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Statistical synthetic boundary conditions for a large 3D model, Scaldis, to reduce computation time

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Abstract—**This paper describes a methodology of using statistical synthetic boundary conditions which represent water level frequencies for a full year in a shorter period to reduce the computation cost for a large 3D model of the Scheldt estuary, Scaldis. For ecotope mapping water level frequencies of a full year are necessary to create the maps. The model is run for a shorter period which is statistically representative for the entire year.**

I. INTRODUCTION

In the framework of the projects "Integral Plan for the Upper Sea Scheldt" and "Agenda for the Future", an integrated plan is developed, in which navigability, safety and nature are combined. Currently, the capacity of the Upper Sea Scheldt is not sufficient and it hinders traffic flows. The river is classified as class IV route upstream Baasrode (located 113 km from the mouth). In the future it is desired to classify the entire Upper Sea Scheldt as a navigational route of Va class. It is important that the design of the enlargement leads to a multifunctional Scheldt with assets for navigability, a sustainable natural system and guarantees for protection against flooding [1].

An integrated model for the Scheldt estuary is developed in the TELEMAC 3D software. The Scaldis model, a new unstructured high resolution model of the tidal Scheldt is developed for the entire estuary, but with special attention to the upstream parts. The upstream part is represented in the model grid in high resolution resulting in a large extra number of computational nodes.

The model is developed and calibrated for 2013. Afterwards, it is adapted for the year 2050 to analyse the effects of several scenarios on the hydrodynamics, sediment transport and ecology. The expected (until 2050) changes in the bathymetry are implemented in the model. More flood control areas (FCA) with controlled reduced tide (CRT) are active in the model (accordingly to the Sigma plan) [2].The de-embanked areas, FCA's and CRT's got an update of their average bed level to account for sedimentation in these zones. Sea level rise and increasing or decreasing tidal amplitude are taken into account in different scenarios for 2050.

For the ecotope mapping it is necessary to calculate water level frequencies based on a full year. However, it is very costly to run the 3D Scaldis model for such a long period. To limit the calculation time, a different approach is used. The model is run for a shorter period which is statistically representative for the entire year.

This paper describes methodology used for the scenario analysis for the year 2050 with the statistical synthetic boundary conditions (water levels downstream and discharges upstream).

II. THE NUMERICAL MODEL

A. *Calibrated model for 2013*

The TELEMAC model developed in the framework of this project covers a large part of the North Sea, the entire Scheldt estuary and the Eastern Scheldt. Upstream, the model extends to the limits of the tidal intrusion (Figure 1).

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

The model grid consists of 459,692 nodes in 2D mesh and 873,419 elements. In the 3D model we use 5 levels totalling 2,298,460 of nodes with the following distribution of sigma layers : 0D, 0.12D, 0.30D, 0.60D, 1D.

Wind and salinity are included in the model. The most recent available bathymetry is used. The downstream model boundary is located in the North sea. Scaldis is nested in the regional ZUNO model of the southern North Sea. The time series of the water level calculated in ZUNO are defined at the downstream boundary of Scaldis (after correction of the harmonic components) [3, 4]. The upstream boundary is located at the tidal border. There are 8 upstream boundaries with prescribed discharge and free tracer.

Figure 1. Model domain

The model is calibrated for 2013 by comparison of the modeled and measured water levels, discharges and velocities [3]. Afterwards it is adapted for the year 2050 by implementation of the expected changes [5].

B. Model adaptation for 2050

For the analysis of different scenarios in 2050 several changes were implemented in the model.

The model bathymetry for the reference scenario is updated accordingly to the Sustainable Management Plan. This plan focusses on maintaining the fairway with respect for the tidal nature. The designed bathymetry takes into account the needs for navigation and the characteristics of the river. The impact on the tidal nature is limited to specific areas. The hydrodynamic and morphological processes can develop to the extent that the safety and tidal nature are not endangered. The Sustainable Management Plan aims to optimize the existing management efforts for navigation and protection of the river banks [6].

The bathymetry of different alternatives was provided by a project partner (IMDC). It was developed based on the requirements for accessibility for ships of a certain class, shipping simulations and design rules for navigational channels. The shape of the river channel is different in some alternatives due to the changes of river width, bends, sills, etc. The model grid had to be adapted so that it can be used for the calculation of the scenarios with different bathymetries. An example of the changes implemented in the model grid is shown in Figure 2. Bathymetry of two different alternatives for the same location is presented in Figure 3 and Figure 4.

The new grid has 472,400 nodes in 2D and 898,372 elements. This is 12,708 nodes more than the grid of Scaldis 2013 (in 2D). In 3D (5 levels) the new model grid has 2,362,000 nodes in total.

More flood control areas are implemented in the model. An estimation is made about the increase in bed level of the FCA's with CRT and the de-embankments by the year 2050 [5]. An example of FCA/CRT area is given in Figure 5.

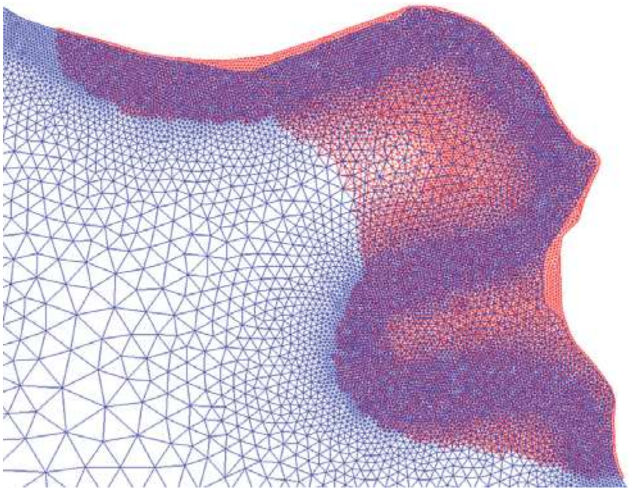

Figure 2. Changes in the model grid near the bend of Kramp in the Upper Sea Scheldt (blue colour: grid 2013, red colour: grid 2050)

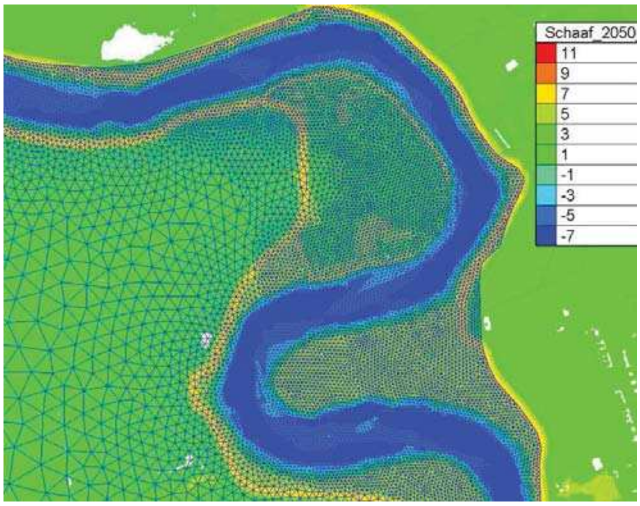

Figure 3. Bathymetry (mTAW) of Schaaf scenario at the bend of Kramp (the adapted grid at the background)

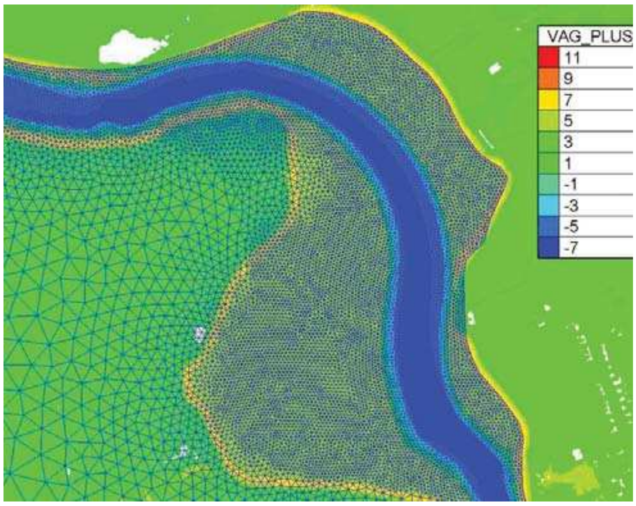

Figure 4. Bathymetry(mTAW) of VaG scenario at the bend of Kramp (the adapted grid at the background)

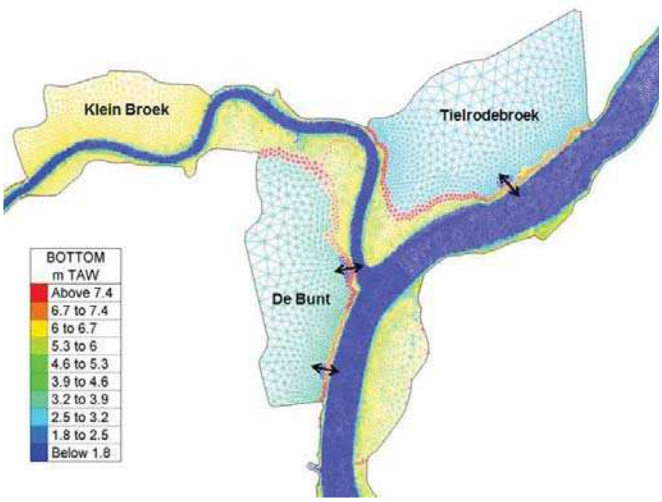

Figure 5. FCA/CRT Tielrodebroek, FCA/CRT De Bunt and the de-embankment of Klein Broek [5]

All these areas were already included in the mesh of the Scaldis model for 2013. In the model representing 2050 culverts connecting FCA's and CRT's are activated. The bathymetry of the flood control areas is updated.

III. METHODOLOGY

A. Introduction

The model 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), under different scenarios (a range of boundary conditions to take into account sea level rise, increasing or decreasing tidal amplitude, high or low discharge).

There are four different alternatives and four scenarios in 2050. This results in 16 simulations. For the ecotope mapping it is necessary to calculate water level frequencies based on a full year. However, it is very costly to run the 3D Scaldis model for such a long period. It takes about 37 hours to simulate 20 days using 180 processors plus it takes several hours to assemble the output files. 2D Selafin file has size of 30 Gb and 3D file is 128 Gb (run of 20 days). It was found that 180 processors is an optimal number for running this model [5]. The use of a larger number of processors does not decrease the simulation time (Figure 6).

In the framework of this project it would be impossible to run the model for the entire year for 16 scenarios. Therefore, it was necessary to find a different approach for the calculation of 1 year model output.

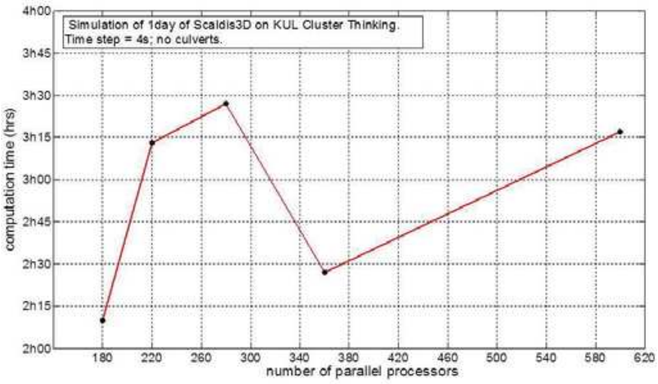

Figure 6. TELEMAC 3D Scaldis model performance on KUL Cluster Thinking on different number of parallel processors [5]

B. Statistical synthetic boundary conditions

Instead of running the model for the entire year two shorter periods with synthetic boundary conditions are simulated.

A period of 3 months is simulated with a synthetic discharge boundary containing events with a return period equal to or smaller than 1/6 year. The downstream boundary is a harmonic boundary without storm surge. In these 3 months a May – June period is represented and also a summer period. This run is the 'normal discharge' scenario. It is representative for the entire year if it is repeated 4 times.

Also the 'events discharge' scenario is simulated. It is a run of about two weeks with a discharge time series that contains 3 discharge events with return periods of 1 year, 1/2 year and 1/3 year. The downstream boundary of this run contains a storm surge period additional to the harmonic signal [1].

The downstream and upstream synthetic boundary conditions are calculated by IMDC. The methodology is described in detail in [7]. The surge is determined based on measurements from 1980 to 2010 at Vlissingen. The independent extreme events are found from the time series by the POT selection. Using these POT values, the empirical surge corresponding to T1, T1/2 and T1/3 was defined. The 30 largest surge events are then used to find the normalized profiles of surge (scaled from 0 to 1) [7]. The time series of the storm surge are found by combination of the normalized profiles and empirical values (Figure 7).

The discharge time series for the 'normal' and 'events discharge' scenarios were calculated by IMDC with the help of 1D hydrodynamic models of the Scheldt basin and its tidal tributaries [7]. The input of these models consists of precipitation time series as determined by the hydrological models. To find the time series representative for the year 2050 the precipitation and evaporation data are perturbed to the year 2050 with the perturbation tool of KULeuven [8]. Long term simulations are performed with the hydrodynamic models for the period 1982 to 2010. Independent events are selected from the time series by the POT selection. The average discharges during all May – June periods are used as a threshold. Based on these POT values the statistical parameters are calculated for the set up of the representative upstream discharges. The normalized profiles are found by normalization (scaling from 0 and 1) of all the time profiles of the biggest yearly May – June events and by calculation of the average profile. The final time series are made by combination of the statistical parameters and normalized profiles.

The 'normal discharge' and 'events discharge' scenarios are simulated for 2013 and for different combinations of alternatives and scenarios in 2050. The water level distribution in specific points, required for the ecotope mapping, is obtained by adding the 4 times 'normal' and 1 time 'events' scenarios.

C. Available data

I. Water levels

The following time series of water levels are available for Vlissingen:

- Storm surge (5 days) for the return periods T1, T1/2 and T1/3;
- Harmonic tide for 3 months for 2013 and 2050 calculated with the overall ZUNO model (a correction of the harmonic components is done);
- Harmonic tide for a short period with an upstream storm for 2013 and 2050.

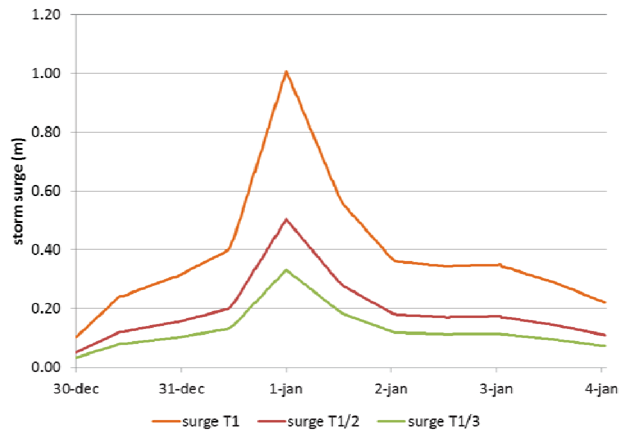

Figure 7. Storm surge at Vlissingen

The downstream boundary of the Scaldis model is located in the North sea. Therefore, the tide in Vlissingen will not be used directly for the calculations. Instead, the storm surge at Vlissingen (Figure 7) will be combined with a harmonic model boundary condition (in the North sea) obtained from a harmonic ZUNO run.

II. Discharges

The following time series of discharge are available for Rupel, Dender (tributaries of the Scheldt) and Scheldt (Leie-Bovenschelde):

- 3 months with representative May – June month and summer month for 2013 and 2050 (Figure 8);
- 7 days with storm events for the return period T1 for 2013 and 2050 (Figure 9);
- 7 days with storm events for the return period T1/2 for 2013 and 2050 (Figure 10).

IV. Scenarios

A. Normal discharge scenario

Downstream boundary of the 'normal discharge' scenario is a harmonic boundary without storm surge. Upstream boundary is a synthetic discharge boundary containing events with a return period equal to or smaller than 1/6 year.

The simulation period is 3 months.

3 months time series of the harmonic tide without storm surge is used as the downstream boundary condition. 3 months discharge time series are used as the upstream boundary conditions.

The maximum discharge of Dender (the second peak in the time series (Figure 8)) is expected 15 hours after the maximum high water at Vlissingen (IMDC, pers. comm.). The maximum high water is selected based on the analysis of 1 year harmonic time series for 2013 and 2050 respectively. The resulting combination of water level and discharge is presented in Figure 11 for the year 2050. A similar analysis was done for 2013.

Different spring-neap cycles are observed during the selected 3 months. Therefore, some of these tides represent average astronomical tide.

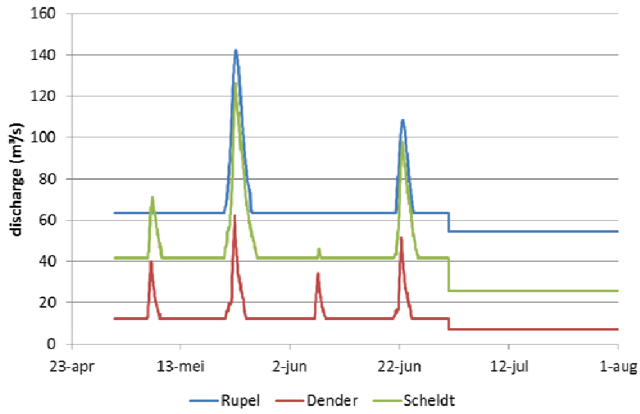

Figure 8. Synthetic discharge time series for 3 months for 2050

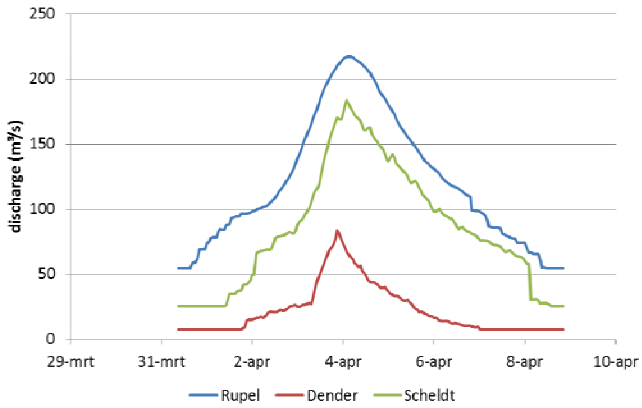

Figure 9. Discharge with return period T1 for 2050

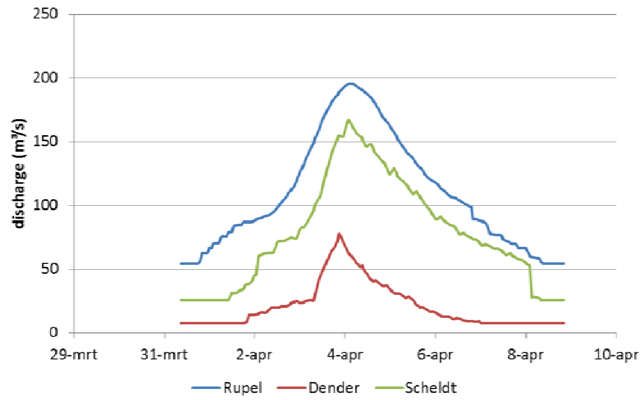

Figure 10. Discharge with return period T1/2 for 2050

The selected periods for the analysis are:

- from 01/08/2013 22:20 to 01/11/2013 21:20 for the current state run;
- from 12/08/2050 22:00 to 12/11/2050 21:00 for the run for 2050. Three days will be added to these periods for the spin up of the model.

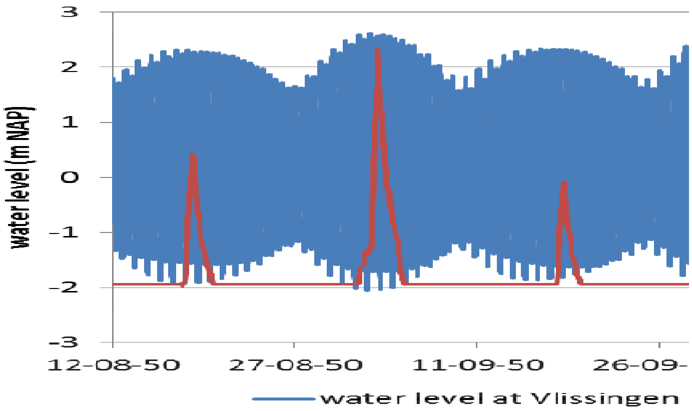

Figure 11. Combination of the time series for 2050 (for 'normal discharge' scenario)

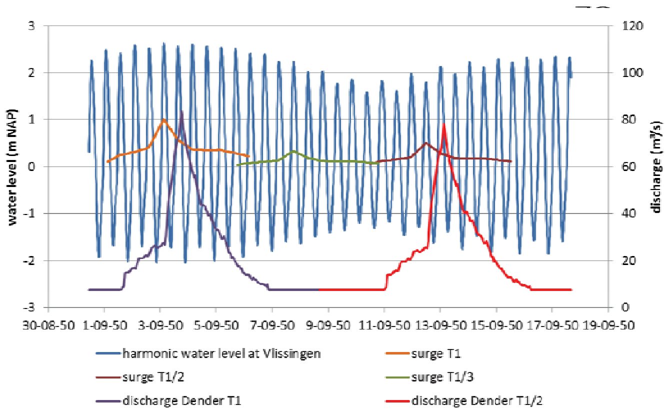

Figure 12. Combination of the time series for 2050 (for 'events discharge' scenario)

B. Events discharge scenario

The downstream boundary is a harmonic signal plus a storm surge signal. The typical storm surge was determined in a statistical way in [7] and is presented in Figure 7.

The upstream boundary is a discharge time series that contain 2 discharge events with return periods of 1 year and 1/2 year.

The simulation period is 2 weeks (or a few days longer depending on the combination of the boundary conditions upstream and downstream).

I. Downstream boundary condition

The water level at Vlissingen calculated in the harmonic ZUNO run is analyzed for the entire year 2013 (and 2050) and the maximum high water is found.

The peak of each storm surge (T1, T1/2, T1/3) should coincide with high water (conservative approach). The time series of the T1 surge is shifted so that the peak of T1 surge coincides with the highest high water at Vlissingen (23/08/2013 03:20 for the current state run, 03/09/2050 3:00 for 2050 run). The same surge time series are used for 2013 and 2050.

The time series of the surges with return periods T1/3 and T1/2 are made to coincide with high waters too. The surges are combined so that there are about 4.5 days between their peaks (Figure 12). To decrease the simulation period we let surges overlap for a limited time. When they overlap, the highest surge is taken for the calculation. The surge signal will be added to the harmonic water levels to get the downstream boundary condition of the Telemac model.

II. Upstream boundary condition

In total 14 days of discharge time series are available (7 days for T1 and 7 days for T1/2 return periods).

The maximum discharge at Dender is observed 15 hours after the maximum surge at Vlissingen. The peak of discharge T1 is therefore put 15 hours after the peak of surge T1; the peak of discharge T1/2 is put 15 hours after the peak of surge T1/2.

When no data are available (between discharges T1 and T1/2) a constant average discharge is used upstream. To decrease the simulation period we put the surge T1/3 between surges T1 and T1/2 (Figure 12).

If the downstream and upstream boundary conditions are combined in the way described above the following periods should be included in the analysis:

- from 20/08/2013 22:20 to 06/09/2013 12:20;
- from 31/08/2050 11:00 to 17/09/2050 16:00.

Three days will be added to these periods for the spin up of the model.

C. Tidal range scenarios

The model will be used to evaluate the effect of an increased and reduced tidal amplitude near Schelle and further upstream in the Upper Sea Scheldt. The increase and decrease of the amplitude will be enforced by changing the roughness in the Western Scheldt. By changing the roughness, the tidal propagation will be influenced, without simulating specific measures in the downstream parts of the estuary (e.g. creating additional flooding areas, deepening, etc.) [1].

Tidal range scenarios A+, A0 and A- will be modeled. In these scenarios the tidal amplitude at Schelle is 5.70, 5.40 and 5.00 m respectively (Table 1).

A necessary change of the bed roughness in the Western Scheldt is found by the sensitivity analysis. First, a modeled tide with a tidal amplitude of 5.40 m at Schelle was found in the calibrated model run. Afterwards a constant change of the roughness field of the Western Scheldt was applied (the area is shown in Figure 13). Different values of the roughness correction were tested (Figure 14).

When the bed roughness is decreased by 0.00426 $m^{-1/3}s$, the tidal amplitude at Schelle increases and becomes about 5.70 m. The increase of the roughness field by 0.00554 $m^{-1/3}s$ results in the tidal amplitude of about 5 m at Schelle.

TABLE I. TIDAL RANGE SCENARIOS

Scenario	Tidal amplitude at Schelle (m)
A+	5.70
A0	5.40 (current tidal range)
A-	5.00

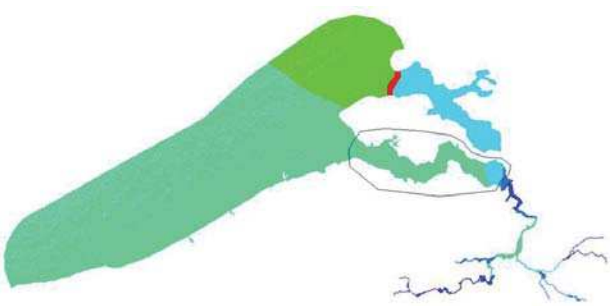

Figure 13. Bed roughness field of the Scaldis model (the polygon indicates the area where the bed roughness is adapted)

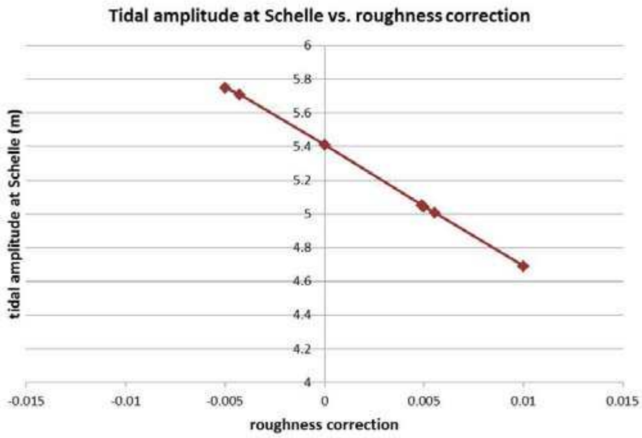

Figure 14. Plot of the tidal amplitude at Schelle vs. roughness correction

D. Sea level rise scenarios

The sea level rise scenarios in this study are based on the KNMI climate scenarios for the Netherlands [1]. The following runs will be modeled for 2050:

- the "low" scenario (CL, +15 cm in 2050);

- the "high" scenario (CH, +40 cm in 2050).

The downstream boundary conditions for year 2050 will be increased with these values.

The tidal range scenario A+ will be combined with the sea level rise CH. The tidal range scenario A- will be combined with the sea level rise CL. More information about the scenarios is given in [1].

V. CONCLUSIONS

This paper describes methodology used for the scenario analysis for the year 2050 with the statistical synthetic boundary conditions.

The model is developed and calibrated for 2013 in the TELEMAC 3D software. Afterwards, it is adapted for the year 2050 to analyse the effects of several scenarios on the hydrodynamics, sediment transport and ecology. The expected (until 2050) changes in the bathymetry are implemented in the model.

For the ecotope mapping it is necessary to calculate water level frequencies based on a full year. To limit the calculation time, two shorter periods ('normal discharge' (QN) and 'events discharge' (QE) runs) with synthetic boundary conditions are simulated instead of running the model for the entire year.

The output of the QN and QE runs is combined to produce the time series for each point for a period 4*QN + QE (which represents one year). These time series are used to calculate percentiles of water levels, tidal amplitudes, maximum and average flood and ebb velocities, bed shear stress, etc., which will be used for the ecological analysis.

REFERENCES

[1] IMDC/INBO/UA/WL (2015). Modelling instruments for Integrated Plan Upper Sea Scheldt. I/NO/11448/14.165/DDP

[2] Smolders S., Leroy A., Teles M.J., Maximova T., Vanlede J., (2016). Culverts modelling in TELEMAC-2D and TELEMAC-3D. Proceedings of the 23rd TELEMAC-MASCARET User Conference, 11-13 October 2016. Paris, France

[3] Smolders, S.; Maximova, T.; Vanlede, J.; Verwaest, T.; Mostaert, F. (2015). Integraal Plan Bovenzeeschelde: Subreport 1 – 3D Hydrodynamisch model Zeeschelde en Westerschelde. WL Rapporten, 13_131. Flanders Hydraulics Research: Antwerp, Belgium

[4] Vanlede, J.; Smolders, S.; Maximova, T.; Teles, M. J. (2015). The unstructured Scaldis model: a new 3D high resolution model for hydrodynamics and sediment transport in the tidal Scheldt. Proceedings of the 36th IAHR World Congress. 28 June – 3 July, The Hague, the Netherlands

[5] Smolders, S.; Maximova, T.; Vandenbruwaene, W.; Vanlede, J.; Verwaest, T.; Mostaert, F. (2016). Integraal Plan Bovenzeeschelde: Deelrapport 5 – Scaldis 2050. WL Rapporten, 13_131. Flanders Hydraulics Research: Antwerp, Belgium

[6] IMDC (2015a). Duurzaam Beheerplan Boven-Zeeschelde. Duurzame bathymetrie. I/RA/11448/14.240/JFA/

[7] IMDC (2015b). Bepalen van randvoorwaarden voor de referentiesituatie (2050) m.b.t. debiet en waterstand. I/NO/11448/15.128/TFR/

[8] Ntegeka V., Willems P., (2009) CCI-HYDR Perturbation Tool: a climate change tool for generating perturbed timeseries for the Belgian climate, Manual version January 2009, K.U.Leuven – Hydraulics Section & Royal Meteorological Institute of Belgium