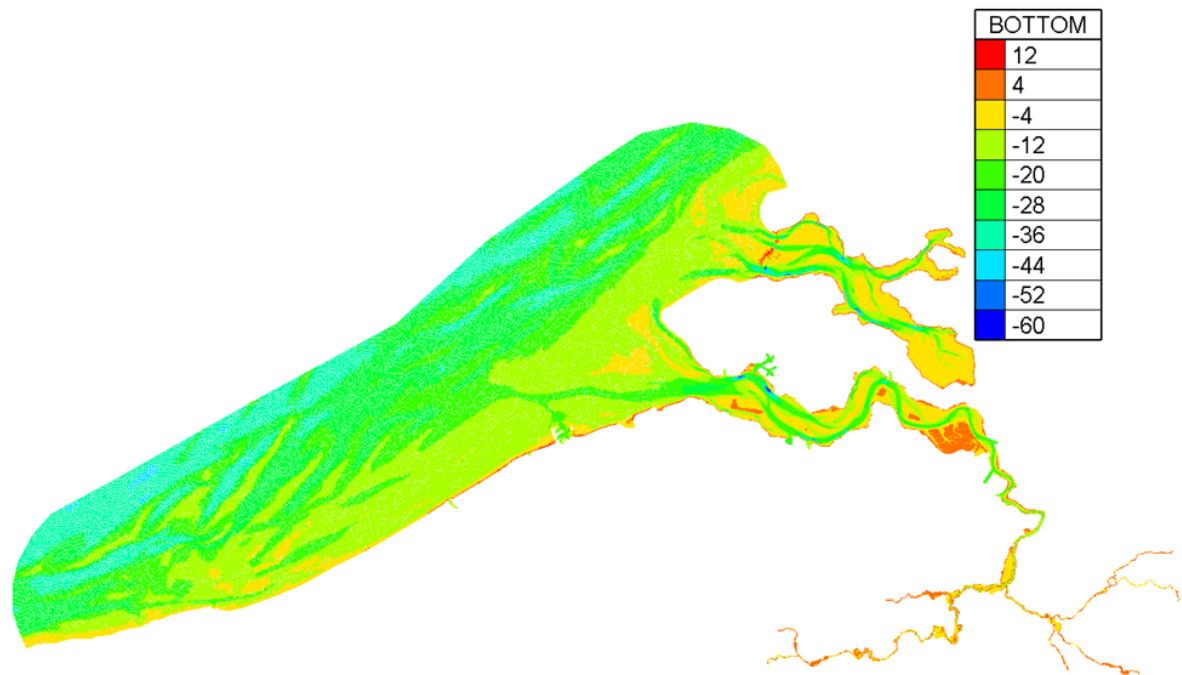


Figure 2: Bathymetry of the SCALDIS model (m TAW)

3.3 Flood Control Areas

In the actualized Sigma Plan for the Sea Scheldt, different restoration techniques are elaborated which combine safety with estuarine restoration (<http://www.sigmaplan.be/>). One example is flood control areas (FCA's) with or without a controlled reduced tide.

In order to include the FCA's in the SCALDIS model, the existing culvert functionality in TELEMAC was extended to better represent the hydrodynamics of water exchange between the Scheldt estuary and these flood control areas (Smolders, 2014 and Teles, this volume). Discharge coefficients for in- and outlet structures are calibrated against measurement data in Lippenbroek and Bergenmeersen. Using this new schematization, all planned FCA's that are foreseen in the Sigma Plan are included in the model.

3.4 Boundary Conditions

The downstream model boundary is located in the North sea. The SCALDIS model is nested in the ZUNO model (Rijkswaterstaat, 2009) from which it gets the downstream boundary conditions for water level and salinity.

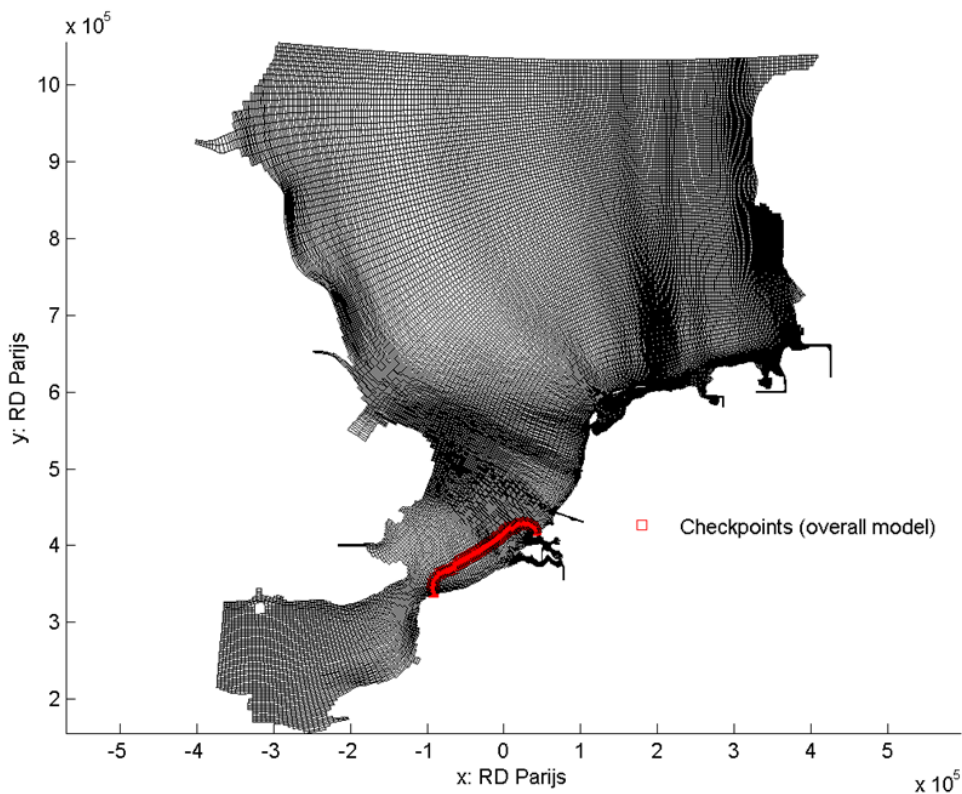


Figure 3: Domain of the ZUNO model (black) and boundary points of the SCALDIS model (red)

A correction of the harmonic components was calculated based on the comparison of the ZUNO results and measurements for a period of 1 year (2013). Phase of M2, M4 and S2 are corrected, together with the average water level Z_0 . Details are given in table 1.

Table 1: Correction in harmonic components from values calculated in the ZUNO model

Component	Correction to value from ZUNO
M2 phase	+4°
M4 phase	-6°
S2 phase	+7°
Z_0 (average water level)	-0,21m

Salinities in ZUNO are corrected based on the comparison of the calculated and measured salinity time series at Vlakte van de Raan. Details of the analysis of the hindcast of 2013 in ZUNO (from which downstream boundary conditions are derived) are given in Maximova et al. (2015).

At the upstream boundaries, measured timeseries of fresh water inflow are prescribed. Additional sources of fresh water are included at Bath and Terneuzen.

3.5 Calculation Time and speed-up

A 3D run with salinity as an active tracer runs with a speed-up of 8,5 on 60 cores (Intel Xeon Westmere X5650 - 2.66GHz Six Core). Including the flood control areas activates the culvert functionality that was added to the code. This slows down the calculation to a speed-up of 3,5. This is linked to the way sources and sinks are implemented in the TELEMAC code. The implementation of the new culvert code makes extensive use of the existing sources and sinks subroutine in TELEMAC. Optimising the sources and sinks subfunction will greatly reduce the cost of using the newly developed culvert functionality. This has been reported as a feature request to the developers in the TELEMAC consortium.

4. CALIBRATION

4.1 Bottom Roughness

The modeled horizontal and vertical tide is calibrated by adapting the bottom roughness, which is represented by Manning's equation for the dimensionless friction coefficient C_f .

$$C_f = \frac{2gn^2}{h^{1/3}} \quad [7]$$

The calibrated roughness field (Manning's n in equation 5) is shown in figure 4.

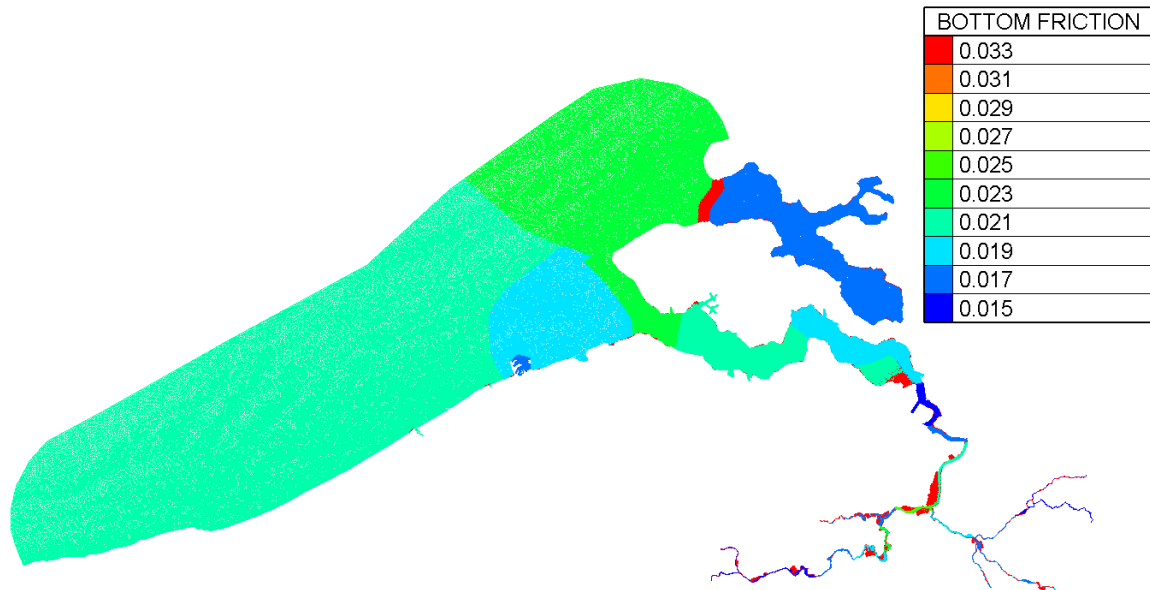


Figure 4: Bed roughness field of the SCALDIS model ($m^{-1/3}s$)

4.2 Cost Function

A weighted dimensionless cost function is calculated for each simulation to assess model performance. Each factor is a particular error statistic with the same unit as the measurements on which they are based. The cost function is made dimensionless by normalizing to the factor score in the reference run. The task of calibration is to minimize this objective function. Within this project we limit the parameter space to roughness in different zones in the model domain.

$$Cost = \sum \frac{Factor_i}{Factor_{i,ref}} * Weight_i \quad [6]$$

Several parameters are selected as factors for the calculation of the cost function. For the vertical tide, the RMSE (Root Mean Square Error) of the complete timeseries, as well as the RMSE of the level of high waters are taken into account. Both modeled and measured water levels are harmonically analyzed using t_tide (Pawlowicz et al., 2002). A vector difference is aggregated over 6 harmonic components and Z_0 (explained in more detail in §5.1). The difference in M2 amplitude between model and measurement is also a factor. By including the amplitude of M2 both in the vector difference as a separate factor, the M2 component gains a higher weight in the total cost than the other harmonic components. This is justified by the fact that M2 is the most important harmonic component in the area of interest.

For the horizontal tide RMAE (Root Mean Absolute Error) of sailed ADCP measurements and RMSE of measured discharges are included as factors.

Table 2 lists the weights used in the cost function (equation 6). Note that the horizontal and vertical tide are given the same weight. This stems from the intended model purpose. The model should be able to accurately describe the evolution of water level over time, with extra emphasis on the prediction of high water. It is equally important however that the model is able to accurately reproduce velocities and fluxes, because it is the intention to use this hydrodynamic model as the basis for sediment transport calculations (both cohesive and non-cohesive) and tracer calculations.

Table 2: Weights used in the cost function

	Zone	Objective Function	Weights [%]		
Vertical Tide (Water Levels)	Western Scheldt	RMSE Time Series	3,50%	14,00%	50%
		RMSE Level High Water	3,50%		
		Vector difference	3,50%		
		delta M2 amplitude	3,50%		
	Eastern Scheldt	RMSE Time Series	1,25%	5,00%	
		RMSE Level High Water	1,25%		
		Vector difference	1,25%		
		delta M2 amplitude	1,25%		
	Lower Sea Scheldt	RMSE Time Series	3,50%	14,00%	
		RMSE Level High Water	3,50%		
		Vector difference	3,50%		
		delta M2 amplitude	3,50%		
	Upper Sea Scheldt	RMSE Time Series	4,25%	17,00%	
		RMSE Level High Water	4,25%		
		Vector difference	4,25%		
		delta M2 amplitude	4,25%		
Horizontal Tide (Velocities and Fluxes)	Western Scheldt	RMAE of Sailed ADCP deep zone	10,00%	13,33%	50%
		RMSE of Discharges	3,33%		
	Lower Sea Scheldt	RMAE of Sailed ADCP deep zone	10,00%	15,83%	
		RMAE of Sailed ADCP shallow zone	2,50%		
		RMSE of Discharges	3,33%		
	Upper Sea Scheldt	RMAE of Sailed ADCP deep zone	15,00%	20,83%	
		RMAE of Sailed ADCP shallow zone	2,50%		
		RMSE of Discharges	3,33%		
			100%	100%	100%

Figure 5 shows the evolution of the dimensionless cost function of the different model runs in model calibration. Model run Scaldis_028_0 corresponds to the lowest cost function and is referred to as the calibrated model.

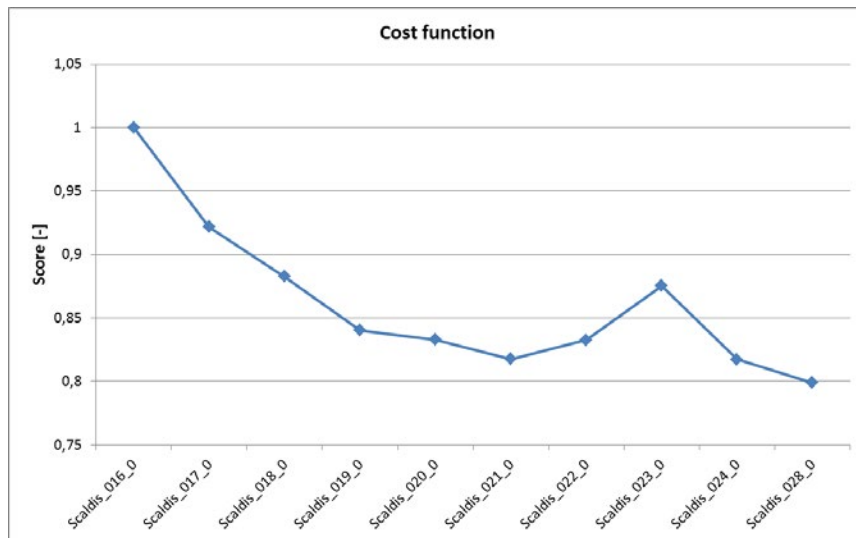


Figure 5: Evaluation of the total dimensionless cost function for the different runs in model calibration. Model run Scaldis_028_0 corresponds to the lowest cost function and is referred to as the calibrated model

5. MODEL SKILL

Model skill is assessed using runs of different periods in 2013. Model and measurements are compared and analyzed using the VIMM toolbox, developed in MATLAB at Flanders Hydraulics Research. This toolbox for skill assessment of hydraulic models automatically determines the difference between a model run and different types of measurements. For this project, more than 5000 figures and 40 tables are generated for each run to give the modeler a deeper insight in the model skill. The toolbox works independently of model software (currently Delft3D, SIMONA and TELEMAC are supported) and measurement data source.

For the sake of readability, of course only a very small subset of these figures can be shown in this article. More detailed information can be found in the technical report (Smolders et al., 2015 and the appendices therein).

5.1 Vertical Tide

The RMSE of high waters and complete water level time series is 7 to 9 cm in the North sea and Western Scheldt, around 10 cm in the Eastern Scheldt and 11 to 14 cm in the Sea Scheldt. The bias of water levels is smaller than 10 cm at most stations.

Modeled and observed tides are harmonically analyzed using t_tide (Pawlowicz et al., 2002). In the region of interest, most tidal energy is present in the M2 tidal component. Figure 6 shows the variation of modelled and measured M2 amplitude and phase along the estuary. The difference between model and measurement in M2 amplitude is smaller than 1 cm in 80% of the stations. The difference in M2 phase is smaller than 2° at 80% of the stations.

From this we can conclude that the model is able to accurately reproduce the celerity of the tidal wave, and the variation of tidal amplitude along the estuary caused by the combination of the funnel shaped system geometry and bottom friction.

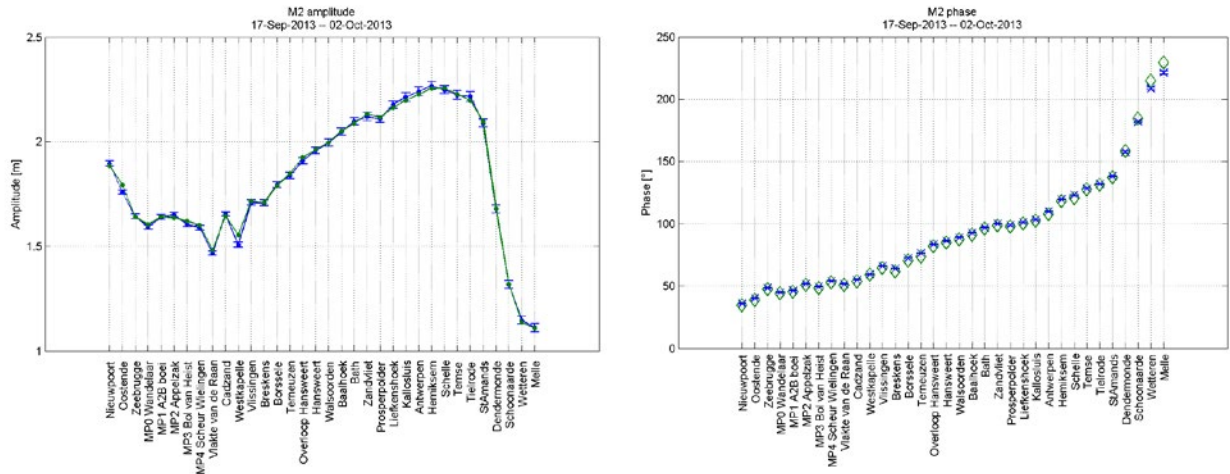


Figure 6: M2 amplitude [m] in the left panel and phase [°] in the right panel for different stations in the North sea and along the Scheldt estuary. The error bars indicate the estimated accuracy of the harmonic analysis. Measurements (in blue) and calibrated model (in green).

Calculated and observed amplitude and phase of different harmonic components can be geometrically combined to a vector difference (Gerritsen, 2003), the lengths of which are summed over selected components and averaged over selected stations (equation 8).

$$e = \frac{1}{N_s} \sum_{i=1}^{N_s} \sum_{j=1}^{N_c} \sqrt{(A_{c,i} \cos(\varphi_{c,i}) - A_{o,i} \cos(\varphi_{o,i}))^2 + (A_{c,i} \sin(\varphi_{c,i}) - A_{o,i} \sin(\varphi_{o,i}))^2} \quad [8]$$

e is the total vector difference with $A_{c,i}$ en $\varphi_{c,i}$ the calculated amplitude and phase of harmonic constituent i and $A_{o,i}$ en $\varphi_{o,i}$ the observed amplitude and phase, summed over N_c components and averaged over N_s stations.

Because the vector difference aggregates error information over different frequencies and different stations, it is a powerful tool during model calibration and validation/verification.

Figure 7 gives shows the stacked vector difference over 6 harmonic components plus Z0 (average water level) and 34 stations in the North Sea and the Scheldt estuary. The lower the stacked graph, the higher the model accuracy at that station. This way the stacked vector difference graph describes the evolution of model skill along the estuary. The sudden decrease in model accuracy in the upstream end of the model domain is attributed to the fact that daily values of fresh water inflow are used as upstream boundary condition. In the upstream end of the Scheldt estuary, discharge still has a significant impact on the vertical tide (water levels). Earlier work has shown that hourly values of fresh water inflow are better to reproduce peak inflows and the effect of peak inflow on water levels, but hourly values were not available in the modeled period.

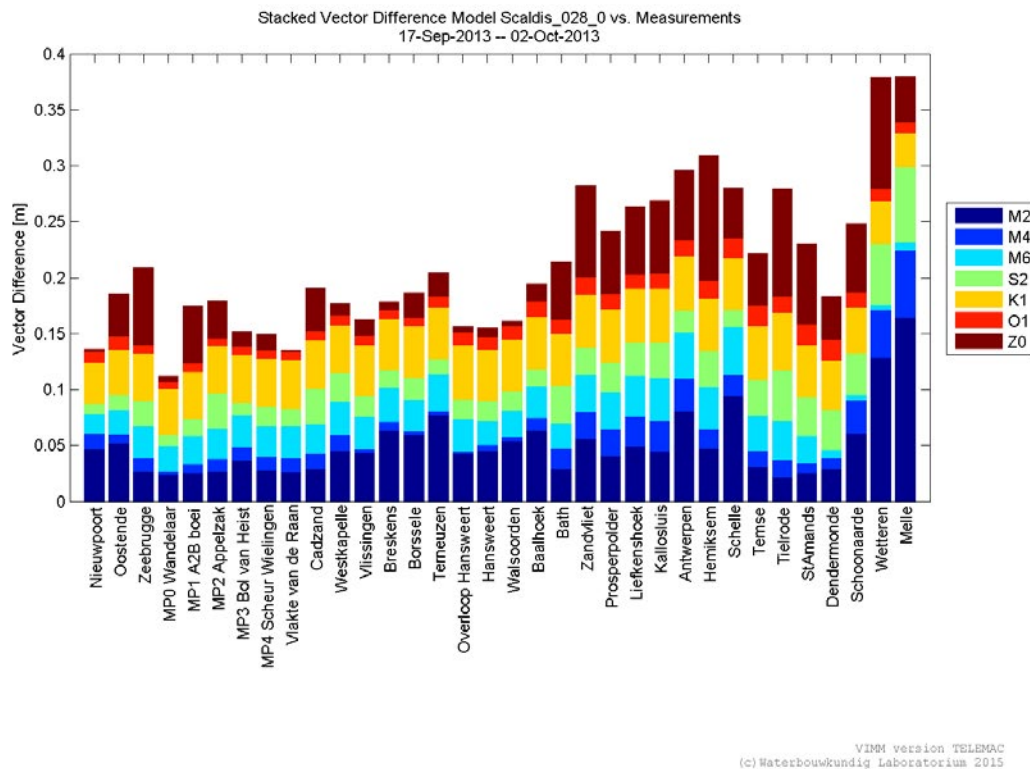


Figure 7: stacked vector difference graph for 34 stations in the North Sea and the Scheldt estuary.

5.2 Horizontal tide

The model is compared to velocity measurements in shallow areas using ensemble analysis or phase averaging where measured and modelled depth averaged velocities are split into individual tidal cycles and averaged out over neap, normal and spring tide.

Phase averaging provides useful information on intratidal dynamics, and focuses the attention on system behavior by averaging out more episodic events.

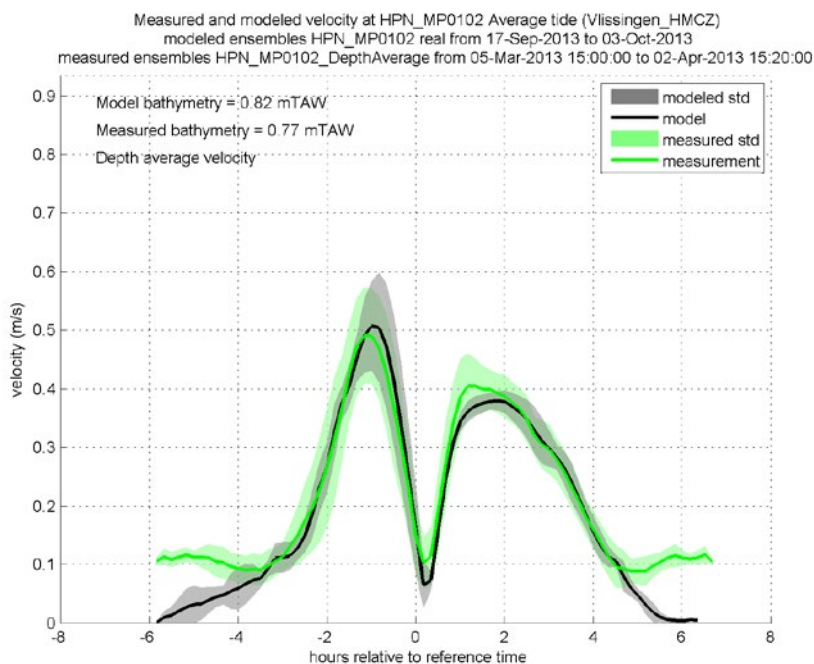


Figure 8: Mean and standard deviation [m/s] over a tidal cycle of the depth averaged current during an average tide at location Hoge Platen Noord in the Western Scheldt.

Figure 8 shows an example of phase averaging applied to depth averaged velocities that are measured by Rijkswaterstaat using a ADCP that has been dug into a shoal in the Western Scheldt (Hoge Platen Noord).

5.3 Salinity

The salinity at Liefkenshoek is compared between model and measurement in figure 9, showing a good agreement, both in absolute value as in the tidal amplitude of the salinity variation. This model result gives confidence that tracer dispersion and related parameters as residence times are accurately described in the model.

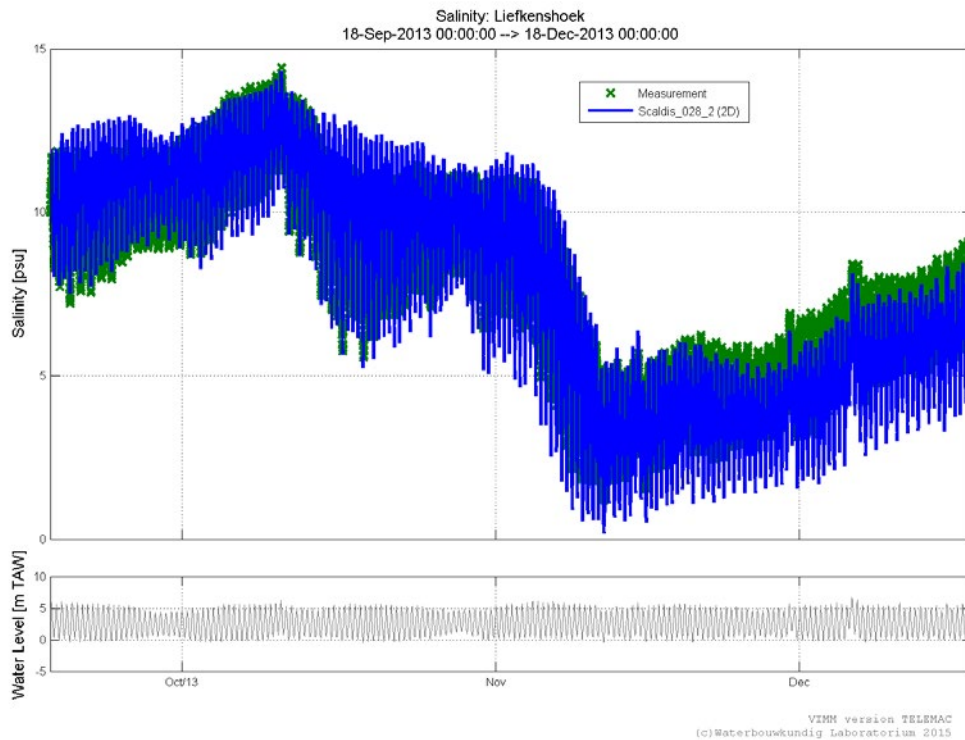


Figure 9: Modelled (blue) and measured (green) salinity. Modelled salinities are depth averaged from the results of the 3D model.

6. CONCLUSIONS

This paper introduces the unstructured SCALDIS model, a new 3D high resolution hydraulics model. Model calibration is done using a weighted dimensionless cost function that attributes equal weight to the horizontal and the vertical tide. The weights are chosen in accordance to the stated model purpose, objectifying and quantifying the process of model calibration.

Assessing model skill can be a tedious and labor intensive work for a modeler. In order to facilitate and partly automate this process, the VIMM toolbox was developed at Flanders Hydraulics Research. This toolbox provides an abstraction layer between the statistical methods that are used for quantifying model skill, the software in which the model schematization is built (currently Delft3D, SIMONA and TELEMAC are supported) and the data source of the measurements. This way, code duplication in between projects and modelers can be avoided. Code quality is guaranteed using a versioning system. By giving the modeler standardized figures and tables that provide a deep insight in model performance, the VIMM toolbox greatly enhances the efficiency of model calibration and quantified skill assessment of hydraulic models.

The quantified model skill of the SCALDIS model shows that the model is well suited to assess the effects of changing the bathymetry and geometry of the Scheldt river on water levels, velocities, tracer dispersion and residence times, and that the hydrodynamics can be used as the basis for sediment transport calculations (both cohesive and non-cohesive).

ACKNOWLEDGMENTS

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