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REPORT

Flemish Government - Department of Mobility and Public Works

Maritime Access Division

Evaluation of the external effects on the siltation in Deurganckdock (2014 - 2017)

Report 1.25: Model study of transient and external effects

10 October 2018 - version 1.00

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Document Identification

Title	Report 1.25: Model study of transient and external effects
Project	Evaluation of the external effects on the siltation in Deurganckdock (2014 - 2017)
Client	Flemish Government - Department of Mobility and Public Works - Maritime Access Division
Tender	16EF/2013/27
Document ref	I/RA/11449/18.105/THL/
Document name	K:\PROJECTS\11\11449_P006421 - Evaluatie externe effecten aanslibbing DGD III (2014 - 2017)\10-Rap\1.25_RA18105_Delwaq study of transient effects\1.25_RA18105_Delwaq study of transient effects Modelstudyoftransienteffects_v1.0.docx

Revision

Version	Date	Description	Author	Checked	Approved
1.0	01/10/18	Concept	T.Lanckriet (IMDC) K.Cronin (Deltares)	G.van Holland (IMDC) T. Van Kessel (Deltares) J. Vanlede (FHR)	J.Claus (IMDC)

Approval

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Checked	GVH	Gijsbert van Holland (Signature) Digitally signed by Gijsbert van Holland (Signature) Date: 2018.10.19 15:00:42 +02'00'
Approved	JCA	Jan Claus (Signature) Digitally signed by Jan Claus (Signature) Date: 2018.10.19 14:48:31 +02'00'

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1. INTRODUCTION

1.1 THE ASSIGNMENT

This report is part of a set of reports concerning the project 'Evaluation of the external effects on the siltation in Deurganckdok (2012 - 2014)'. The terms of reference were prepared by 'Department of Mobility and Public Works of the Flemish Government, Maritime Access Division' (16EF/2011/28). Part 1 of the study was awarded to International Marine and Dredging Consultants NV in association with Deltares on February 3rd 2012.

This study is a follow-up study on the study 'Evaluation of the external effects on the siltation in Deurganckdok' (2009 - 2012) and the study 'Siltation Deurganckdok (2006 - 2009)'.

The data and information that are used in this project are provided or collected by Flanders Hydraulics Research, Maritime Access Division and the Agency for Maritime Services and Coast. Flanders Hydraulics Research provided data on discharge, tide, salinity and turbidity along the river Scheldt. Maritime Access Division provided maintenance dredging data. Agency for Maritime Services and Coast – Coast Division provided depth sounding and density profile measurements.

The purpose of this study is to evaluate the external effects on the siltation in the Deurganckdok (DGD). External effects are those effects caused by recent human interventions in and around Deurganckdok:

- The deepening and widening of the navigational channel in the Lower Sea Scheldt between the entrance of the Deurganckdok and the access channels to the locks of Zandvliet-Berendrecht (2008–2010) (a.k.a. Drempel van Frederik);
- The deepening of the entrance to the Deurganckdok by removing the sill at the entrance (2009–2010);
- The construction of the Current Deflecting Wall (CDW) downstream of the entrance of the Deurganckdok (2010–2011);
- The change in maintenance depth or strategy of the Deurganckdok (2011);
- The construction of the Kieldrecht lock at the landward end of Deurganckdok (2011-2016)

It is noted that investigating the consequences of the changes in the dock (maintenance) on the sediment concentrations in the river is not part of this scope.

1.2 SCOPE OF THE REPORT

The aim of the present report is to investigate the transient (=non-steady state) evolution of suspended sediment concentration and mud dredging volume in the Scheldt in relationship to the Deurganckdok in the period after the opening of the dock, the period around 2011 when the upstream discharge was reduced and the maintenance dredging strategy changed, and in the years following the peak.

The study is performed using long-term numerical model simulations over the period 2006-2015. In consultation with the client, it was opted to perform the simulations using the existing LTV-model instruments, consisting of the NEVLA3D model for hydrodynamics and a DELWAQ model for sediment transport, with an offline coupling between the two models (van Kessel *et al.*, 2010).

1.3 READING GUIDANCE

Chapter 2 provides a further introduction and overview of the study, including the observations that motivated it, a list of the model scenarios that are considered, and the research questions that will be answered. The setup of the numerical model train is discussed in Chapter 3. Model results are presented in Chapter 4, followed by a general discussion in Chapter 5. Conclusions are offered in Chapter 6, as well as recommendations for further research.

2. STUDY OVERVIEW

2.1 BACKGROUND

2.1.1 Observations

Within estuaries, a balance exists between the net import/export of fine sediment from the seaward and landward boundaries, and the local storage of sediment within the estuary system (predominantly in the bed, but also in the water column). This balance is determined by both natural processes and by human interventions (large infrastructure, dredging works). This general truth regarding estuaries also applies to the Scheldt estuary and Deurganckdok.

Since the opening of Deurganckdok in 2005, suspended sediment concentrations (SSC) in the Scheldt have changed significantly. There is broad agreement that maintenance dredging and disposal works (including, but not limited to the Deurganckdok), have contributed to the changes in sediment concentrations. Based on a multivariate regression model of dredging volumes, upstream discharge, tidal characteristics and sediment concentrations, a conceptual model was established by IMDC (IMDC, 2016). Fluctuations in the upstream discharge create a downstream/upstream migration of the estuarine turbidity maximum (ETM). Periods of increased maintenance dredging activity are linked with elevated suspended sediment concentrations, both in the vicinity of the sediment disposal zones as well as further upstream.

In 2011, a peak occurred in suspended sediment concentrations, in concurrence with an exceptionally dry year (low upstream discharge, Figure 2-2). The 2011 peak in suspended sediment concentrations was mostly observed in the continuous turbidity sensors at Oosterweel, (near the sediment disposal area, Figure 2-3) but also in the upstream station at Driegoten (Figure 2-4). At the Boei 84 measurement station, downstream of the dredging and disposal areas, no peak is observed in 2011 (Figure 2-5). In the SSC measurements based on samples, a more gradual peak is observed (Figure 2-6).

In the same year 2011, a change in the maintenance dredging strategy at Deurganckdok occurred (Figure 2-1). The dock, which was originally constructed with a bottom level of -18.0 m TAW, was maintained with an intervention level of -15.5 m TAW between 2005 and 2010[1], essentially creating a sediment sink as the dock volume between -18.0 m TAW and -15.5 m TAW was allowed to fill with (fine) sediment. In 2011, the intervention level was reverted to -18.0 m TAW, generating a (temporary) increase in dredging and disposal volumes as the sediment below -15.5 m TAW was removed from the dock.

In the period after 2011, both suspended sediment concentrations and maintenance dredging volumes were lower than in 2011 (but still higher than in 2010), although SSC decreased more slowly than maintenance dredging volumes. In the following years (2013-

[1] It is noted that the dock was gradually opened between 2005 and 2008, and was only fully operational in April 2008. This is reflected in Figure 2-1, in which the dredging volume in Deurganckdok gradually increases from 2005 to 2008.

2017), the dredging intensity in Deurganckdok was similar to the period 2008-2009, but with a different maintenance depth.

Other measures which may have affected the dredging volume in Deurganckdok are the removal of a sill (shallow area) at the entrance of Deurganckdok in 2009, the third deepening and widening of the Scheldt (which was executed in 2009-2010 in the Belgian parts of the estuary), the construction of a turning circle in front of the Europa terminal in 2009, the construction of the Current Deflecting Wall in 2010 and the opening of the Kieldrecht Lock in 2016. In addition, the stopping of sediment disposal in the Waaslandhaven (in which mud was removed from the system) in 2000, as well as the deepening[2] of the drempel van Zandvliet in 2001 – 2003, may have generated a response in the system that was still ongoing in 2005 and beyond. It is also noted that from 2010 the maintenance volume (mud) at the Drempel van Frederik increased in importance, with high values in 2011 as well.

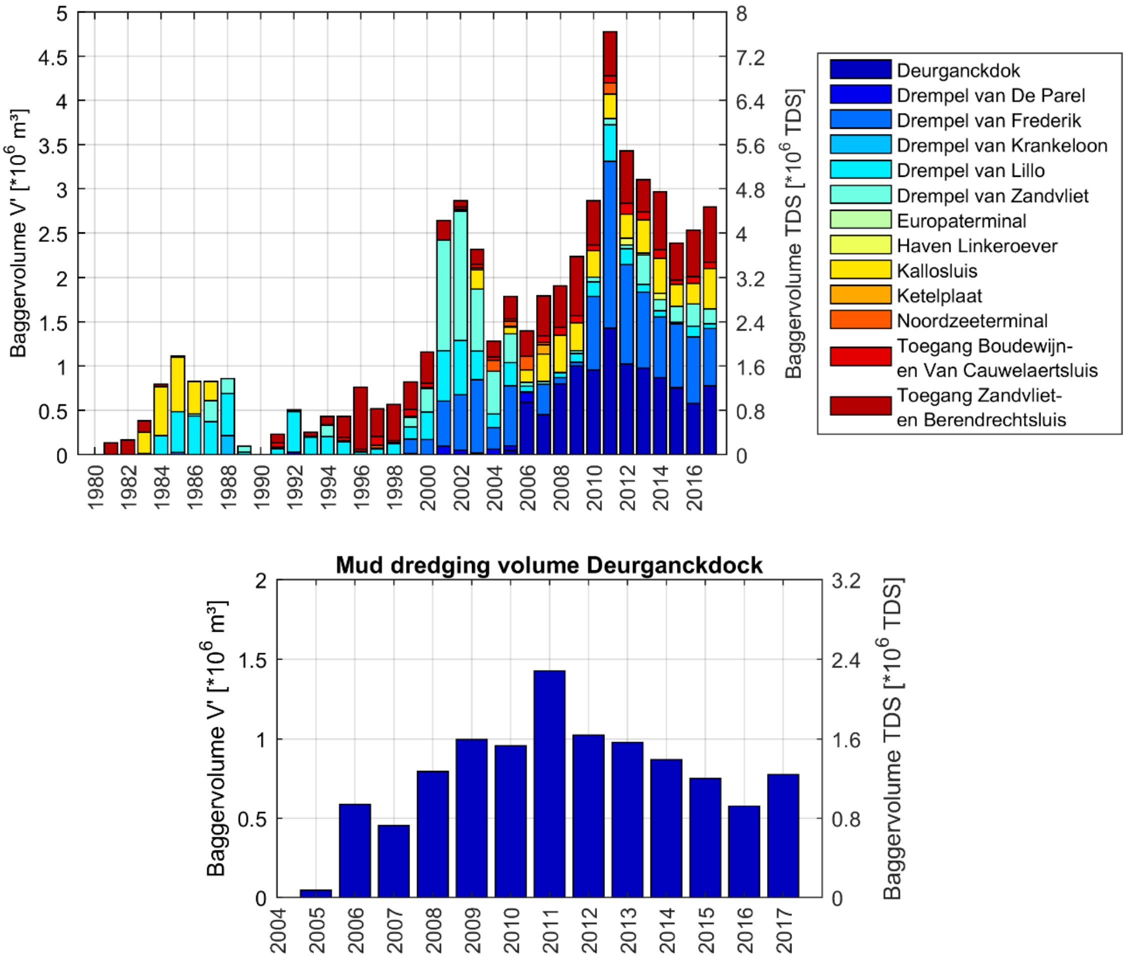

Figure 2-1: Maintenance dredging volumes off all maintenance zones including Deurganckdok (top) and only Deurganckdok (bottom).

[2] Note that maintenance and capital dredging in the statistics were only distinguished from 2009 onwards.

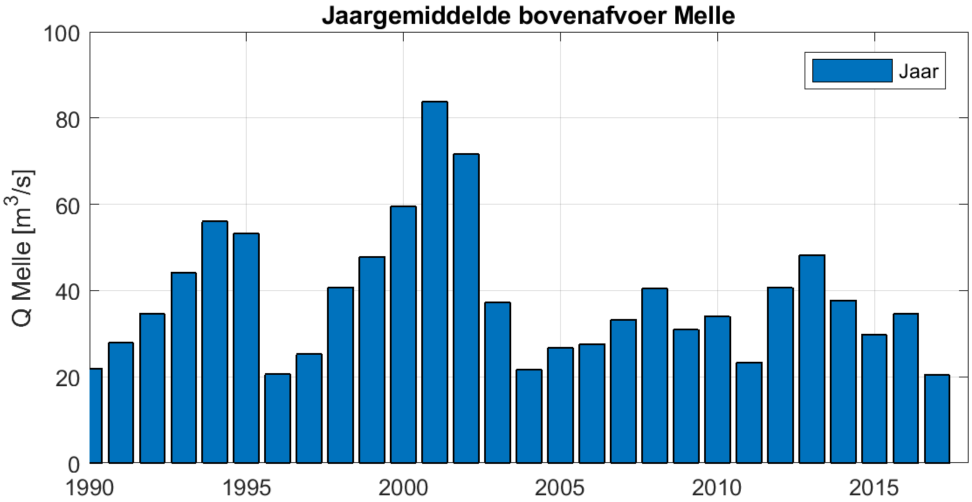

Figure 2-2: Yearly-average upstream discharge at Melle.

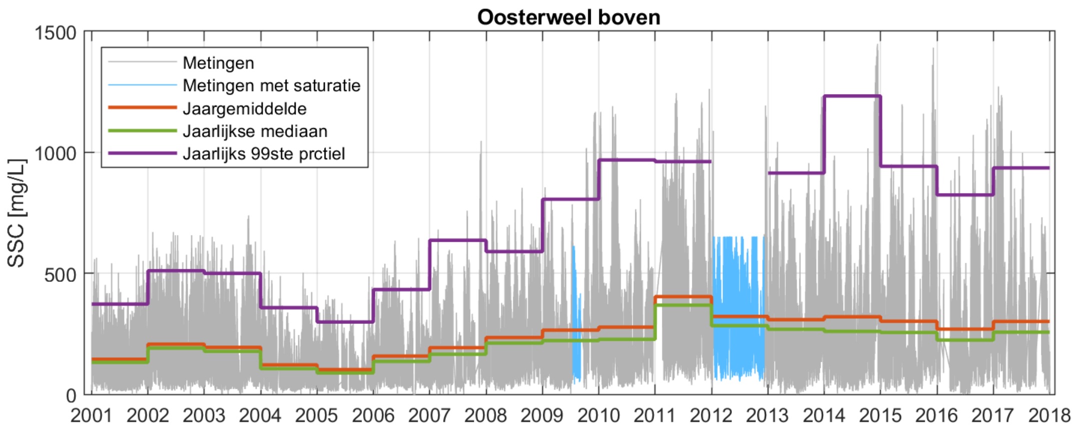

Figure 2-3: Continuous sediment concentration measurements at Oosterweel.

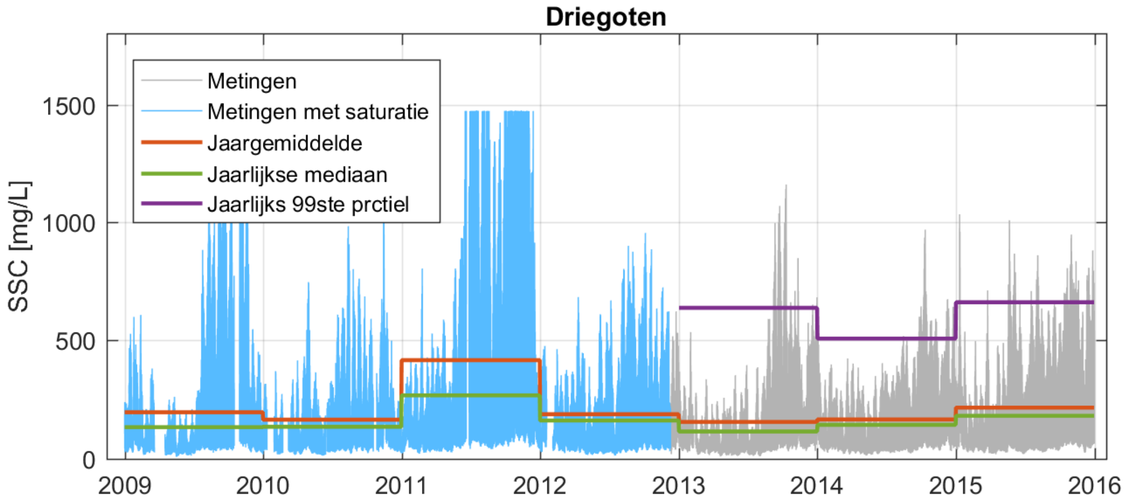

Figure 2-4: Continuous sediment concentration measurements at Driegoten.

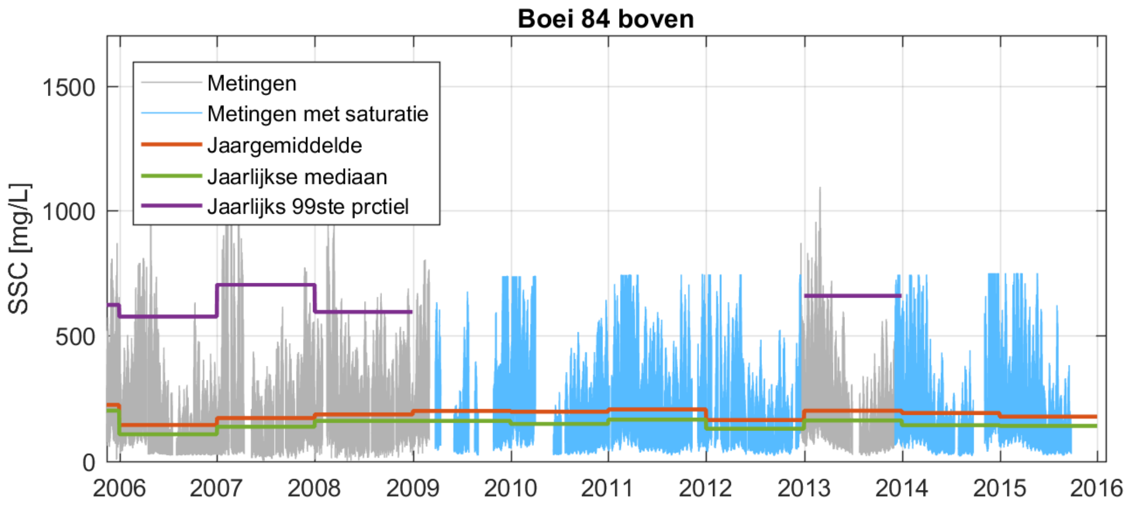

Figure 2-5: Continuous sediment concentration measurements at Boei 84.

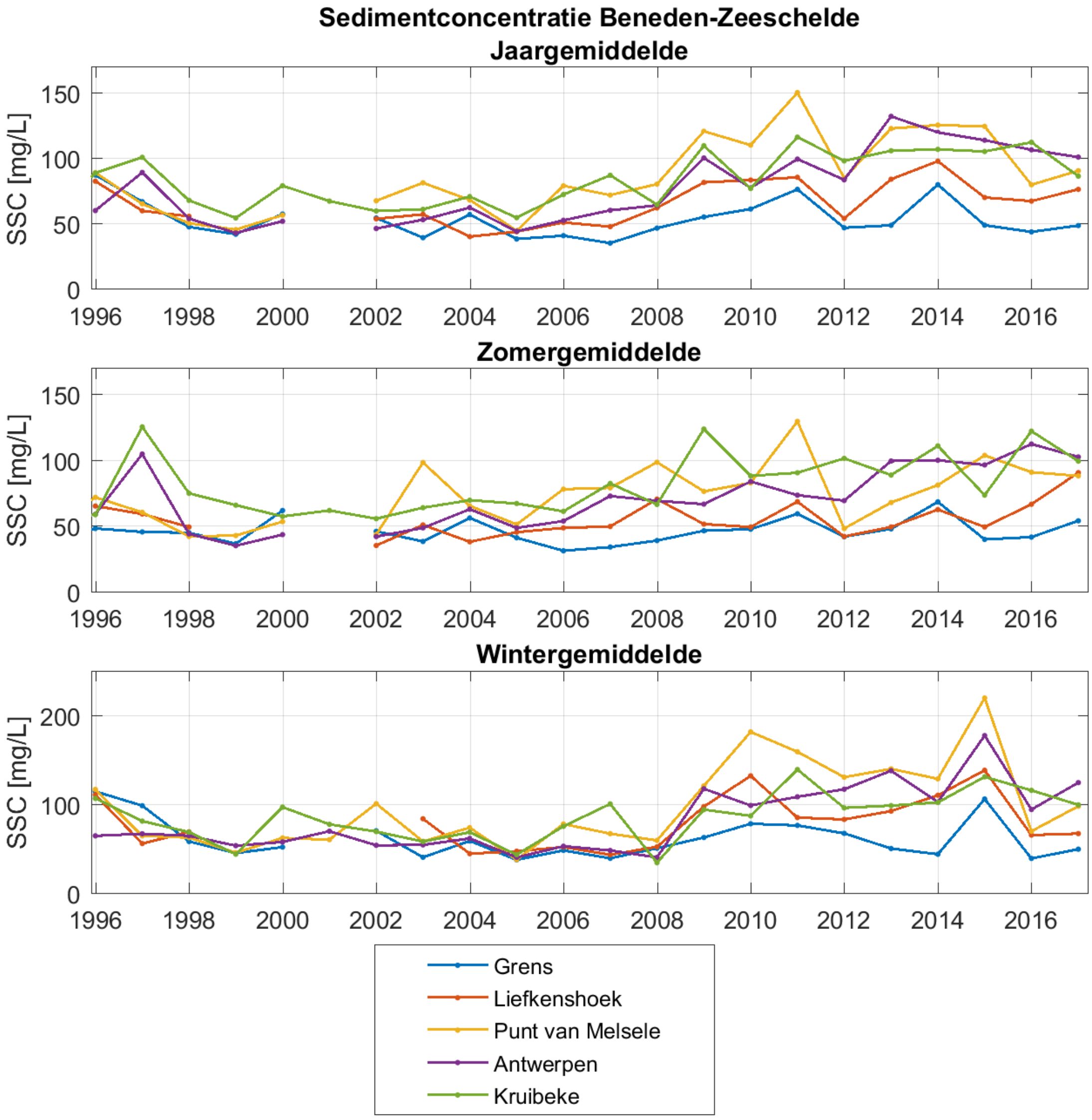

Figure 2-6: Yearly- and seasonal average SSC measurement from OMES samples (Maris and Meire, 2016).

2.1.2 Hypotheses

There are multiple hypotheses regarding the elevated SSC levels in 2011. One possible explanation is that due to the increased dredging and disposal activity in 2011, the sediment input temporarily exceeded the estuary system’s capacity for processing and storing the sediment, causing a (local and temporary) increase in the sediment concentrations in the water column. As the excess sediment dispersed and was stored in deposition areas such as mudflats, SSC values decreased again.

A second hypothesis is that due to the (low) upstream discharge, sediment concentrations increased in the system or in the ETM region, or that an upstream shift of the ETM occurred so that certain locations (possibly including the Deurganckdok entrance) experienced a higher SSC (see conceptual model of IMDC, 2016). In this case, the elevated SSC in 2011 was rather a result of natural fluctuations in the boundary conditions.

2.2 AIM OF THE STUDY

The aim of the present study is to investigate the transient (=non-steady state) evolution of suspended sediment concentration and mud dredging volume in the Scheldt in relationship to the Deurganckdok. The evolution is traced for the period after the opening of the dock, around the SSC peak in 2011, as well as in the years following the peak.

The study is performed using long-term numerical model simulations over the period 2006-2015 in which both the boundary conditions (upstream discharge) and the dredging strategy changes over time. The simulations are performed using the existing LTV-model instruments, consisting of the NEVLA3D model for hydrodynamics and a DELWAQ model for sediment transport, with an offline coupling between the two models (van Kessel *et al.*, 2010). Using this well-established and validated model train reduces model uncertainties during the execution of the project.

2.3 MODEL SCENARIOS

Since the analysis focuses on long-term evolutions in which the changing boundary conditions play a central role, the simulations consist of three representative hydrodynamic years, which are combined with different dredging strategies to form three different 15-year simulation periods.

2.3.1 Hydrodynamic simulations

Three representative years of hydrodynamics were simulated:

A. Reference year (including upstream discharge and seaward boundary conditions). The bathymetry of 2014 (removal of the sill at the Deurganckdok entrance, construction of CDW[3] and lower dredging maintenance depth in Deurganckdok (reference case).
B. Q-2011: Measured upstream discharge from 2011. Seaward boundary conditions are held equal to simulation A to focus on effect of upstream discharge. All other aspects are held equal to simulation A.
D. Bathymetry-2009: Bathymetry of Deurganckdok and entrance sill is changed to the level of 2009. All other aspects are held equal to simulation A.

It is noted that the bathymetry of the three scenarios differs only inside and in the direct vicinity of the Deurganckdok. As such, the deepening of the Lower Seascheldt of 2008-2009 is included in all scenario's and therefore not part of the present investigations.

The year 2014 was selected as the reference year for upstream discharge boundary conditions in simulations A and D. The three selected hydrodynamics scenarios allow to investigate the effect of the opening of Deurganckdok, the change of the maintenance level and the effect of a reduced upstream discharge.

[3] As the Current Deflecting Wall (CDW) is not included in the existing numerical model, it is not included in the simulations.

2.3.2 Mud transport simulations

The mud simulations consist of one spin-up simulation (A0) and three 15-year production runs for the period 2006-2015 to investigate the different research questions detailed in §0. The production runs are listed in Table 2-1 and consist of a series of (offline-coupled) hydrodynamic simulations as described in §2.3.1:

0. **Spin-up period without Deurganckdok** (A0). This simulation uses a repeating series of hydrodynamics from simulation A, starting with no sediment on the bed and in the water column. As sediment enters the domain from the upstream and downstream boundaries, a natural arrangement of sediment on the bed and in the water column forms until an equilibrium state is reached. The result of this simulation is used as the initial condition for the three production runs.
   Note that the Deurganckdok is included in the hydrodynamic simulation A. However, in the sediment transport simulation A0, deposition in the dock is prevented to emulate the sediment dynamics without the dock. The fact that the Deurganckdok is present in the hydrodynamics in simulation A0 may cause some dissimilarities with observations in the first years after the opening of the dock; these dissimilarities are further discussed in §5.1.
1. **Impact of reduced upstream discharge.** Bathymetry of 2014 is used for entire simulation, and in 2011 a year with lower discharge is imposed. Hydrodynamic forcing for periods 2006-2010 and 2012-2015 are from simulation A, and for 2011 from simulation B. The dock is maintained following the post-2011 dredging approach.
2. **Impact of not deepening the dock**. Entire period 2006-2015 is simulated with dock bathymetry of 2009 (hydrodynamic simulation D). The dock is maintained following the pre-2011 dredging approach.
3. **Impact of lower intervention level in the dock.** Period 2006-2010 with original dock bathymetry (hydrodynamic forcing from simulation D). Period 2011-2015 with deepened dock (hydrodynamic forcing from simulation A). In 2011 the dredging approach is changed. As a result, in 2011, the mud disposal volume is temporarily increased due the lowered maintenance depth in the dock (delayed maintenance).

Table 2-1: Overview of 15-year production simulations.

	<'05	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
1. Reduced upstream discharge	A_0	A_1	A_2	A_3	A_4	A_5	B_6	A_7	A_8	A_9	A_{10}
2. Not deepening Deurganckdok	A_0	D_1	D_2	D_3	D_4	D_5	D_6	D_7	D_8	D_9	D_{10}
3. Lower intervention level in Deurganckdok	A_0	D_1	D_2	D_3	D_4	D_5	DA_6	DA_7	DA_8	DA_9	DA_{10}

It is noted that the real historic development, in which both a reduced upstream discharge and a lowering intervention level in Deurganckdok occurred in 2011, is not simulated.

Instead, the two aspects (discharge and intervention level) are split in scenarios 1 and 3 to investigate their relative importance.

2.4 RESEARCH QUESTIONS

The numerical simulations were designed to answer the following research questions:

- What is the effect of a dry year? This is investigated by comparing simulations B6 and A5 in simulation 1.
- How does the system restore after a dry year? This is investigated using simulation 1, by comparing the simulation B6 (2011) with the following years (A7-A10).
- What is the initial impact of deepening the dock? This is investigated by comparing simulations D6 and DA6.
- How does the system restore itself after a period of deepening and increased dredging activity? This is investigated by comparing the simulations 2 and 3, and in particular the period after 2011 (simulations DA7-10 and D7-D10).
- How does the system evolve after the opening of the dock in the absence of reduced upstream discharge and other external factors? This is investigated by analyzing simulations D1-D5 with the simulation results from before opening Deurganckdok (A0).
- How would the system have evolved if the intervention level in the dock was held at 18.0 m TAW throughout the entire period? This is investigated by comparing the simulations 1 and 2 over the period 2006-2010 (A1-A5 and D1-D5).

3. MODEL SETUP

3.1 HYDRODYNAMIC MODEL

The setup of the hydrodynamic model is described in detail in the memo “Update of the NEVLA3D model to the year 2014” (Chu, 2018), which is included as Annex A of this report.

The hydrodynamic model is the NEVLA3D model, a 3D model of the Dutch and Belgian parts of the Scheldt Estuary using the version 2010 of the SIMONA software, that was calibrated by Vanlede et al. (2015). For the simulations used in the present study, the bathymetry of the existing NEVLA3D model was adjusted to the 2014 bathymetry (Figure 3-1).

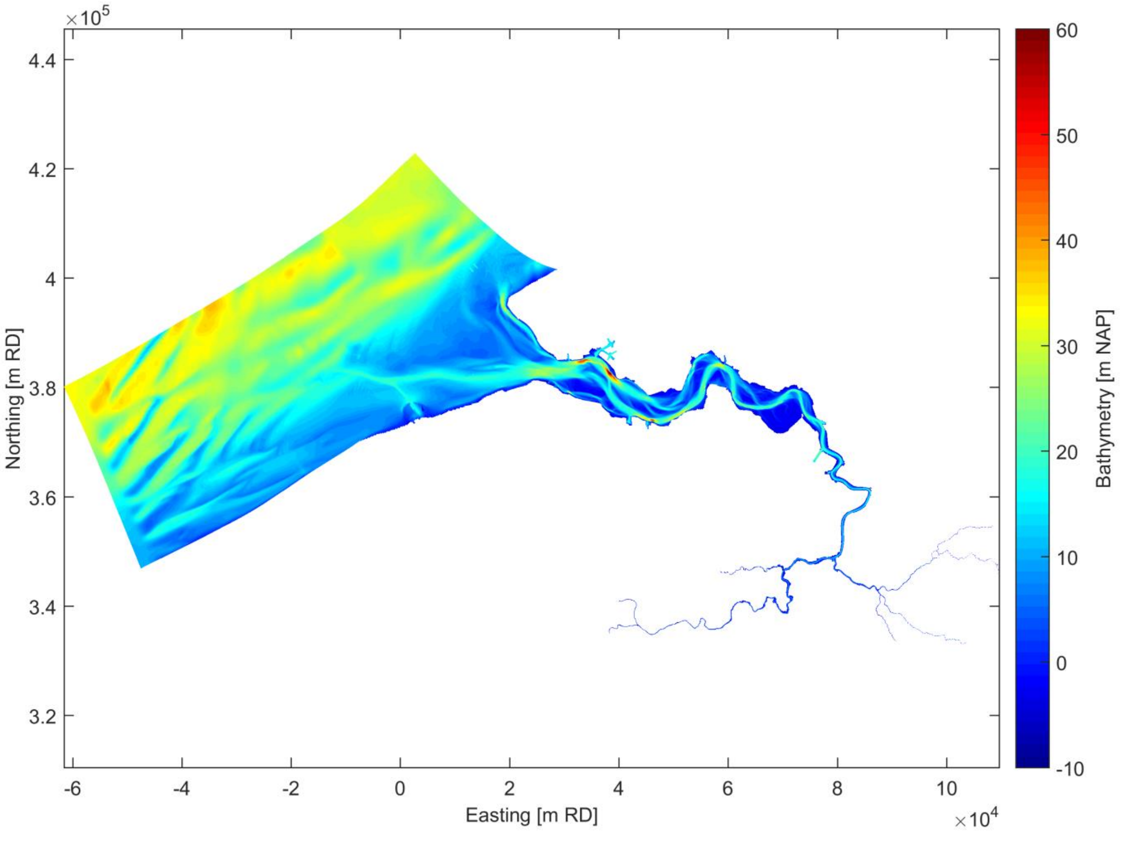

Figure 3-1: Spatial extent and bathymetry (positive downward) of the NEVLA3D model.

For the scenario D, the model bathymetry inside the DGD (including the sill) was replaced with measurements from year 2009, which includes a sill at the dock entrance. Figure 3-2 shows a comparison between the bathymetry near the dock in scenarios A and B (top) and scenario D (bottom).

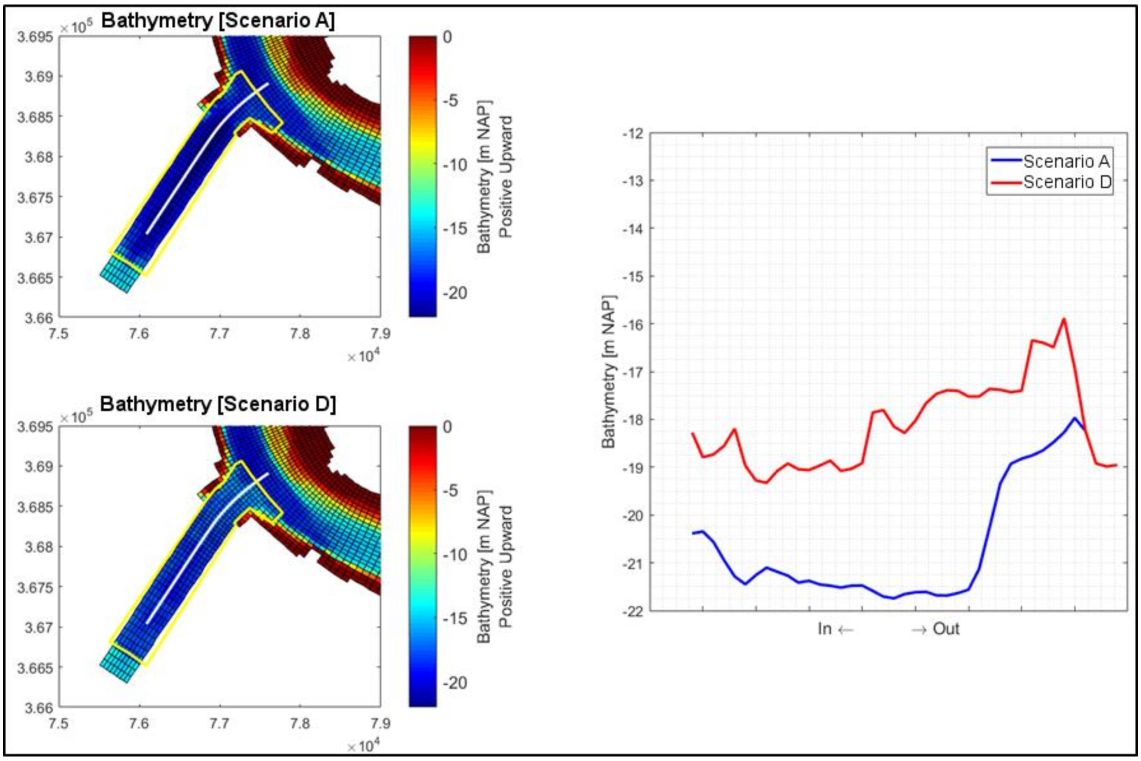

Figure 3-2: Comparison of bathymetry near Deurganckdok for scenarios A and B (top), which represents the 2014 situation with no sill at the dock entry, and scenario D (bottom), including a sill at the dock entrance.

As detailed in §2.3.1, the scenario A and D runs are forced with the upstream discharge measurements from 2014, and the scenario B run is forced with the upstream discharge of 2011 (Figure 3-3). The average discharge in Melle was 23.3 m^3/s in 2011, which is low compared to the more typical year 2014 (average discharge 37.7 m^3/s, see Figure 2-2). The impact of the discharge on the salinity (which is also included in the NEVLA3D model) in June is shown in Figure 3-4 and December in Figure 3-5. In June and during the first half of December, the salinity front intrudes further upstream in 2011 than in 2014, as a result of the low discharge through the year. In the second half of December, upstream discharge was higher in 2011 than in 2014 (Figure 3-3), resulting in a downstream migration of the salinity front.

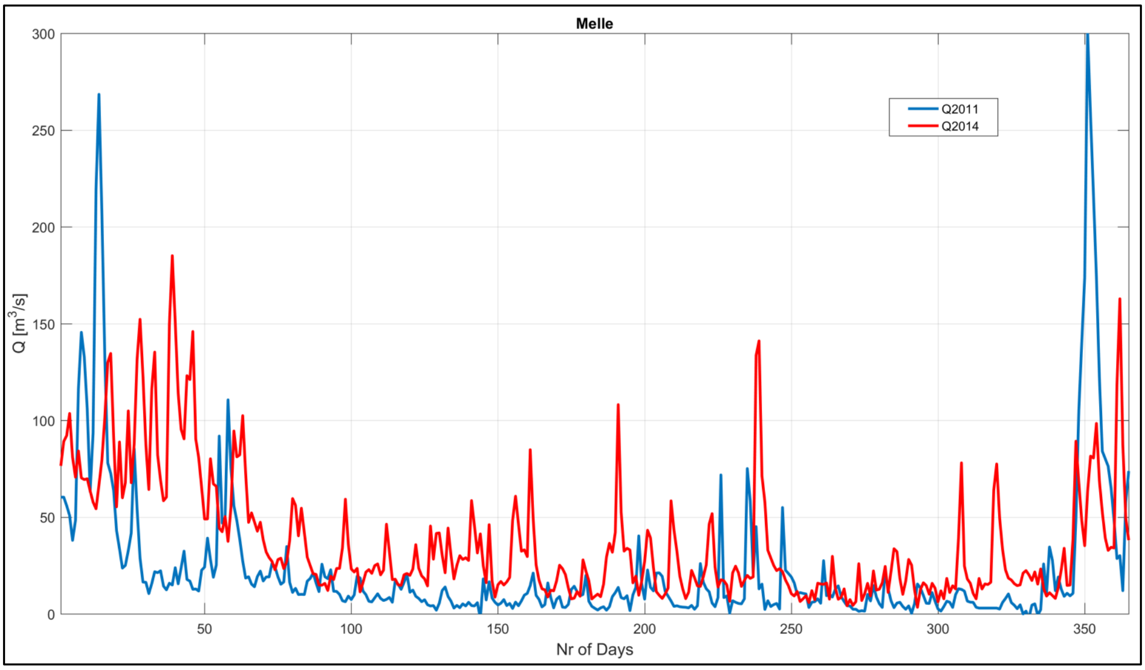

Figure 3-3: Upstream discharge at Melle in 2011 (blue) and 2014 (red).

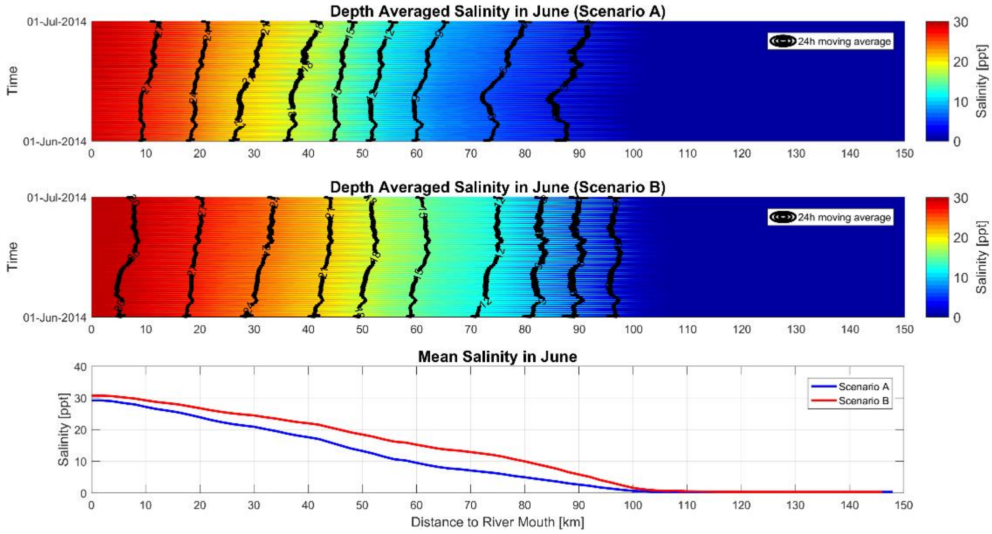

Figure 3-4: Depth averaged salinity in June along the navigation channel of Scheldt. (Upper panel: Scenario A with 'normal-year' river discharge; Middle panel: Scenario B with 'dry-year' discharge; Lower panel: Time averaged salinity in June between Scenario A and B).

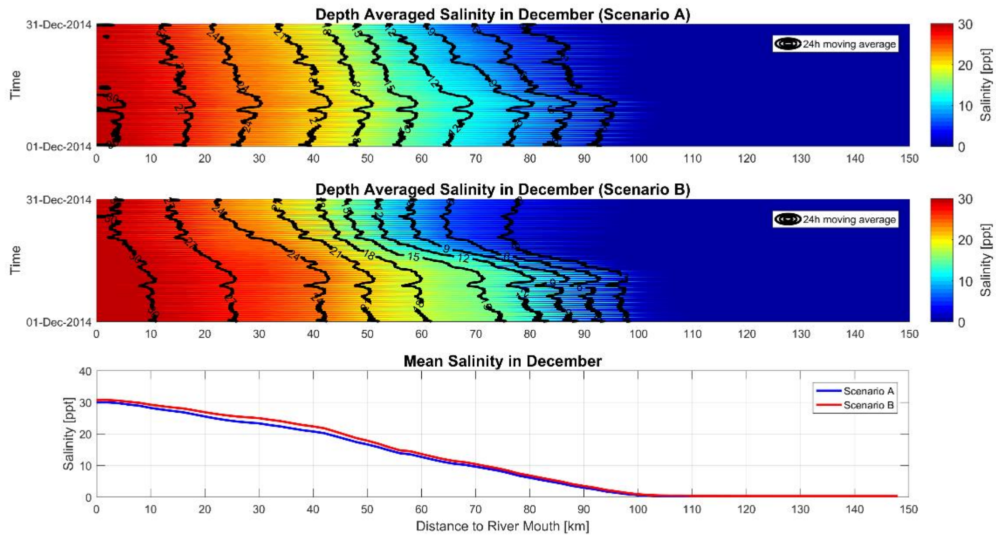

Figure 3-5: Depth averaged salinity in December along the navigation channel of Scheldt. (Upper panel: Scenario A with 'normal-year' river discharge; Middle panel: Scenario B with 'dry-year' discharge; Lower panel: Time averaged salinity in December between Scenario A and B).

3.2 SEDIMENT TRANSPORT MODEL

3.2.1 Model background

Within the framework of the LTV (Long Term Vision) for the Western Scheldt, a fine sediment model of the estuary has been developed and upgraded in various stages between 2006 and 2016. The fine sediment model, developed with Delft3D-WAQ, is used to calculate the direct effects of potential developments, both anthropogenic and natural in the Scheldt estuary on SPM dynamics. This model is coupled offline with hydrodynamics from the SIMONA model (§3.1) and applies the buffer model approach (§3.2.2). The type of updates that have been implemented in the most recent version of the LTV model (LTV 2015) include the synchronisation of settings with other studies that have been developed in recent years on mud dynamics in the North Sea (Arentz *et al.*, 2012; Cronin and Blaas, 2013), Wadden Sea (van Duren *et al.*, 2015), Ems (Van Maren *et al.*, 2014) and the Scheldt estuary mouth (Vroom *et al.*, 2016), which include two mud fractions (microflocs and macroflocs) rather than one fraction as in the previous LTV mud model (2010). In addition, spatially varying parameter settings are no longer applied in LTV2015 in order to simplify interpretation and newly available validation data is compared with model output.

The new settings and the addition of coarser fractions resulted in improved levels of suspended sediment concentrations both up-estuary and near the estuary mouth (Zeebrugge) but intra-tidal variability, though improved, is still less than observed. Siltation rates in the harbours and docks are also in the right order of magnitude but sedimentation rates on the intertidal flats are underestimated in the Western Scheldt and overestimated in the Sea Scheldt. More details can be found in Cronin *et al.* (2018).

The LTV2015 version was used as a basis to run the simulations for this work without any further calibration of the model. The only modifications made were to represent different configurations of the Deurganckdok for the different scenarios (see §3.1).

3.2.2 Buffer model

The buffer model is a bed module (within Delft3D-WAQ) that accounts for buffering of fine sediments in the bed at various timescales (spring-neap, seasonal). Fine sediments are stored in the seabed during calm conditions and released from the seabed during stormy conditions (van Kessel *et al.*, 2011). This model contains two bed layers which interact in a specific way. The thin fluffy layer forms during slack tide and is easily resuspended by tidal currents. This layer accounts for rapid resuspension and settling that in reality is thought to occur in fluffy patches on the sea floor. The total sediment mass in this layer is small. The sandy buffer layer, on the other hand, can store fines for longer times and releases SPM only during highly dynamic conditions, such as spring tides or storms. Detrainment of silt from the matrix of sand occurs only beyond critical mobilization conditions for the sand grains, whereas slow entrainment occurs during subcritical conditions. The time-averaged sediment fluxes between the buffer layer and the water column are small, whereas the storage capacity of silt in the sea bed may be large, depending on the assumed mixing depth. As a result, the overlying water column is directly interacting with both layers but with different rates, representing the different physical process that play a role. Figure 3-6 illustrates the exchanges between both bottom layers and the water column for the buffer parameterization.

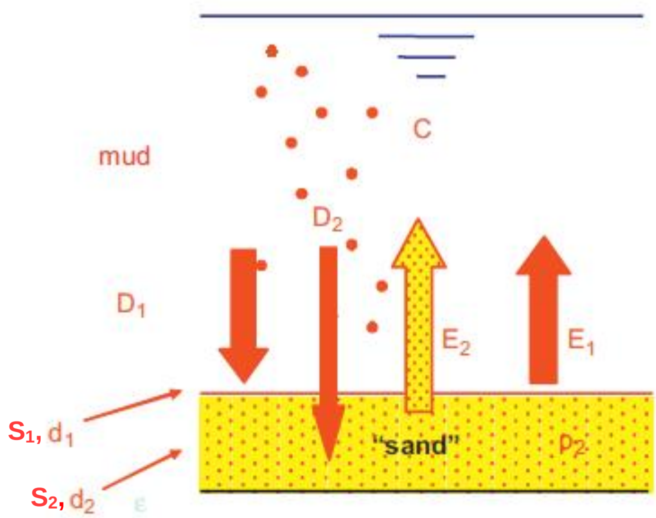

Figure 3-6: Schematic representation of the buffer model. Layer S_1, thickness d_1: thin fluff layer. Layer S_2, thickness d_2: sandy sea bed infiltrated with fines. D_j deposition flux towards layer S_j, E_j erosion flux from layer S_j ($j \in [1,2]$) and C: SPM concentration (adopted from van Kessel et al.*, 2011).*

Deposition towards layer S_1 and S_2 is determined by settling velocity V_{Sed}, and a factor $\alpha \ll 1$ that distributes the flux to the fluff and buffer layer. A critical shear stress for sedimentation is not applied:

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

$$D_{2,IM_i} = \alpha_{IM_i}V_{Sed,IM_i}C_{IM_i}$$

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

Resuspension E_1 of each fraction out of the fluff layer is proportional to the excess shear stress times a grain size dependent first-order rate (V_{Res}) until a certain saturation concentration in the bed is attained beyond which a uniform zero-order rate (Z_{Res}) applies. The coarse and fine fractions have a different critical shear stress for resuspension (τ_{cr}). The zero-order formulations are based on Partheniades (1965), the first order expression is based on Van Kessel et al. (2011). The process is implemented for all three sediment fractions IM_i.

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

$$E_{1,IM_i} = \min\left(Z_{\mathrm{Res},IM_i}, V_{\mathrm{Res},IM_i}M_{i,1}\right)\left(\frac{\tau}{\tau_{\mathrm{cr},S_1 IM_i}} - 1\right)$$

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

In this formulation, the following definitions hold:

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

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

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

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

Por_{S_2} the volumetric porosity of the bed,

ρ_{sand} the mass density of sand.

3.2.3 Setup of the runs

The mud transport model was set up using the Delft3D-WAQ software coupled offline with hydrodynamics from TRIWAQ, a module of SIMONA for the year 2014. The Delft3D-WAQ model applies the buffer parameterisation developed by van Kessel *et al.* (2011) for deposition, storage and erosion of sediments. The hydrodynamic model has six layers with a logarithmic layer distribution which gives the model a higher resolution near the water surface and near the bed. This model has gradually evolved in the period 2006 – 2016 (with regard to grid schematisation, boundary conditions and process description etc.) and a detailed description of the evolution towards the current model set up, including calibration and validation can be found in previous reports (van Kessel *et al.*, 2008, 2010, 2011, 2011; van Kessel and Vanlede, 2009; Cronin *et al.*, 2018).

The hydrodynamic forcing of 2014 was applied with LTV 2015b settings as described in Cronin et al. (2018) were applied to these runs. This includes two fine sediment fractions with different settling velocities of 2 mm/s and 0.5 mm/s representing macro- and microflocs respectively.

The general adaptations made to the model set up for this work were:

1. Grid aggregation was implemented to decrease the resolution of the Delft3D-WAQ grid by a factor of 2 compared to the Simona grid everywhere except in Deurganckdok. In Deurganckdok the full grid resolution of the hydrodynamic model was maintained. This aggregation was used for the three hydrodynamic scenarios as described in §2.3.1.
2. Modified dredging and dumping settings were also necessary to assess the rate of sediment dredged and dumped from the different maintenance areas of Deurganckdok.
3. The two sediment fractions present in the model were tagged to represent background sediment (01) and sediments that were dredged and dumped from Deurganckdok to enable tracking of this material (02).

Scenario specific adaptations include:

1. In the A0 run the presence of Deurganckdok is artificially ‘removed’ by simulating a concrete bed that does not allow for any settling of sediment or exchange with the bed. The bed is activated again for runs A1-A10

2. Depending on the scenario, dredging was activated for different maintenance areas of Deurganckdok. In the A1-A10 and the DA6 to DA10 runs the dock was fully dredged as is the current situation. For the D1-D10 runs dredging was only activated in the mouth and centre maintenance areas of the dock (indicated as DGD North and DGD Mid in Figure 4-13). This meant that the back maintenance area of the dock were not dredged in these simulations.

Table 3-1 provides a general overview of all model simulations.

Table 3-1: General overview of model simulations

	<2005	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**
Scenario 1. Effect low discharge											
	A0	**A1**	**A2**	**A3**	**A4**	**A5**	**B6**	**A7**	**A8**	**A9**	**A10**
Hydro	2014 hydro	2014 hydro	2014 hydro	2014 hydro	2014 hydro	2014 hydro	**2014 hydro + 2011 discharge**	2014 hydro	2014 hydro	2014 hydro	2014 hydro
Dredging	no siltation DGD	regular dredging	regular dredging	regular dredging	regular dredging	regular dredging	regular dredging	regular dredging	regular dredging	regular dredging	regular dredging
Restart from		A0	A1	A2	A3	A4	A5	B6	A7	A8	A9
Other											
Scenario 2. Not deepening Deurganckdok											
	A0	**D1**	**D2**	**D3**	**D4**	**D5**	**D6**	**D7**	**D8**	**D9**	**D10**
Hydro	2014 hydro	2014 hydro; 2009 DGD bathy	2014 hydro; 2009 DGD bathy	2014 hydro; 2009 DGD bathy	2014 hydro; 2009 DGD bathy	2014 hydro; 2009 DGD bathy	2014 hydro; 2009 DGD bathy	2014 hydro; 2009 DGD bathy	2014 hydro; 2009 DGD bathy	2014 hydro; 2009 DGD bathy	2014 hydro; 2009 DGD bathy
Dredging	no siltation DGD	dredging in DGD mouth + mid	dredging in DGD mouth + mid	dredging in DGD mouth + mid	dredging in DGD mouth + mid	dredging in DGD mouth + mid	dredging in DGD mouth + mid	dredging in DGD mouth + mid	dredging in DGD mouth + mid	dredging in DGD mouth + mid	dredging in DGD mouth + mid
Restart from		A0	D1	D2	D3	D4	D5	D6	D7	D8	D9
Other		Allow sedi-mentation									

	<2005	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**
Scenario 3. Lower intervention level in Deurganckdok											
	A0	**D1**	**D2**	**D3**	**D4**	**D5**	**DA6**	**DA7**	**DA8**	**DA9**	**DA10**
Hydro	2014 hydro	2014 hydro; 2009 DGD bathy	2014 hydro; 2009 DGD bathy	2014 hydro; 2009 DGD bathy	2014 hydro; 2009 DGD bathy	2014 hydro; 2009 DGD bathy	2014 hydro	2014 hydro	2014 hydro	2014 hydro	2014 hydro
Dredging	no siltation DGD	dredging in DGD mouth + mid	dredging in DGD mouth + mid	dredging in DGD mouth + mid	dredging in DGD mouth + mid	dredging in DGD mouth + mid	**Regular dredging criteria**	regular dredging criteria	regular dredging criteria	regular dredging criteria	regular dredging criteria
Restart from		A0	D1	D2	D3	D4	D5	DA6	DA7	DA8	DA9
Other		Allow sedi-mentation in DGD									

4. MODEL RESULTS

4.1 LONG-TERM SIMULATION 1: IMPACT OF REDUCED UPSTREAM DISCHARGE

4.1.1 Dredging volume

Figure 4-1 displays the long-term evolution of dredging volumes for simulation 1. The bathymetry and hydrodynamic forcing for this simulation stems from hydrodynamic simulation A (see §2.3) which has the bathymetry of 2014 (including the removal of the sill at the Deurganckdok entrance), and the evolution after the opening dock is therefore not directly comparable with the recorded dredging volumes of Figure 2-1. A comparison with the recorded dredging volumes is therefore postponed to §4.2.

For the period 2006-2010 (the years after the opening of Deurganckdok), the dredging volume decreases slightly. By 2010, the evolution in the dredging volume following the opening of Deurganckdok has mostly stabilized as the system has (nearly) reached a new equilibrium. During the year with reduced discharge (2011 – simulation B6), the dredging volume in all maintenance zones decreases. The volume remains low in the following year (2012 – A7), which has again a ‘normal’ upstream discharge. In 2013, the disposal volume is again elevated, after which it slowly decreases again toward its equilibrium value from before 2011.

To investigate the dredging volume evolution around the low-discharge year 2011 in greater detail, Figure 4-2 – Figure 4-5 display the dredging volume on a monthly basis for the years 2010-2013. In the ‘normal year’ 2010, the dredging volume increases in January-May as a result of the wet winter/spring months, and then decreases during the dryer summer months (Figure 4-2). In 2011, in contrast, the dredging volume remains low during January-May and during the following summer months (Figure 4-3). A small rebound in dredging volumes is seen in the first months of 2012 (Figure 4-4) but dredging volumes generally remain low until early 2013 (Figure 4-5).

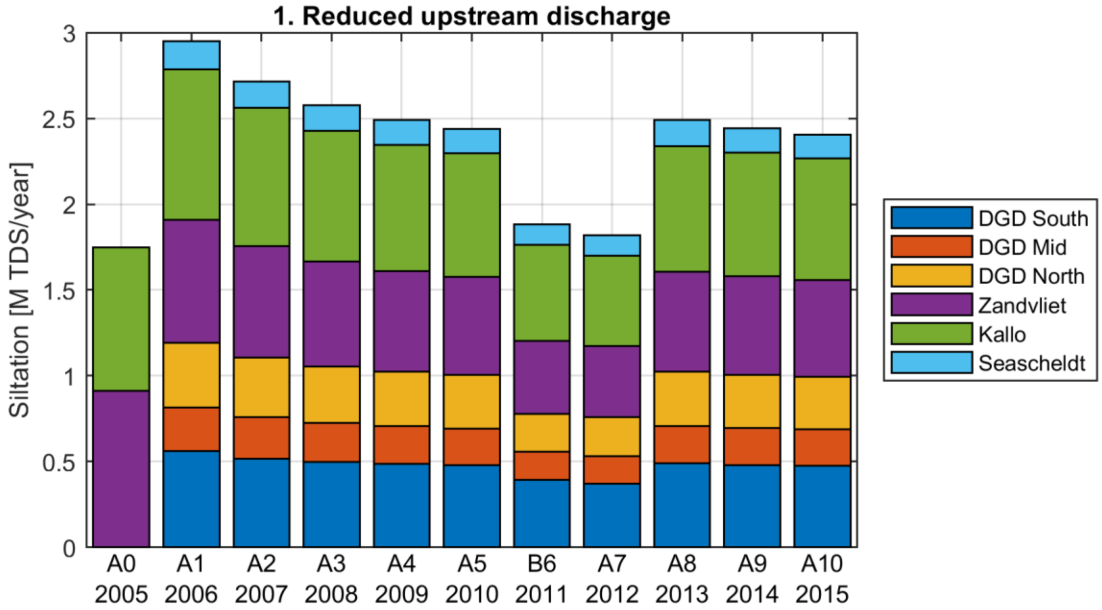

Figure 4-1: Long-term siltation and dredging rates for long-term simulation 1.

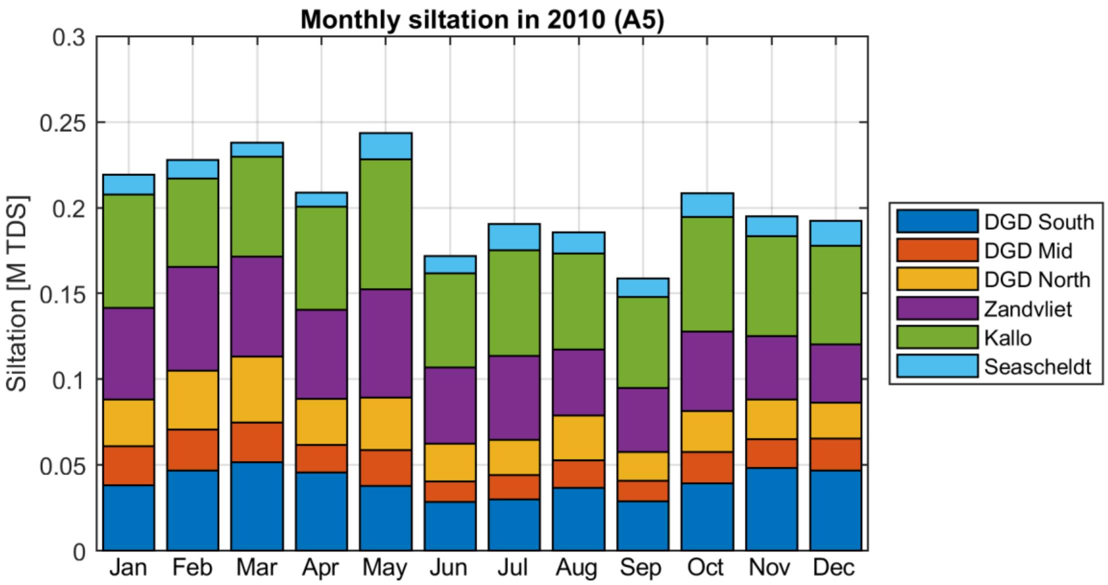

Figure 4-2: Monthly siltation and dredging rates for year 2010 of simulation 1 (A5).

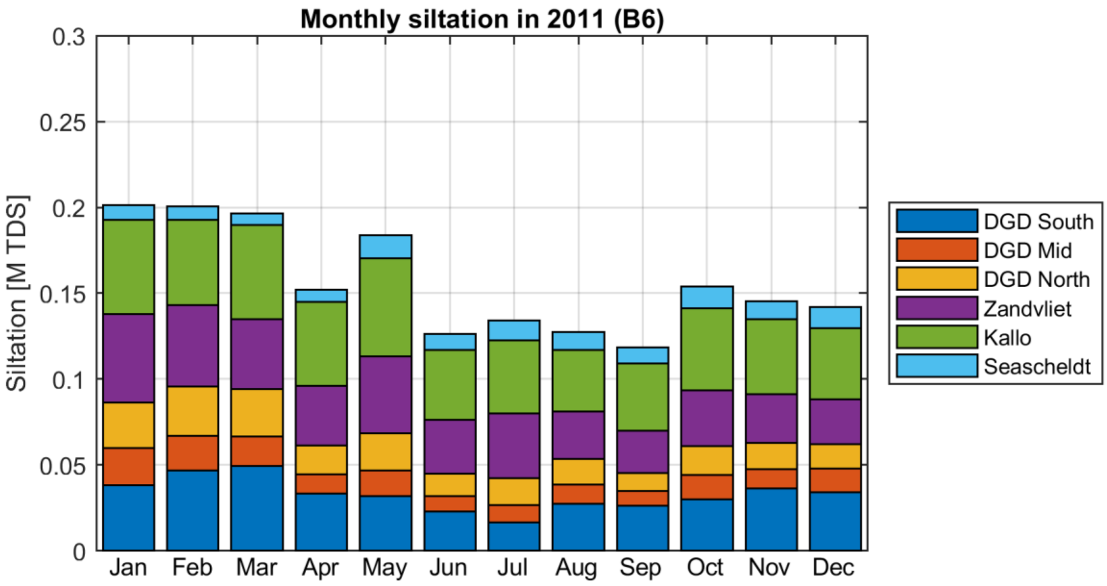

Figure 4-3: Monthly siltation and dredging rates for year 2011 of simulation 1 (B6).

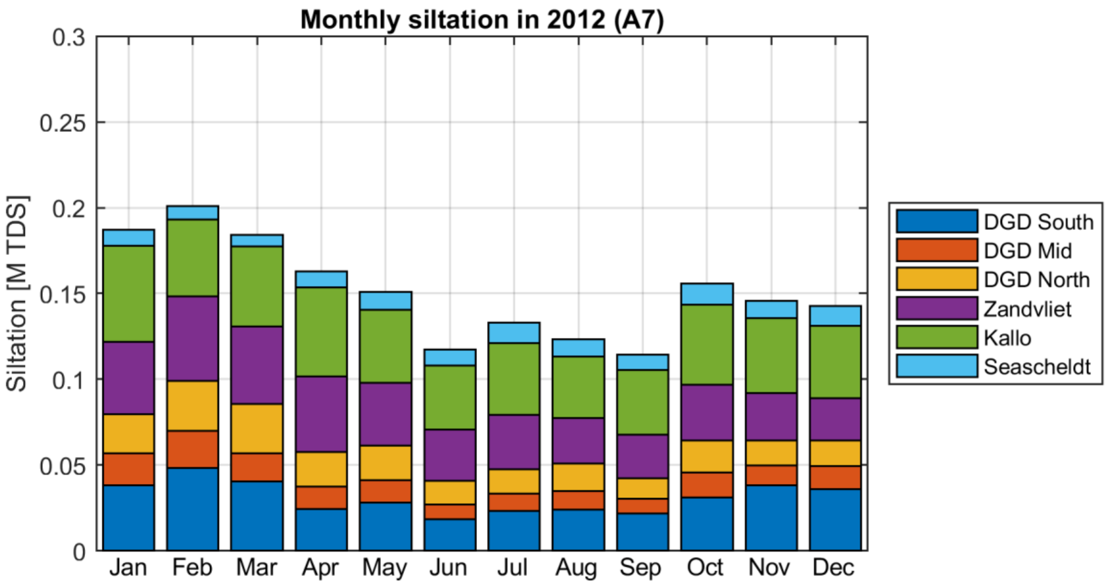

Figure 4-4: Monthly siltation and dredging rates for year 2012 of simulation 1 (A7).

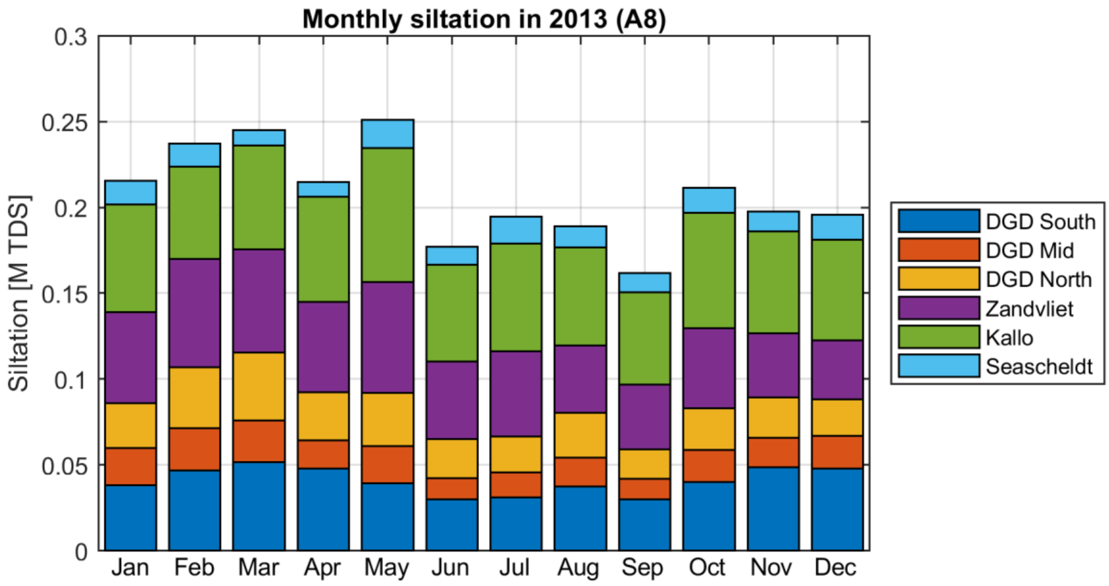

Figure 4-5: Monthly siltation and dredging rates for year 2013 of simulation 1 (A8).

4.1.2 Spatial distribution of sediment

The spatial distribution of sediment is shown in Figure 4-6 to Figure 4-9, where Figure 4-6 displays the amount of sediment in suspension (SSC) and on the bed in the thalweg (navigation channel) during December of 2010 and 2011 (= the last month of a dry/normal year), and Figure 4-7 shows the information for June of 2010 and 2011. Figure 4-8 and Figure 4-9 display the yearly-mean and yearly-maximum depth-averaged sediment concentrations for all years.

As seen in Figure 4-6C, the position of the Estuarine Turbidity Maximum does not shift upstream/downstream in the model with the higher and lower discharge. Instead, the position of the ETM remains the same but the concentrations in the ETM zone are generally lower. This is also visible in Figure 4-8, which shows generally lower sediment concentrations in 2010 and 2011, but no spatial shift of the ETM. These lower suspended sediment concentrations are a likely explanation for the lower dredging volumes predicted by the model in 2011 (Figure 4-1).

Mid-December 2011, a high-discharge event occurred that ended the dry period (see Figure 3-3). As seen in Figure 3-5, this event had a clear impact on the salinity front in the estuary, which was pushed downstream by the increased upstream freshwater flux. In contrast, the SSC does not show a strong response to the discharge event (Figure 4-6). In the upstream parts of the estuary (upstream of km 100), elevated SSC levels briefly occur that are associated with the higher sediment influx from the upstream boundary, but the main ETM (between km 70 and 100) does not shift downward or upward.

Figure 4-7 displays the amount of suspension (SSC) and on the bed during June of 2010 and 2011 (= during the dry period). Again, the location of the ETM is similar in 2010 and in 2011, but the SSC levels are generally lower in 2011 than in 2010. Interestingly, the location of the ETM is very similar in June (Figure 4-7) and in December (Figure 4-6).

Figure 4-9 shows the yearly maximum depth-averaged SSC simulations for 2010 (A5), 2011 (B6) and 2012 (A7). Sediment concentrations in the upstream sections of the Scheldt do become elevated during (a brief period of) 2011, but this does not remain the case for an extended period of time in 2011.

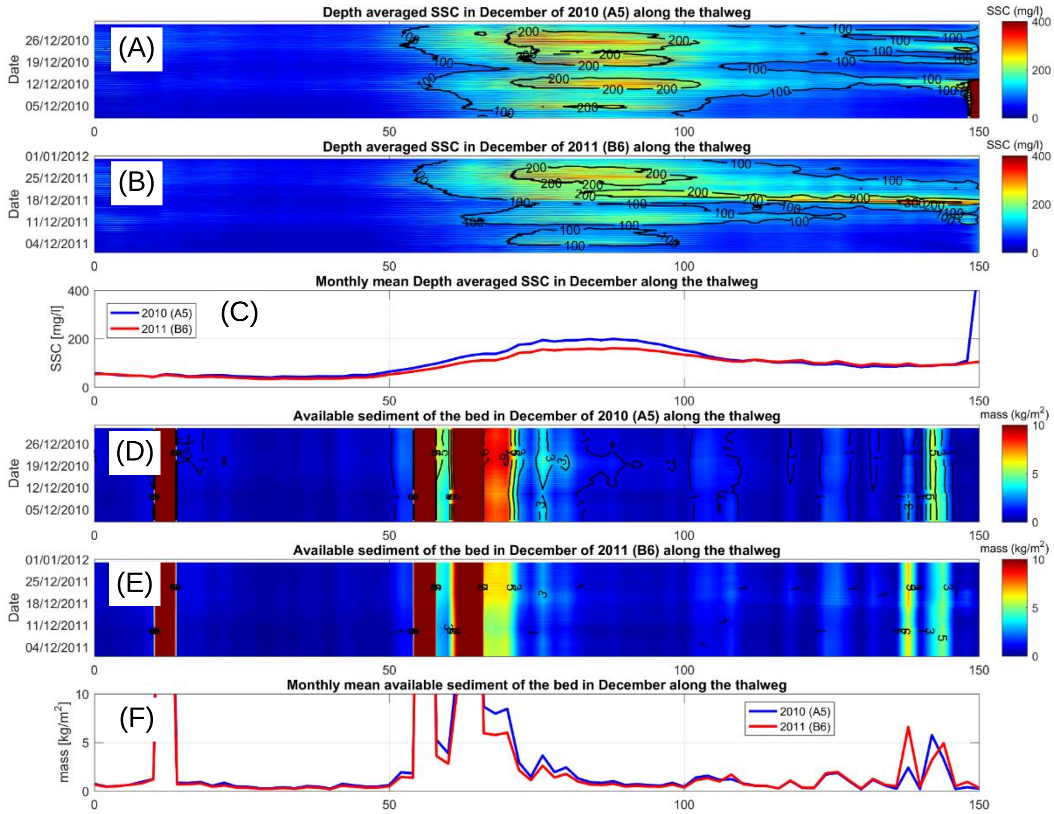

Figure 4-6: Contour plot of depth-averaged SSC in December 2010 (A) and 2011 (B). Vertical axis denotes time. (C): Depth- and monthly average of SSC in December 2010 (blue) and 2011 (red). Contour plot of available sediment in the bed in December 2010 (D) and 2011 (E). (F): Depth- and monthly average of SSC in December 2010 (blue) and 2011 (red).

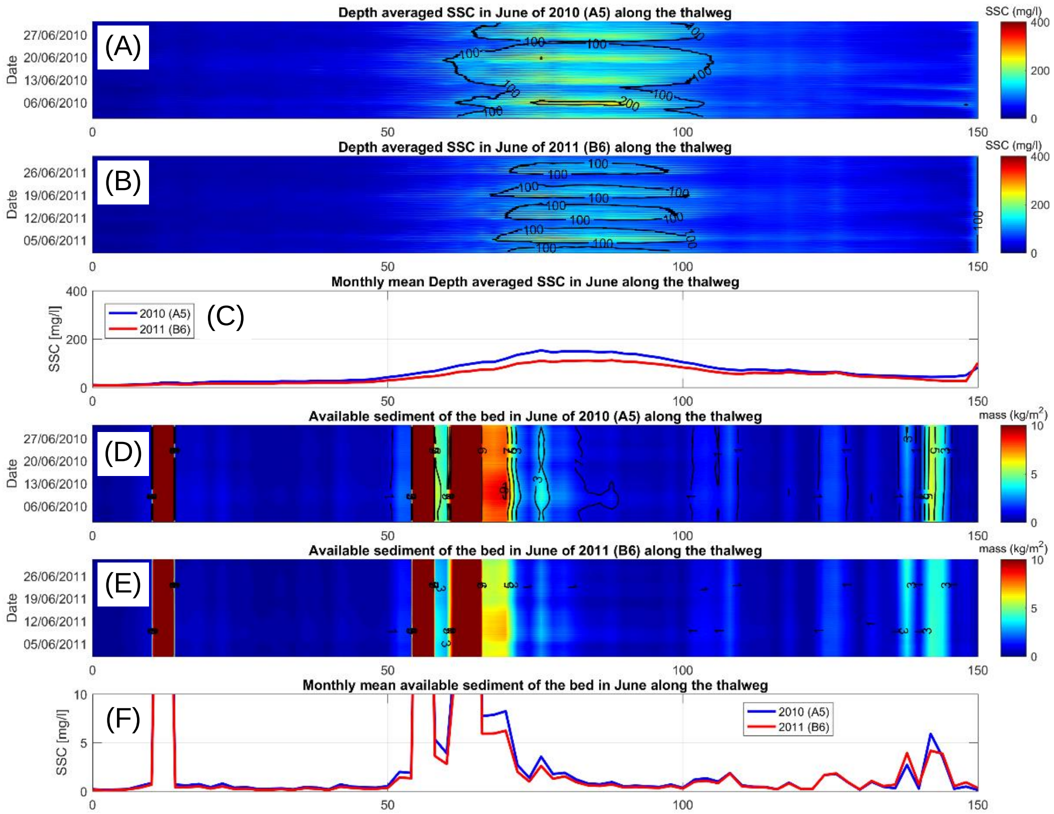

Figure 4-7: Contour plot of depth-averaged SSC in June 2010 (A) and 2011 (B). Vertical axis denotes time. (C): Depth- and monthly average of SSC in June 2010 (blue) and 2011 (red). Contour plot of available sediment in the bed in June 2010 (D) and 2011 (E). (F): Depth- and monthly average of SSC in June 2010 (blue) and 2011 (red).

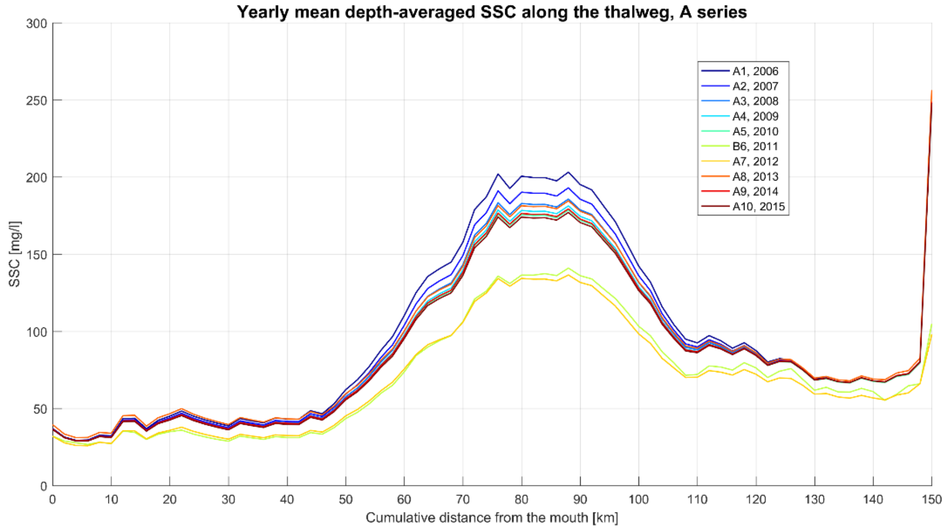

Figure 4-8: Yearly mean depth-averaged SSC along thalweg, scenario 1.

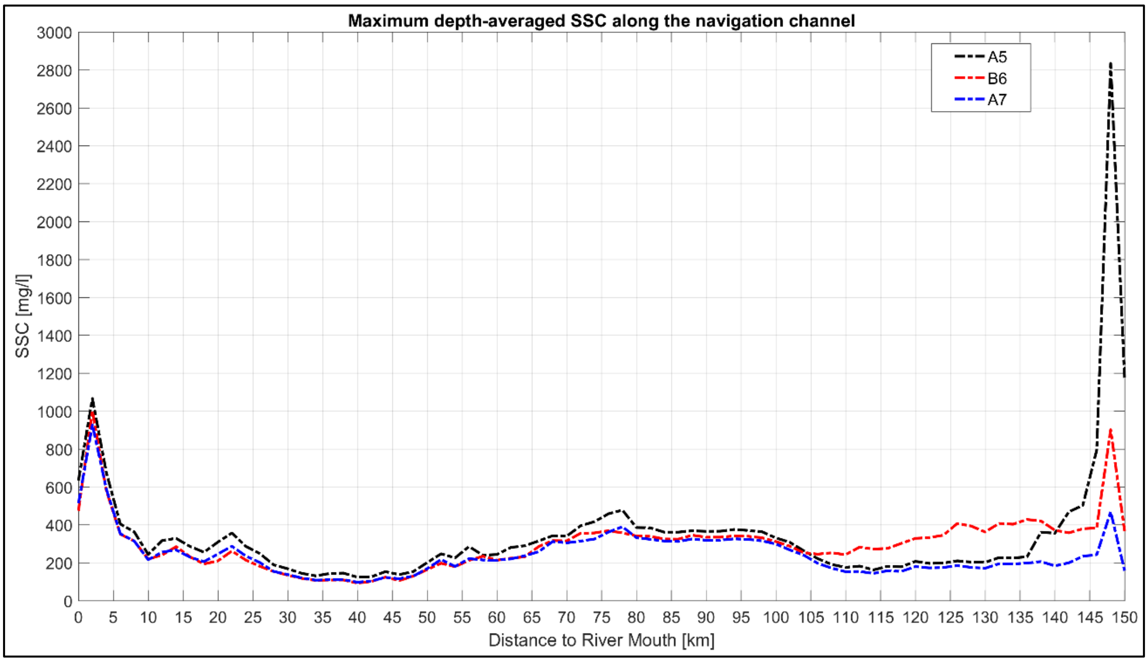

Figure 4-9: Yearly maximum of depth-averaged SSC for simulations A5 - 2010 (black), B6 -2011 (red) and A7-2012 (blue).

4.1.3 Distribution of sediment originating from Deurganckdok

In the DELWAQ model, sediment was labelled according to the whether it entered the model by disposal after it was dredged from Deurganckdok, or whether it entered the model through a different pathway (disposal after being dredged in a different dredging zone, entering the model through the upstream of downstream boundary).

Figure 4-10 displays which fraction of sediment that deposits in the maintenance zones in the lower Sea Scheldt (Deurganckdok, fairway, entrance channels to Kallo lock and Zandvliet and Berendrecht locks) originates from sediment disposal from Deurganckdok. The figure shows that a substantial fraction (roughly 70-90%) of the sediment that is dredged from Deurganckdok, returns and deposits in the dock after a certain period of time (although this time period may be large).

Figure 4-11 and Figure 4-12 display the spatial distribution of the sediment that originates from Deurganckdok for 2010 and 2011, respectively. The shape of the spatial distribution (in the port area) is similar for the sediment originating from Deurganckdok (second panel) and the general sediment distribution (top panel), indicating that the sediment disposal (from Deurganckdok, but also from other maintenance zones) is a strong controlling factor for the spatial sediment distribution and ETM location in the model. The relative importance of sediment originating from Deurganckdok (third panel in Figure 4-11 and Figure 4-12) is highest near the disposal area. In 2011 (the year with reduced discharge), the zone of relative importance of Deurganckdok sediment extends further upstream than in 2010. This may be explained by the fact that the Deurganckdok sediment propagates further upstream during the period of reduced discharge.

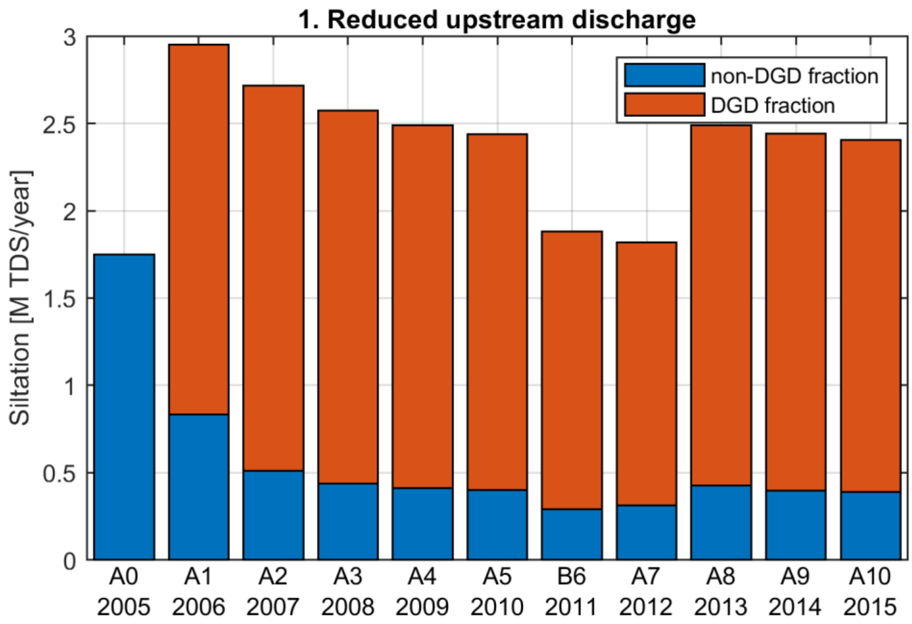

Figure 4-10: Fraction of dredged sediment from the dredging zones in the Sea Scheldt that originates from Deurganckdok, scenario 1.

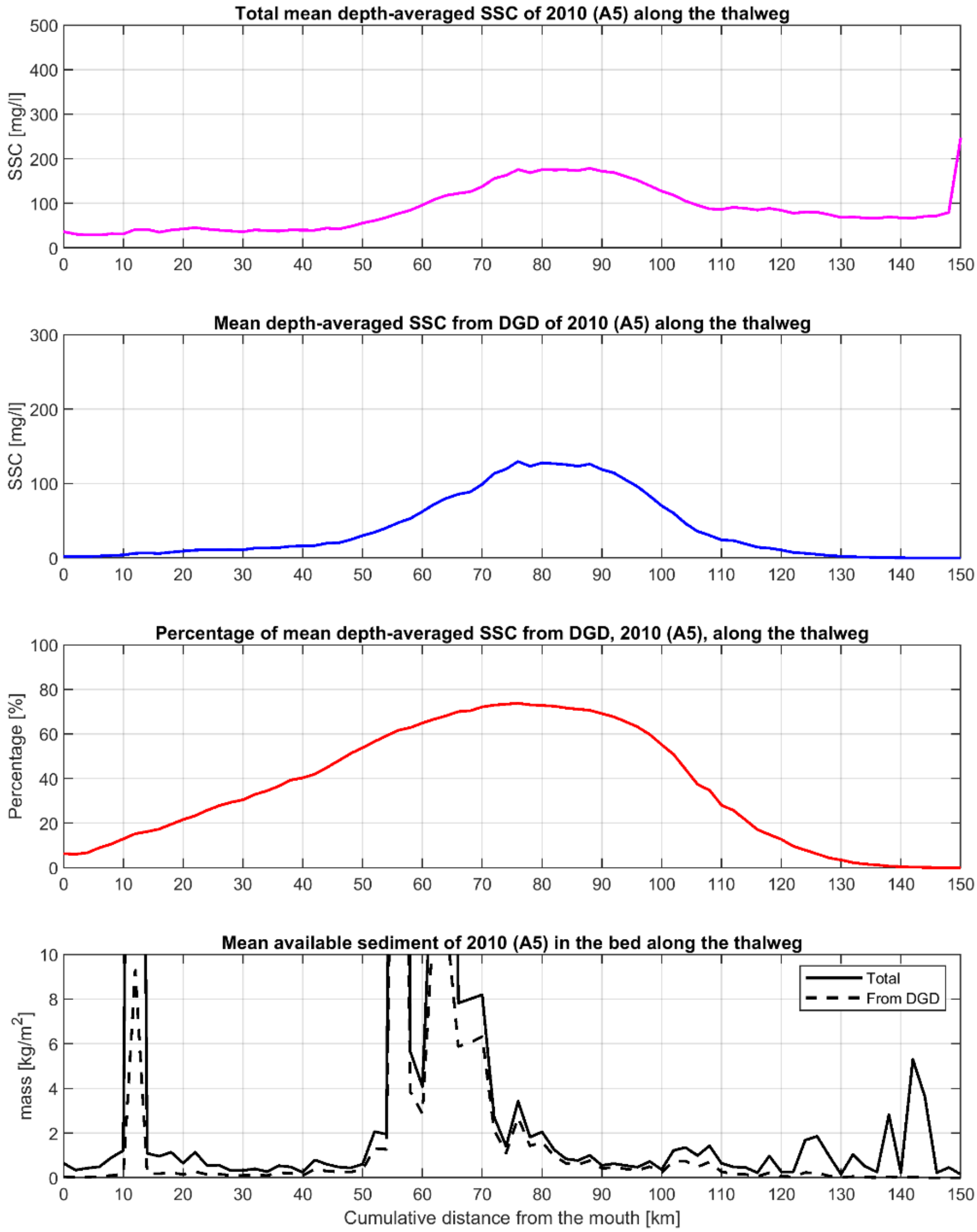

Figure 4-11: Depth-averaged SSC and contribution from Deurganckdok, simulation A5.

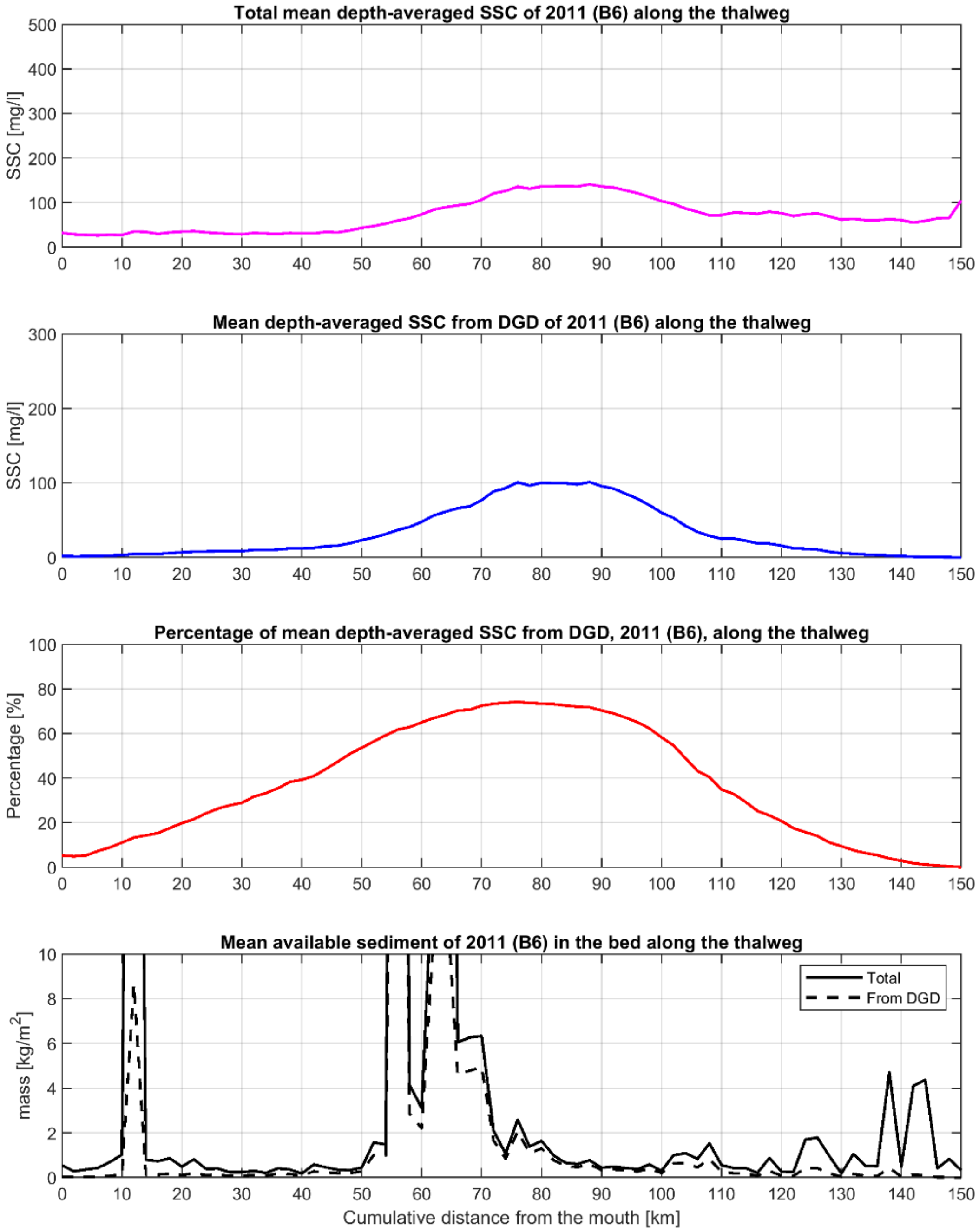

Figure 4-12: Depth-averaged SSC and contribution from Deurganckdok, simulation B6.

4.2 LONG-TERM SIMULATION 2: IMPACT OF NOT DEEPENING DEURGANCKDOK

4.2.1 Dredging volume

Figure 4-13 displays the long-term siltation rate in Deurganckdok for simulation 2, in which the dock is kept at the bathymetry (including entrance sill) and intervention level of before 2009. Dredging volumes are generally lower than in Simulation 1.

The first years of simulation 2 have roughly the same bathymetry and intervention level as the real historic simulation[4], and dredging volumes predicted by the model can therefore be compared to the recorded dredging volumes of Figure 2-1. In contrast with the recorded dredging volume, which increases in the years following the opening of the dock, the dredging volumes predicted by the model decrease over time between 2006 and 2010. In both the model and in the real system, the opening of the dock presents an abrupt change in the system, after which the system seeks a new equilibrium state of sediment concentration and dredging volume. In the model, the Deurganckdok acts as a sediment sink and the disposal area (near Plaat van Boomke) acts as a sediment source. As a result, sediment concentrations in the main channel decrease near Deurganckdok and increase near Plaat van Boomke from A0 to A1, leading to an increase in the dredging volume at the Kallo lock entrance (Figure 4-1).

In the model, the rear section of the Deurganckdok (zone DGD-South in the model) is not maintained by dredging and therefore acts as a sediment sink (Figure 4-14). As a result, the dredging volume in Deurganckdok in 2006 is roughly half that of scenario 1, in which the entire dock is maintained by dredging. In reality, the dock (roughly) acted as a sediment sink until 2010, until the intervention level was altered in 2011. In the model however, the DGD-South section remained a sink throughout the entire simulation (Figure 4-14). In 2010, 5 years after the opening of the dock, a new equilibrium dredging volume is reached, after which the dredging volume remains approximately constant for the remainder of the simulation (2010-2015).

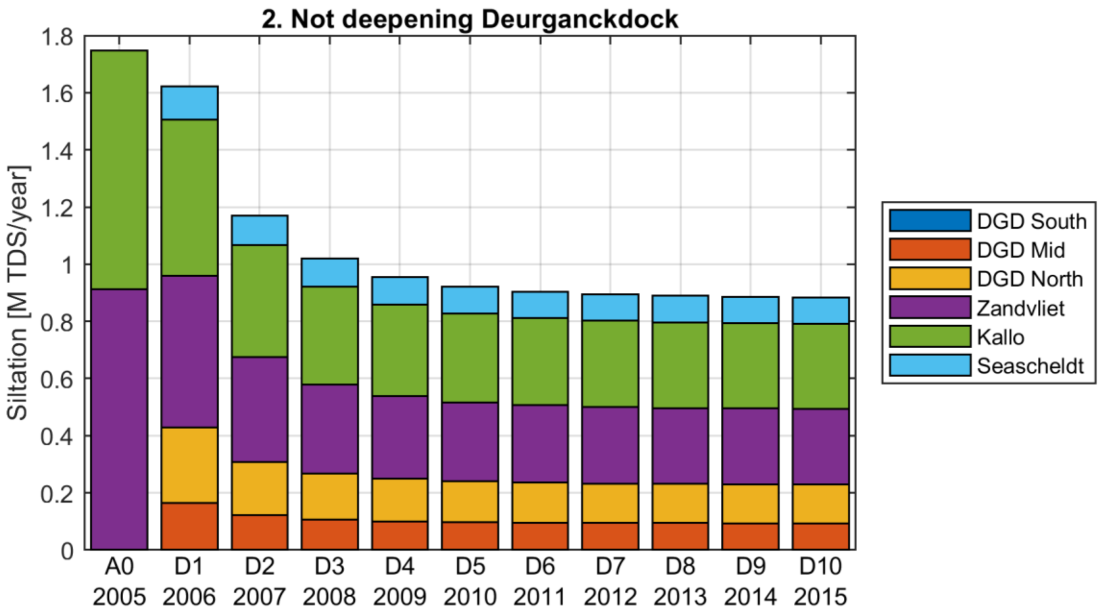

Figure 4-13: Long-term siltation and dredging rates for long-term simulation 2.

[4] The modelled and recorded dredging volumes cannot be compared exactly, since the dock was opened gradually in 2006-2008 in reality, whereas the entire dock is opened at once in 2006 in the simulation.

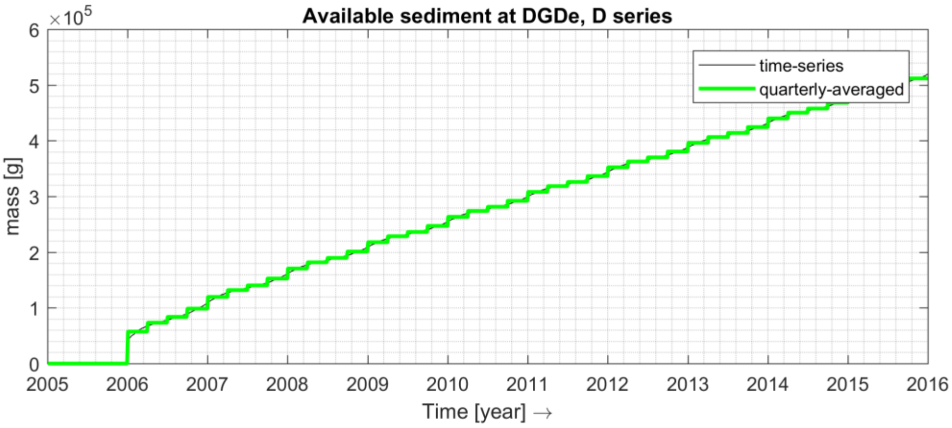

Figure 4-14: Sediment mass accumulation at DGDe zone (location indicated in Figure 4-15).

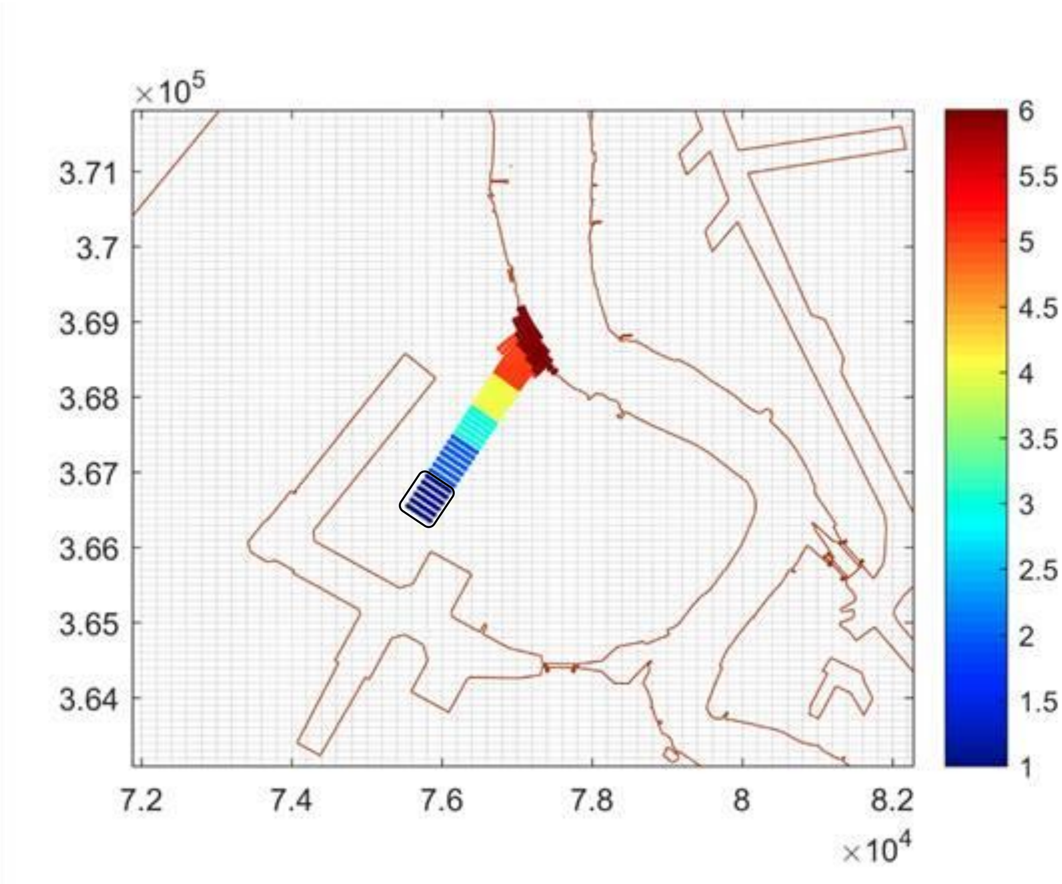

Figure 4-15: Location of sedimentation zone DGDe (see Figure 4-14).

4.2.2 Spatial distribution of sediment

The yearly-mean depth-averaged sediment concentration for scenario 2 is shown in Figure 4-16. In the first four years of the simulation, the sediment concentration in the zone around Deurganckdok gradually decreases as a result of the sediment storage in the rear areas of the dock. By 2010, an (approximately) steady-state situation is reached, as was the case for the dredging volumes in Figure 4-13. In the steady-state situation, the ETM around the sediment disposal zone is much less pronounced, due to the lower sediment disposal volume.

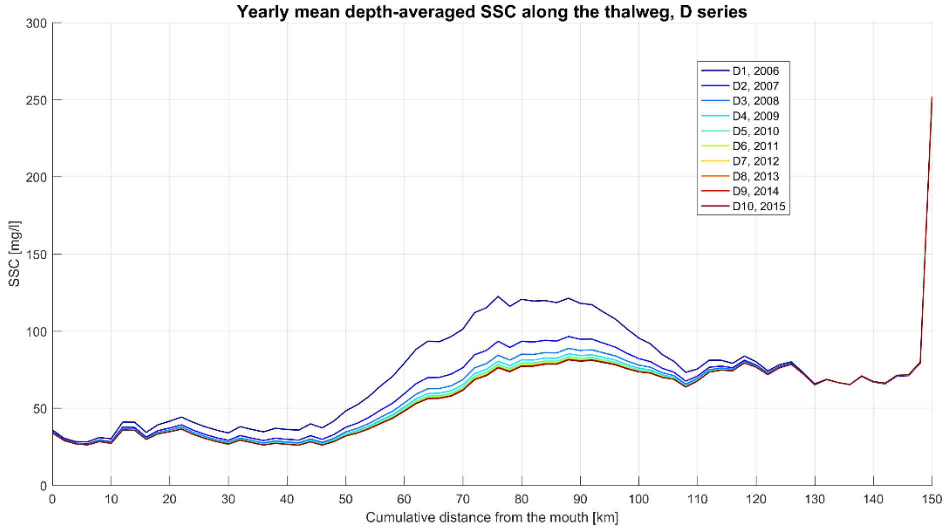

Figure 4-16: Yearly mean depth-averaged SSC along thalweg, scenario 2.

4.2.3 Distribution of sediment originating from Deurganckdok

Figure 4-17 displays the sediment fraction originating from Deurganckdok. The fraction originating from Deurganckdok is roughly 50%, which is lower than in scenario 1, because only a part of the dock is dredged. This is also visible in Figure 4-18: roughly 40% of the sediment in the water column near Deurganckdok originates from the dredging and disposal activities in the dock.

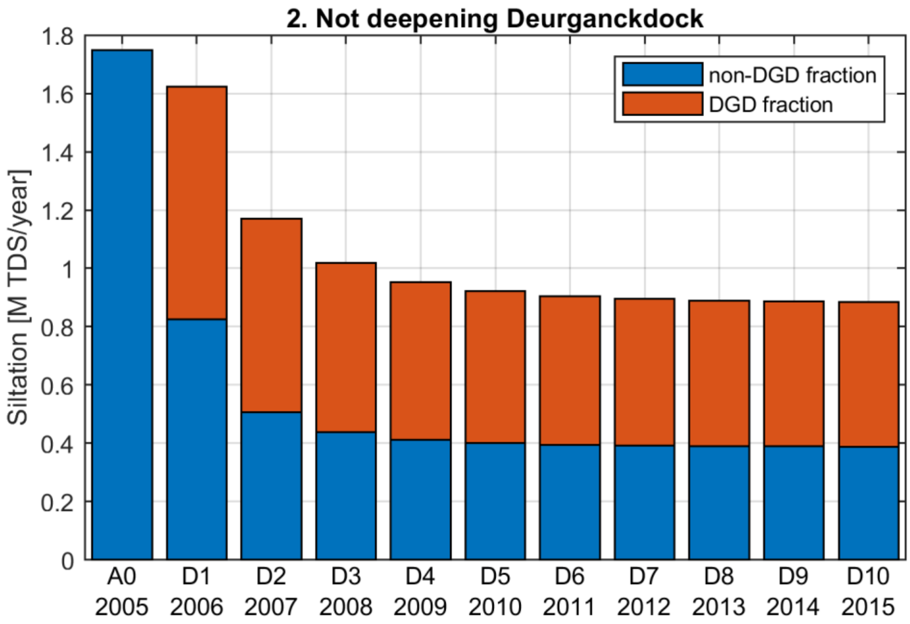

Figure 4-17: Fraction of dredged sediment from the dredging zones in the Sea Scheldt that originates from Deurganckdok, scenario 2.

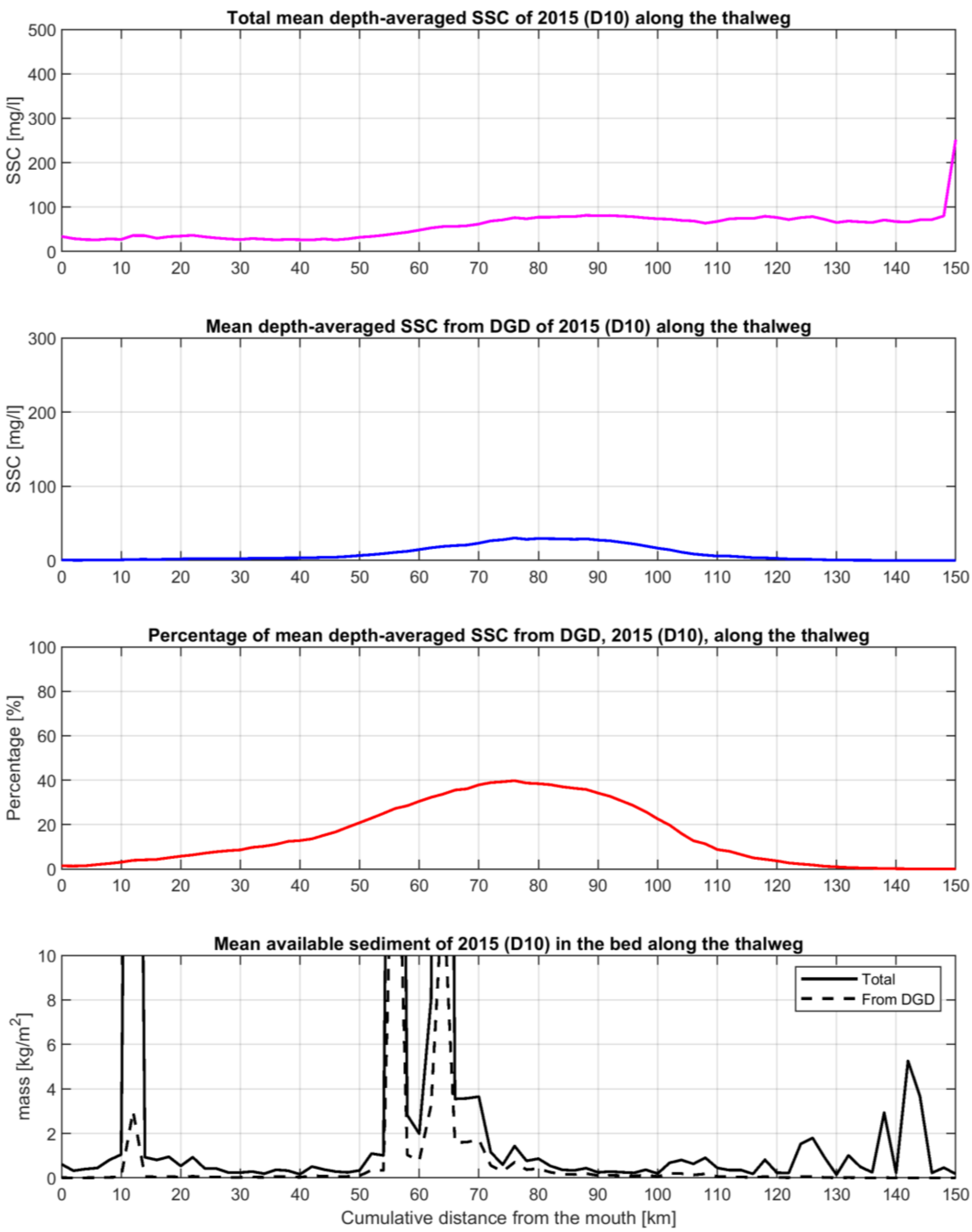

Figure 4-18: Depth-averaged SSC and contribution from Deurganckdok, simulation D10.

4.3 LONG-TERM SIMULATION 3: IMPACT OF REDUCED INTERVENTION LEVEL IN DEURGANCKDOK

4.3.1 Dredging volume

Figure 4-19 displays the long-term dredging volumes in simulation 3, in which the dredging intervention level in Deurganckdok changed from -15.5 m TAW to -18.0 TAW in 2011.

Removing the sediments that had deposited between -18.0 m TAW and -15.5 m TAW in the years before leads to a peak in the dredging volume in 2011. In the years after 2011, the dredging volume returns to a new, higher equilibrium volume This is likely due to the changes in bathymetry before and after 2011 (see §2.3): before 2011, the hydrodynamic scenario D was used (which has the bathymetry of 2009 for Deurganckdok, including the sill at the dock entrance). From 2011 on, the scenario hydrodynamic scenario A was used, which includes the removal of the sill and the deepening/widening of Deurganckdok.

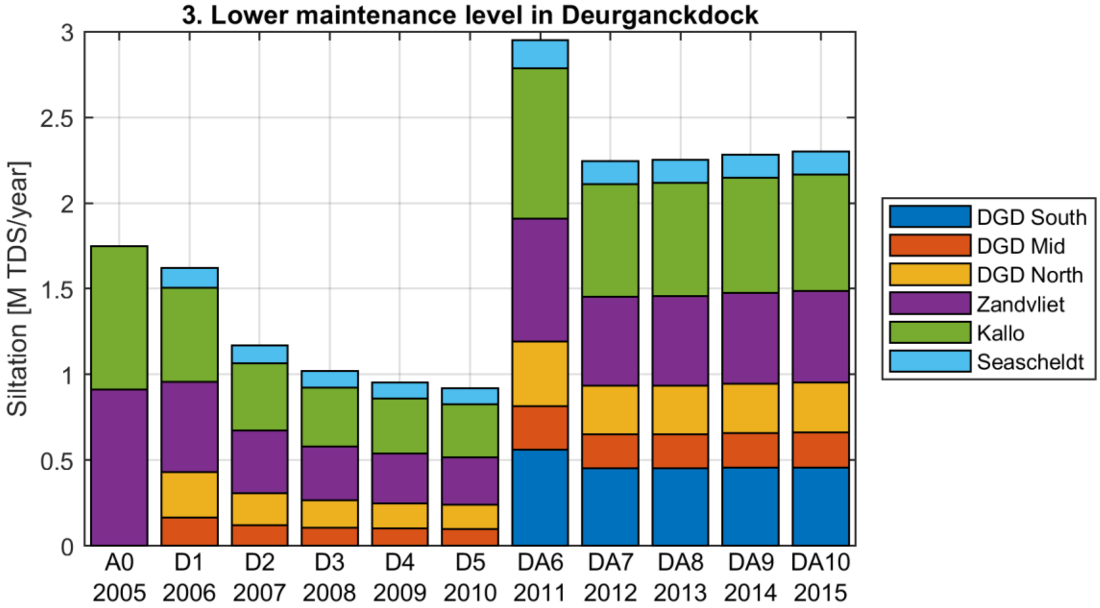

Figure 4-19: Long-term siltation and dredging rates for long-term simulation 3.

4.3.2 Spatial distribution of sediment

Figure 4-20, Figure 4-21 and Figure 4-22 display the yearly-averaged sediment concentrations from 2010, 2011 and 2015 of simulation 3, respectively. Figure 4-23 displays the year-and depth averaged concentrations for all years of the simulation.

In 2011, the sediment concentrations show a strong increase compared to the previous year, due to the altered bathymetry and intervention level and the one-time increase in dredging activity. In 2015, sediment concentrations are less high than in 2011, but still higher than in 2010.

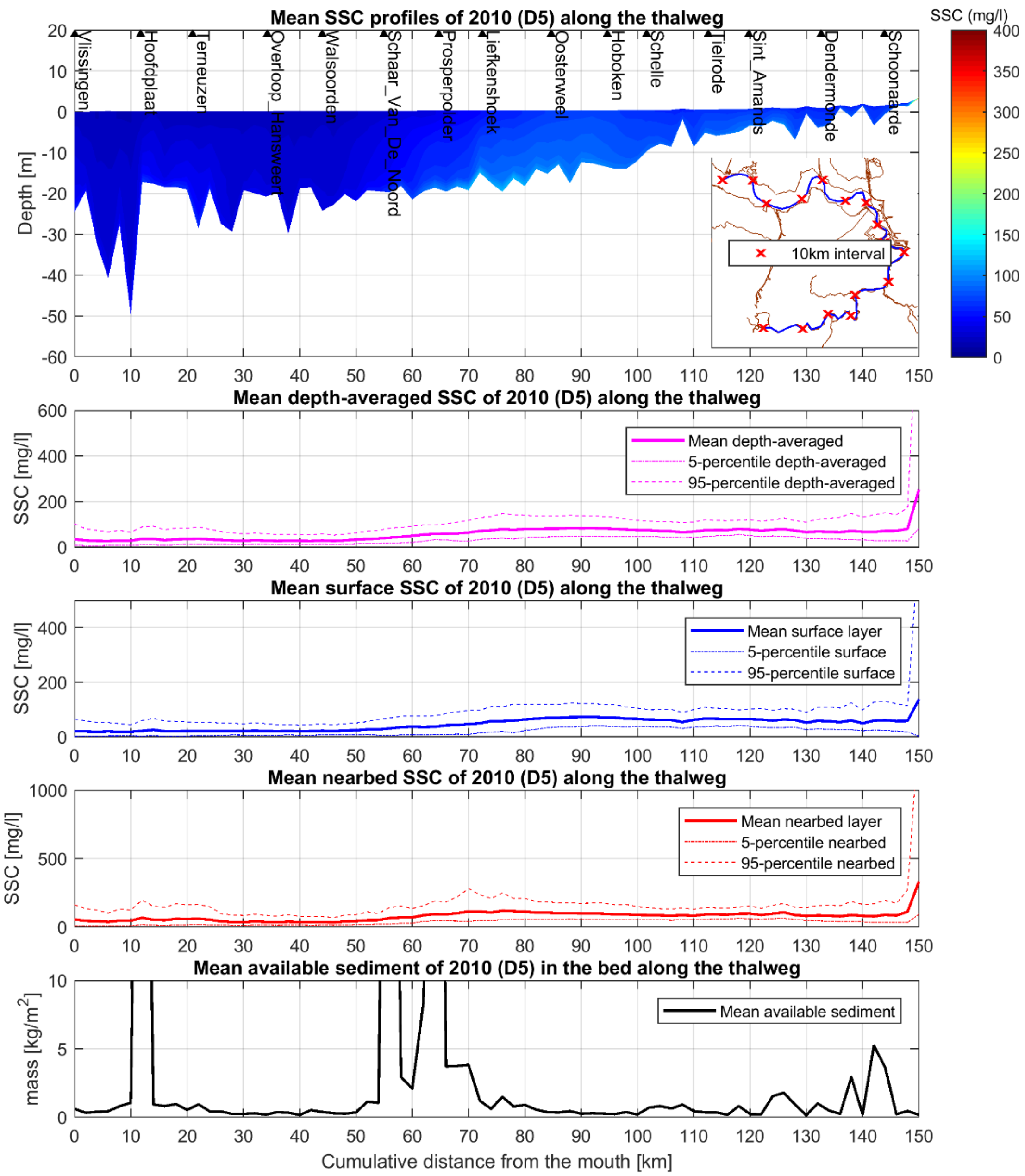

Figure 4-20: Yearly-averaged sediment concentration in 2010 (D5).

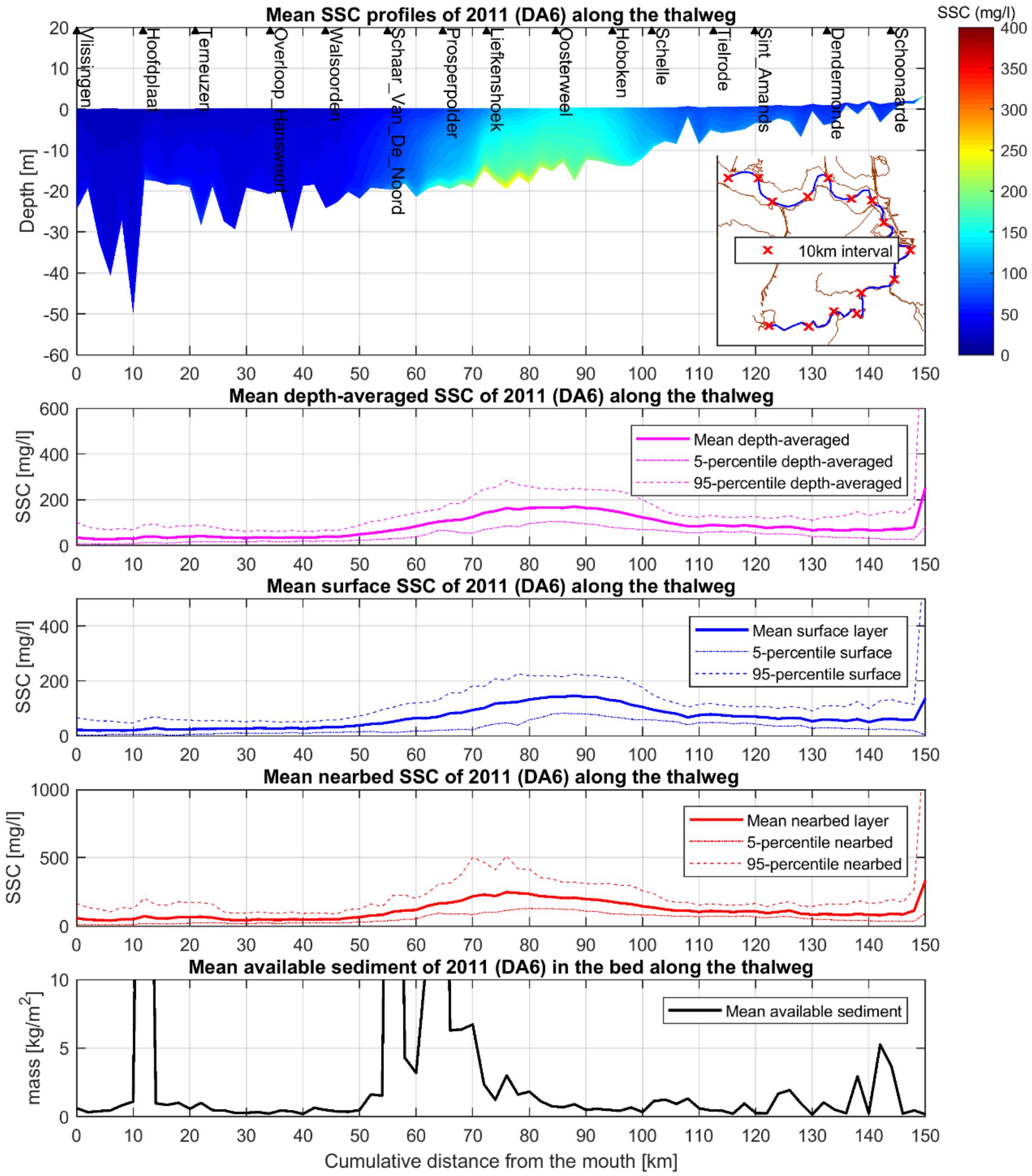

Figure 4-21: Yearly-averaged sediment concentration in 2011 (DA6).

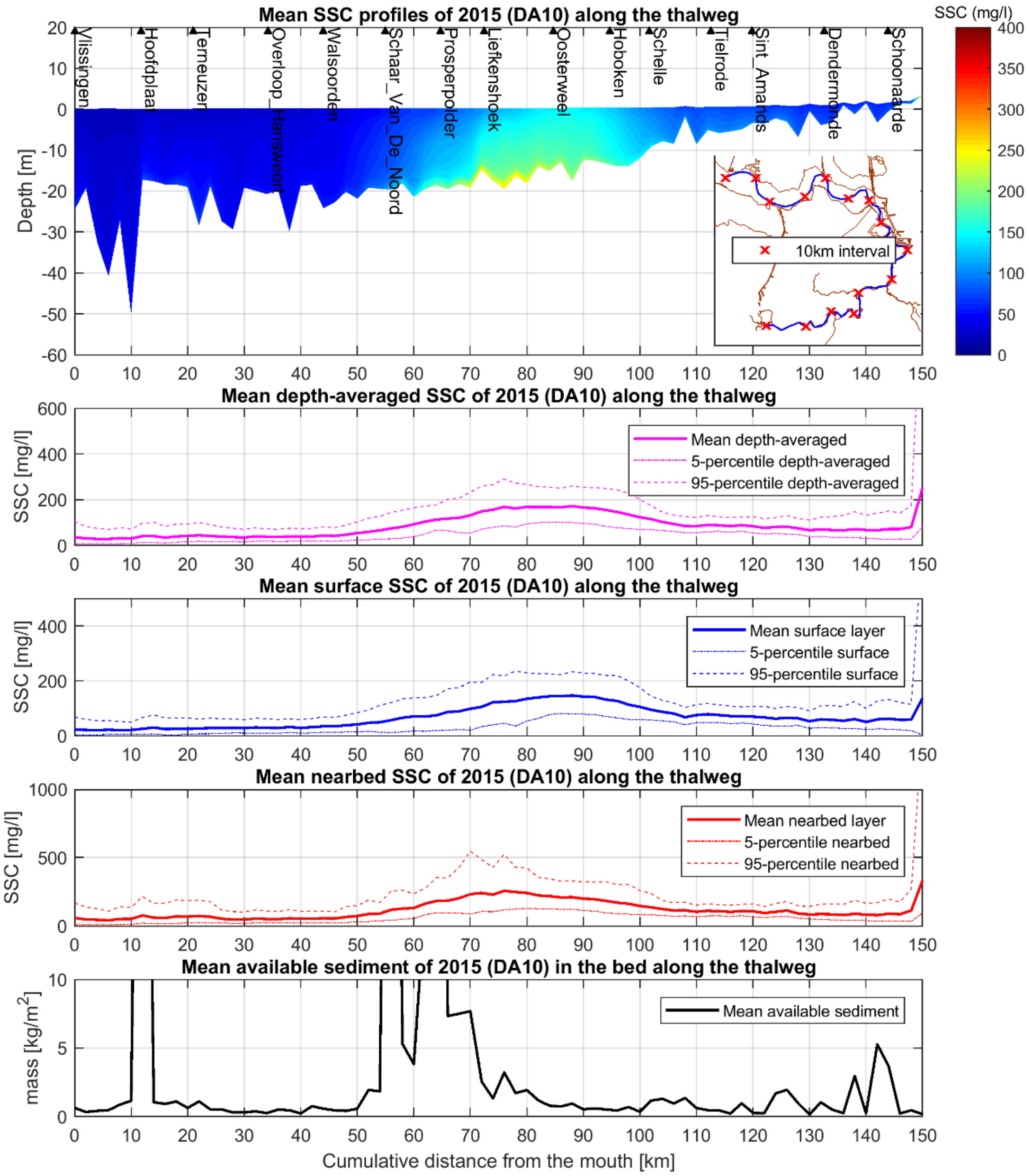

Figure 4-22: Yearly-averaged sediment concentration in 2015 (DA10).

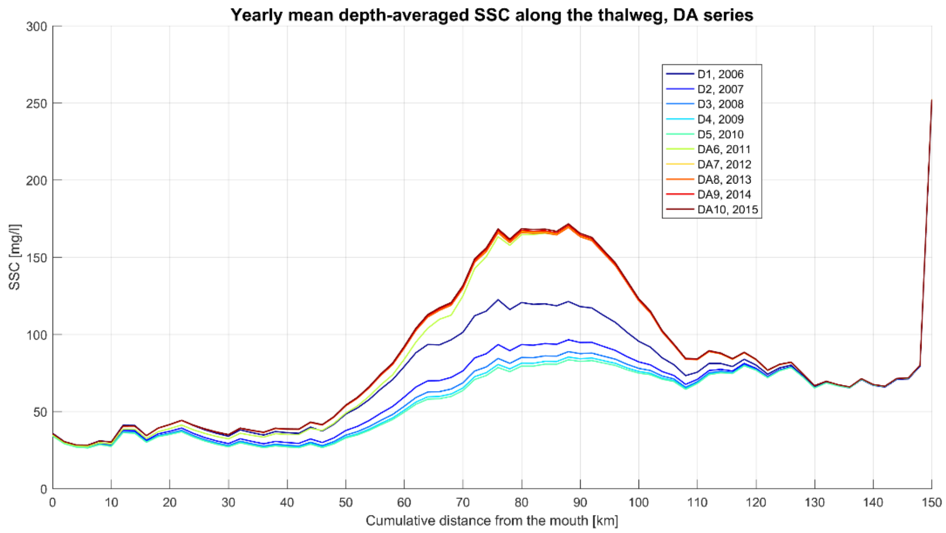

Figure 4-23: Yearly mean depth-averaged SSC along thalweg, scenario 3.

4.3.3 Distribution of sediment originating from Deurganckdok

Figure 4-24 displays the distribution of sediment originating from Deurganckdok for scenario 3. For 2006-2010, the values are the same as in scenario 2. In 2011 and the years thereafter, the importance of Deurganckdok increases significantly, due to the increased dredging intensity in the dock (Figure 4-19).

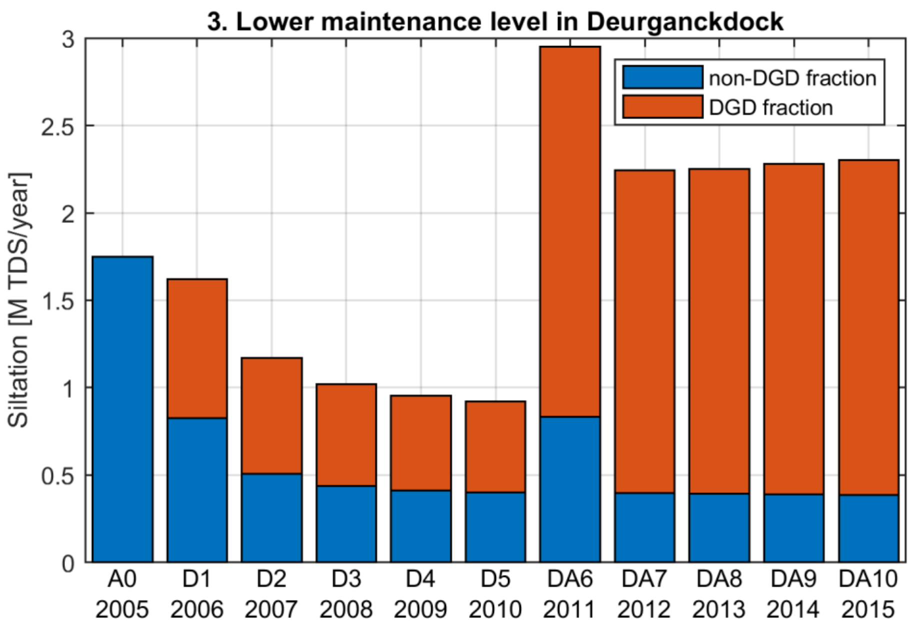

Figure 4-24: Fraction of dredged sediment from the dredging zones in the Sea Scheldt that originates from Deurganckdok, scenario 3.

5. DISCUSSION

In this chapter, the results of the numerical model simulations are further compared and discussed, with the research questions formulated in §2.4 being used as a guideline.

5.1 INITIAL RESPONSE AFTER OPENING OF DEURGANCKDOK

The (transient) impact of opening the Deurganckdok on the total dredging volume can be investigated from the first years of simulation 2 (Figure 4-13), or the first years of simulation 3 (Figure 4-19), as these are identical. The recorded dredging volume (Figure 2-1) displays a gradual increase in the total dredging volume over the period 2005-2010. In the model simulations, however, the total dredging volume initially increases after the opening of Deurganckdok (2006) and then decreases gradually in the following several years. In both the model simulations and in reality, the opening of Deurganckdok in 2006 presents a disturbance of the pre-existing (quasi-)equilibrium state in the sediment system, after which the system evolves to a new equilibrium that includes exchange with Deurganckdok. There are several possible reasons why the response of the predicted model is different from the recorded dredging volumes:

i. In the model, the Deurganckdok is opened in its entirety in the beginning of 2006. Subsequently, the model simulations D1-D5 (2006-2010) all have a constant hydrodynamic forcing and constant bathymetry (the bathymetry of 2009, which included a sill at the Deurganckdok entrance). In reality, however, the dock was gradually opened between 2005 and 2008, and was only fully operational in April 2008. There were also other gradual changes over the period 2006-2010, such as the third deepening of the Scheldt, which was executed in 2009-2010 in the Belgian part of the Scheldt and is not included in the scenario's[5].

ii. For computational reasons, the hydrodynamic forcing simulation (simulation A) that was used in the spin-up simulation A0 did include the Deurganckdok model in its domain, and the effect of Deurganckdok on the sediment dynamics was only removed by disabling siltation in the dock. In this sense, the equilibrium situation of the model at the end of A0 was not entirely equal to the real situation without a dock, but instead it included the impact of the dock on the hydrodynamics.

iii. Moreover, in the A0 simulation, even though deposition was prevented, sediment accumulation could still take place in the water column in the Deurganckdok as a result of the hydrodynamic import mechanisms. In the equilibrium state of the A0-simulation high sediment concentrations inside the dock led to an export balancing the import. After allowing sedimentation in the first year after opening of the Deurganckdok, these high concentrations led to an artificial, large and (quasi) instantaneous deposition and subsequent dredging. As such, the dredging volume as well as the resulting increase in

[5] The bathymetry of 2014 is used as a basis for all simulations, including the deepening of the Scheldt. The impact of the deepening is not a subject of this investigation.

sediment concentrations will have been overestimated in the first year after opening.

iv. In the model, the spin-up simulation A0 was executed until the system had truly reached an equilibrium state. The real system, however, may have not been near an equilibrium state at the moment when the Deurganckdok was opened, but instead may still been evolving. For example, the high upstream discharge during the years 2001-2002 (Figure 2-2), or the fact that sediment storage in the Waaslandhaven was ended in 2001 (see Section 2.1.1) may still have had an effect on the system by the time Deurganckdok was opened.

Especially item (i), (ii) and (iii) above explain the difference between the model and observations in the period after opening the dock: the gradual opening of the dock in 2005-2008 in reality cause a increase in dredging volume in the period 2005-2008 as seen in the observations (Figure 2-1), and the fact that the Deurganckdok was included in the hydrodynamics of simulation A0 caused a decrease in dredging volume in the model in the same period 2005-2008.

5.2 IMPACT OF LOW UPSTREAM DISCHARGE, AND RESPONSE IN SUBSEQUENT YEARS

The impact of the reduced upstream discharge that occurred in 2011 can be investigated using the results of simulation 1 (Figure 4-1). This simulation predicts a lower dredging volume in all dredging zones in 2011 than in previous years, in contrast with the recorded dredging volumes (Figure 2-1).

The model does not predict any upstream/downstream migration of the ETM with the seasonal variations in discharge (see Figure 4-6 and Figure 4-7) or between years with high and low discharge. Measurements, however, show a clear seasonal variability in which the ETM is located further downstream during wet winter months, and further upstream during dry summer months (Figure 5-1). This shift between summer and winter has become significantly stronger since approximately 2009; the reason for this is still subject to research (Cox *et al.*, 2015).

Previous versions of the LTV model, which did not have the dredging and disposal cycle incorporated, did display a variation of ETM as a function of upstream discharge (van Kessel *et al.*, 2010). Therefore, it is possible that the process of dredging and disposal, where all the dredged sediment is disposed at Plaat van Boomke, forcibly keeps the ETM in the same location in the model.

In other words, the observations in Figure 5-1 show a decrease in the concentration near Deurganckdok and an increase in the concentration in the upper Sea Scheldt during low discharge conditions (summer). In the model, the concentration near Deurganckdok decreases during low discharge but the concentration in the upper Sea Scheldt remains more or less equal (see Figure 4-8 & Figure 4-9).

Statistical analysis of (bi-)monthly sampling in the Scheldt estuary demonstrated that sediment concentrations in the Upper Seascheldt are strongly related to variations in upstream discharges, while concentrations in the Lower Seascheldt have a strong correlation to the maintenance dredging volume. As such it could be hypothesized that different processes are associated with the observed response. Downstream, the reduced dynamics lead to lower concentrations and thus lower dredging volumes. Upstream flushing by the discharge is reduced and the residence time increases, leading to higher concentrations. Perhaps even the asymmetry of the sediment transport is reversed as a result of the reduced river discharge, leading to a residual upstream transport of sediment.

However, the present LTV model was mainly developed and calibrated for the region downstream of Antwerp, and the fact that the upstream increase in sediment concentrations is not predicted by the model may be due to the fact that the upstream reaches are not fully resolved.

The fact that the model (and the observations) displays a lower sediment concentration (in the port area) during the 2011 period of lower discharge is a likely explanation for the predicted reduction in dredging volumes in the long-term simulation 1.

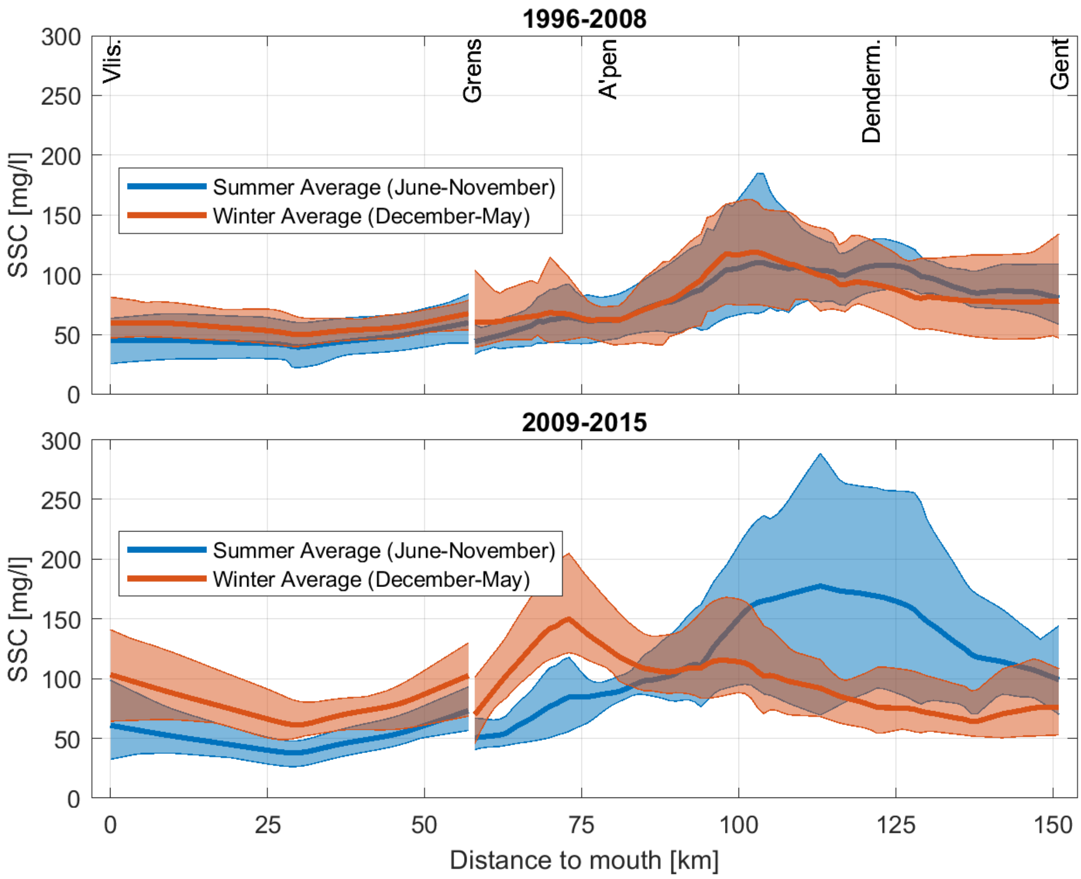

Figure 5-1: Summer- and winter-average of suspended sediment concentration measured at the surface (OMES data, Maris and Meire, 2016).

5.3 IMPACT OF LOWERED DREDGING INTERVENTION LEVEL, AND RESPONSE IN SUBSEQUENT YEARS

In simulation 3, the dredging intervention level in the dock was reduced from -15.5 m TAW to -18.0 m TAW in 2011, and the sill at the entrance of Deurganckdok was removed. This is similar to reality, except that the upstream discharge was held constant in the model. This effectively isolates the effect of changing the dredging intervention level and the one-time increased dredging activity in 2011, from the reduced upstream discharge conditions.

The model predicts a higher dredging activity in all dredging zones in 2011 (also the zones other than Deurganckdok, which did not see a change in intervention level). Associated with the higher dredging volumes, an increase in sediment concentrations is also observed (Figure 4-21), and this likely generated an additional sedimentation in the maintenance zones, which is also observed in the recorded dredging volumes (Figure 2-1).

In 2012, the year following the higher dredging activity, the dredging volumes are lower again, but still higher than in the years before 2010. In the following years, a very slight increase in the dredging volumes occurs as the model evolves to a new equilibrium. The fact that dredging volumes after 2011 are higher than before is likely due the new bathymetry (which includes the removal of the entrance sill) and the lower intervention level. The gradual increase of the modelled dredging volumes in 2012-2015 is different from the recorded volumes (Figure 2-1), which show a gradual decrease after the peak year 2011.

5.4 IMPACT OF NOT DEEPENING THE DOCK

Simulations 1 and 3 are forced with the bathymetry and dredging intervention level of 2014 (hydrodynamic simulation A) for their last 4 years. In these last years, the two simulations evolve to an equilibrium state that is almost identical (compare result for 2015 in Figure 4-1 and Figure 4-19). In contrast, simulation 2 is forced with the bathymetry and dredging intervention level of 2009 (hydrodynamic simulation D) until the end of the 10-year simulation, and evolves to a different equilibrium state. This allows to compare and investigate what the dredging activity would be today if the bathymetry and intervention level had remained the same since 2009.

The final equilibrium state in simulation 2 (Figure 4-13) shows significantly lower dredging volumes, both for Deurganckdok as well as for the other maintenance zones. Note that the deposition in the DGD South section is unlimited in the model, which is not realistic. This may lead to an equilibrium state with lower sediment concentrations in the river, as the accumulation in the Deurganckdok is overestimated.

6. CONCLUSIONS

Three long-term simulations of hydrodynamics and sediment transport over the period 2006-2015 were performed to investigate the transient behavior of dredging activity and suspended sediment concentrations in relationship to the Deurganckdok, and in particular the possible causes for the elevated dredging volumes and suspended sediment concentrations that occurred in 2011. The model is an idealized/simplified version of the complex system formed by the Scheldt estuary, Deurganckdok and maintenance dredging. Since the model predictions do not always agree with the observed evolutions, care must be taken in interpreting the model results. However, the model can still provide useful information regarding the sediment dynamics in Deurganckdok and the Scheldt.

Regarding the **initial response after the opening of Deurganckdok** (2006)**,** the model predicts a gradual decrease in the total dredging volume, whereas observations show a gradual increase. This is mainly due to the fact that the dock was opened gradually in reality over the period 2006-2008 but opened instantaneously in the model, and because the Deurganckdok was included in the hydrodynamics and sediment dynamics of the spin-up simulation A0.

During periods of **low upstream discharge** both the model and observations display a decrease in the suspended sediment concentration in the region around Deurganckdok, which leads to a decrease in dredging volume in Deurganckdok as well as the other nearby maintenance zones. In the Upper Seascheldt, measurements display an increase in suspended sediment concentrations during low discharge, commonly referred to as an upward migration of the ETM, which is not reproduced in the model. The LTV model, however, was originally developed for the region downstream of Antwerp, and its predictions for (or representation of the processes in) the upstream reaches are therefore considered as less reliable.

The impact of **lowering the dredging intervention level from -15.5 m TAW to -18.0 m TAW in 2011**, and the resulting **temporary increase in dredging activity**, is an increased dredging volume and SSC according to the model. In the long term, the equilibrium dredging volumes predicted by the model are significantly higher for the 2014 situation (-18.0 m TAW intervention level, no sill at the dock entrance) than for the 2009 situation (-15.5 m TAW intervention level, sill at the dock entrance).

Typical **time scales** according to the model associated with response of the system to the opening of the Deurganckdok, the change in intervention level and removal of excess sediments resulting from the increase dredging are 4 to 5 years.

In conclusion, the model simulations show that the elevated suspended sediment concentrations and dredging volumes that were observed in 2011 are (at least partially) due to the lowering of the dredging intervention level and the resulting temporary increase in dredging activity. The elevated sediment concentrations and dredging volumes in 2011 were probably not the result of the low discharge during this period; this rather caused a decrease in sediment concentrations and dredging volumes.

Recommendations for further research

The model simulations that were presented in this report provide useful insights in the evolution of sediment concentration and dredging volumes at Deurganckdok over the period 2005-2015 and the processes that govern these. There are a number of actions that could be taken to further extend the knowledge on these issues:

- The spin-up simulation A0 was now run with the hydrodynamic run A, including Deurganckdok. Running a specific hydrodynamic simulation without Deurganckdok would provide a more realistic spin-up and thus more realistic initial conditions for the scenarios. However, this would require some work effort since the grid would need to be modified compared to the existing simulations.

- In long-term simulation 2, the back end of the Deurganckdok acts as a sediment sink indefinitely, which is not fully realistic. To counter this, a (higher) intervention level for dredging could be implemented in the back end of the dock in this simulation, to impose an upper limit on the sedimentation in this part of the dock.

- In long-term simulation 3, an increase in sediment concentration and dredging volume is observed in 2011 as a result of the lowered intervention level and the resulting increase in sediment disposal. Repeating the scenario 3 without this temporary push of sediment would make it possible to visualize the transition to a new equilibrium due to the intervention level change alone.

- The simulations demonstrate that the dredging and disposal of sediment from Deurganckdok has an important impact on the sediment concentrations in the region. This could be further investigated by studying the holiday period during the last two weeks of the year, during which dredging works are suspended. This period provides an opportunity to observe the system response to dredging- and disposal-free conditions, either via a measurement campaign or a model simulation of this period.

- The present LTV model was developed and calibrated specifically for the region downstream of Antwerp, and does not reproduce the observed increase in sediment concentrations during low discharges in the upstream reaches. To better capture the sediment dynamics in the entire Scheldt estuary, including the areas upstream of Antwerp, the model could be extended with improved resolution of the upstream regions.

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Annex A Hydrodynamic model: Update the NEVLA3D model to the year 2014

Memo

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Titel: Update the NEVLA3D model to the year 2014

Datum: 20/06/2018

Auteurs: Chu, Kai

Ref.: [Trefwoorden]

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1 INTRODUCTION

The objective of the study is to evaluate the external effect on the siltation in Deurganckdok (DGD) for the year 2014 - 2017. Previous studies have been carried out for the year 2006-2009 (IMDC 2009), 2009 – 2012 (IMDC 2013) and 2012-2014 (IMDC 2016). The external effects are understood as the effects that from recent or planned human interventions in the vicinity of the DGD, such as the sill removal (2009-2010), the construction of the CDW (2010-2011), the change of maintenance depth of DGD (2011-2012) and the construction of Kieldrecht lock (2011-2016) etc. The more severe siltation in DGD in 2011 leads to more costly dredging, which is deemed to be related to the reduced fresh water discharge in 2011 and/or to the deepening of the DGD in 2011. The related scientific question is: are these changes due to an intervention year of 2011 or rather cumulative effect?

In order to clarify the problem, the LTV-slib model for mud transport simulation is prepared. An update of the existing NEVLA3D model to a more recent year becomes necessary. This memo describes the technical details in terms of the updates which involves the migration of model inputs and forcing to the year 2014. The model runs for the entire year of 2014, starting from 01-01-2014 until 31-12-2014. The first two days are used for model spin-up. The real model calculation starts from 03-01-2014.

Within the framework of the modelling undertaken for the External Effects Siltation Deurgangck Dock study two additional scenario runs of the mud transport simulation have been performed (see descriptions below), for which the NEVLA3D model is adapted to run with different hydrodynamic conditions correspondingly.

A. Reference simulation with a representative year of 2014.

B. River discharges are imposed with measurements of 2011 which represents a dryer year compared with 2014; the rest of the model settings are the same as the reference simulation [Scenario A].

C. The model bathymetry inside the Deurganckdok (DGD) is modified based on measurements from 2009, the rest of the model settings are the same as for the reference simulation [Scenario A]. The vertical reference level used by NEVLA3D is NAP which is about 3.07 m above LAT level (see transformations in Annex1). Table 1-1 shows the change of maintenance level at DGD (IMDC, 2016) in both LAT and NAP.

Table 1-1: Description of the level of maintenance work near DGD.

Date	maintenance depth quays [mLAT]	maintenance depth trench [mLAT]	maintenance depth sill [mLAT]
May 2008 – December 2010	-14.8 – -15.7 m (variable)	-15.0 – -17.0 m (variable)	No maintenance of sill (except sweepbeam)
March 2011	-15.9 m	-17.5 m	-15.2 m
October 2012	-15.9 m	-18.0 m	-15.2 m
Date	**maintenance depth quays [mNAP]**	**maintenance depth trench [mNAP]**	**maintenance depth sill [mNAP]**
May 2008 – December 2010	-17.87 – -18.77 m (variable)	-18.07 – -20.07 m (variable)	No maintenance of sill (except sweepbeam)
March 2011	-18.97 m	-20.57 m	-18.27 m
October 2012	-18.97 m	-21.07 m	-18.27 m

2 BATHYMETRY

2.1 Overall bathymetry

In order to perform model simulations for the year 2014, the NEVLA3D model bathymetry is updated with bathymetric measurements (combination of the year 2014 and 2015). Figure 1 presents the bathymetric measurements merged from 4 different data sources. Table 2-1 presents the detailed description of the source data.

For the area where the latest bathymetric data are not available in the NEVLA domain (Figure 1), the bathymetry is taken from the final NEVLA3D calibration run simG160 (Vanlede et al., 2015).

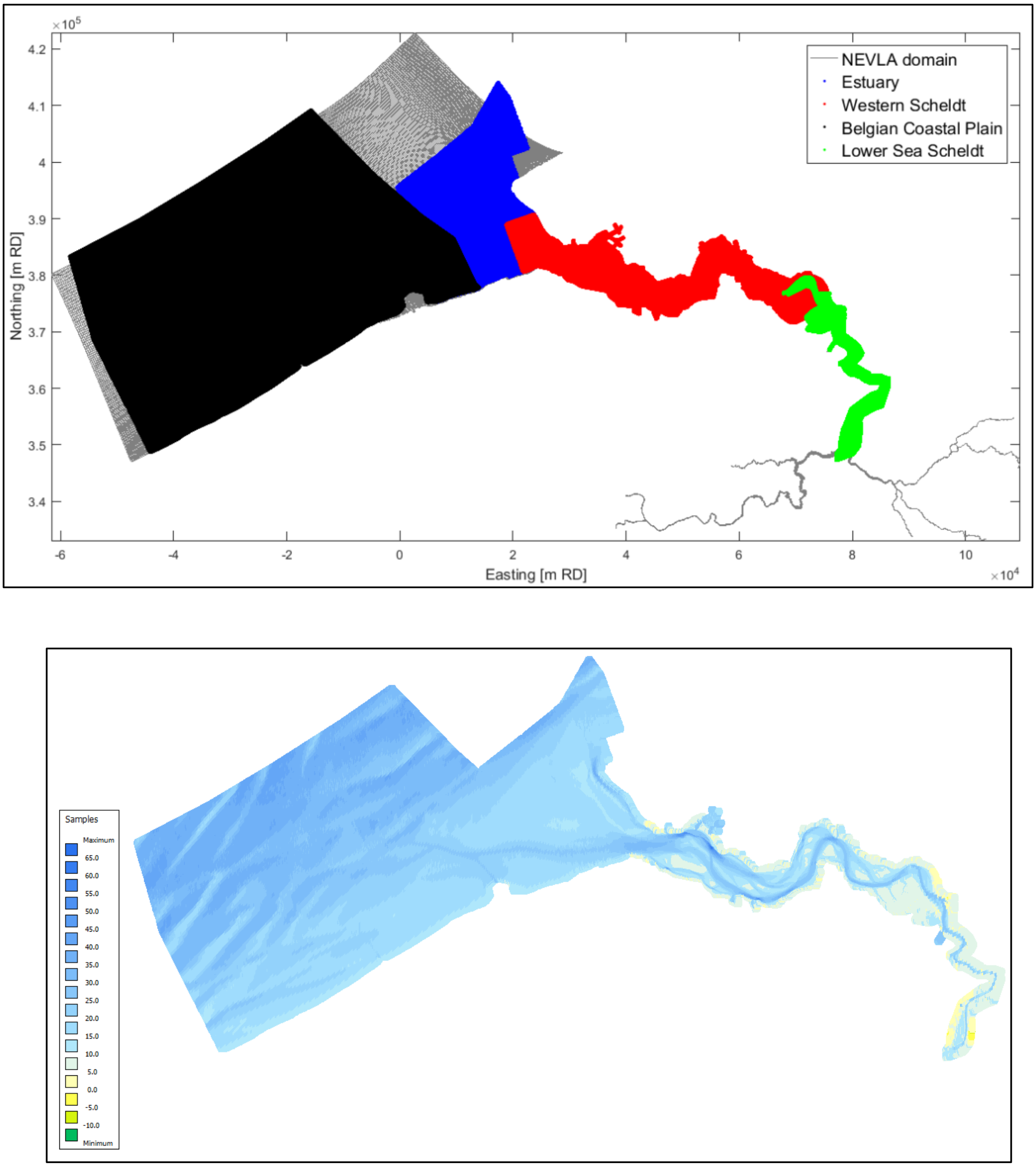


Figure 1: Demonstration of the four different sources of bathymetric data (upper panel) and the values of the data (lower panel; positive downwards [m NAP]).

Table 2-1: Description of bathymetric sample data 2014.

Zones	Year	Resolution [m]	Source Files
Belgian Coastal Plain	2004-2016	20 x 20	G:\Masterarchief\tob\BCP_bth_2004-2016_VH_utm31etrs89_taw_R_meest-recent-beschikbaar-in-2016\
Estuary Mouth	2014	20 x 20	G:\Masterarchief\tob\WES_bth_2014_RWS_rds_NAP_R°_vaklodingen-vak-11-19\export ascii\
Western Sea Scheldt	2015	20 x 20	G:\Masterarchief\tob\WES_tob_2015_RWS_RDS_nap_R°\ga2015_in_m.tif
Lower Sea Scheldt	2014	5 x 5	G:\Masterarchief\tob\BEZ_tob_2014_MT_rds_taw_R

2.2 Bathymetry of surroundings of DGD

To prepare for the simulation of Scenario C, the model bathymetry inside the DGD (including the sill) is replaced with measurements from year 2009. Table 2-2 presents the detailed description of the source data.

Table 2-2: Description of bathymetric sample data 2009.

Zones	Year	Resolution [m]	Source Files	Source
DGD	2009	5 x 5	G:\Masterarchief\tob\BEZ_bth_2009_MT_lam72_taw_R°	090925_TERM_DGD_SB_33

Figure 2 shows the comparison of local bathymetry near DGD. The bathymetry of 2009 along the central trench is about 18-19 m NAP which agrees with the maintenance level as described in Table 1-1.

Be aware that the bathymetric data inside DGD both in 2009 and 2014 are recorded with single beam (SB) echo sounder with frequency of 33 kHz. Both bathymetries are rather deeper when compare with data recorded by a 210kHz-echosounder.

For example, the 2014 bathymetry (Scenario A) used by the NEVLA model is about 20-22 m NAP along the trench (Figure 2). However, Figure 3 (IMDC 2015) shows that the bathymetry measured by a 210kHz-echosounder in 2014 along the DGD trench is only about 16 mTAW = 18.35 mNAP.

As the aim is to observe the effects of the deepening, it is therefore not problematic as the differences of the bathymetries between Scenario A and C are substantial.

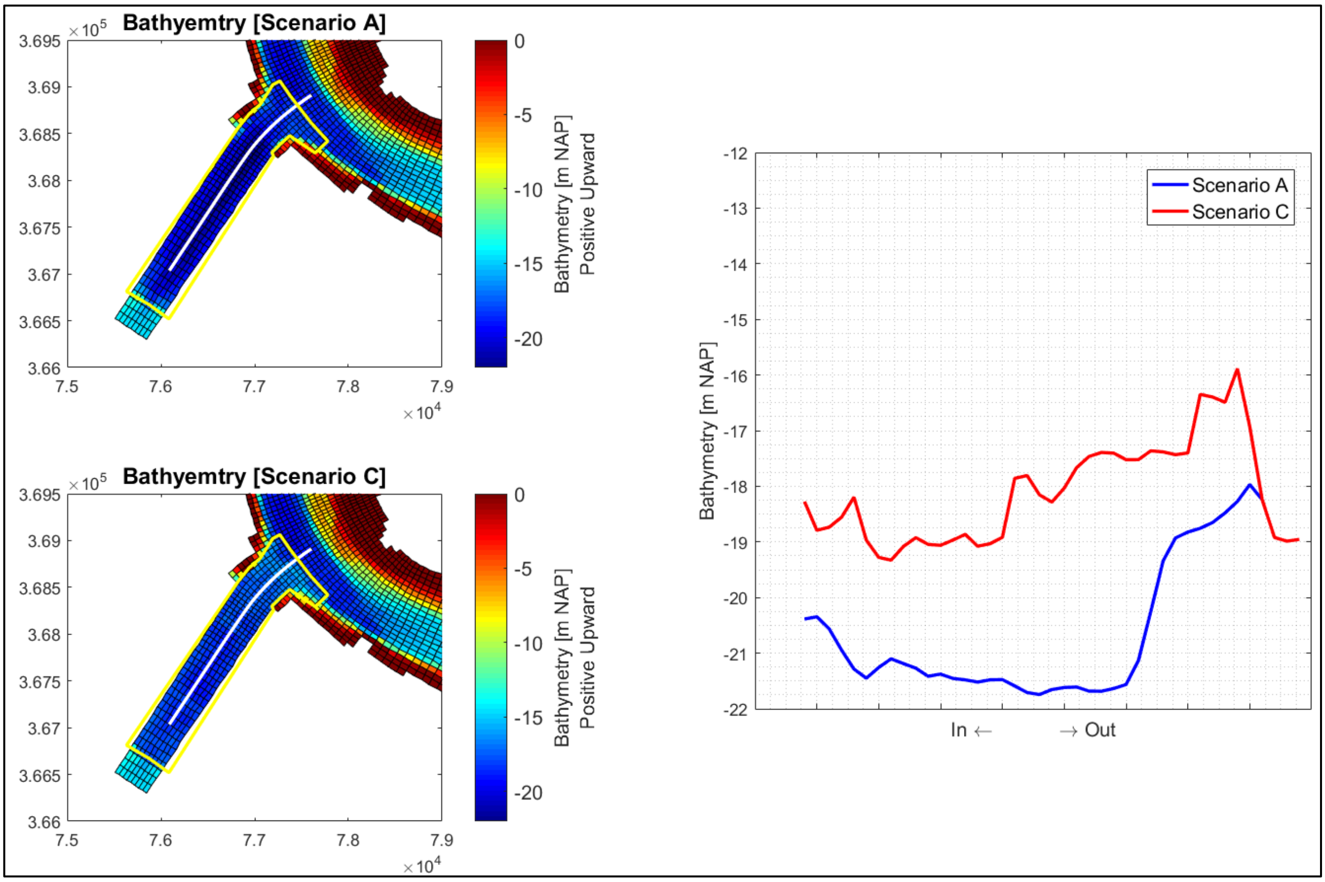


Figure 2: Comparison of the local bathymetry near DGD between 2014 (Scenario A) and 2009 (Scenario C). The white line represents the central trench; the yellow polygon represents the area where the local bathymetry are changed.

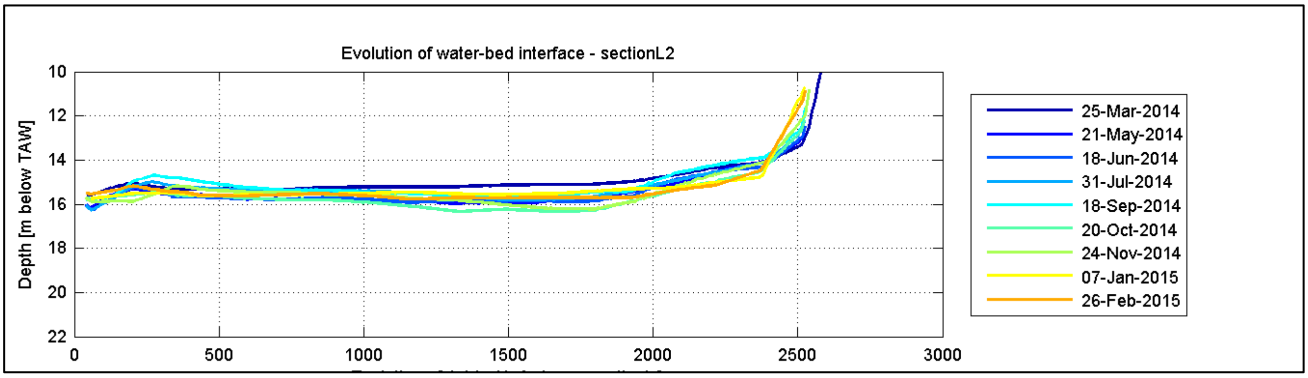


Figure 3: Water depth [m TAW] measured by a 210kHz-echosounder along the trench of DGD. X of 0 indicates DGD zuid.

3 SALINITY

Salinity measurements are available at 8 stations (see locations in Figure 4) and are listed in Table 3-1. Salinity measurements are used to initialize the NEVLA3D. The initial salinity map is constructed by linear interpolation along the estuary of the salinity measurements at the various locations (Figure 4).

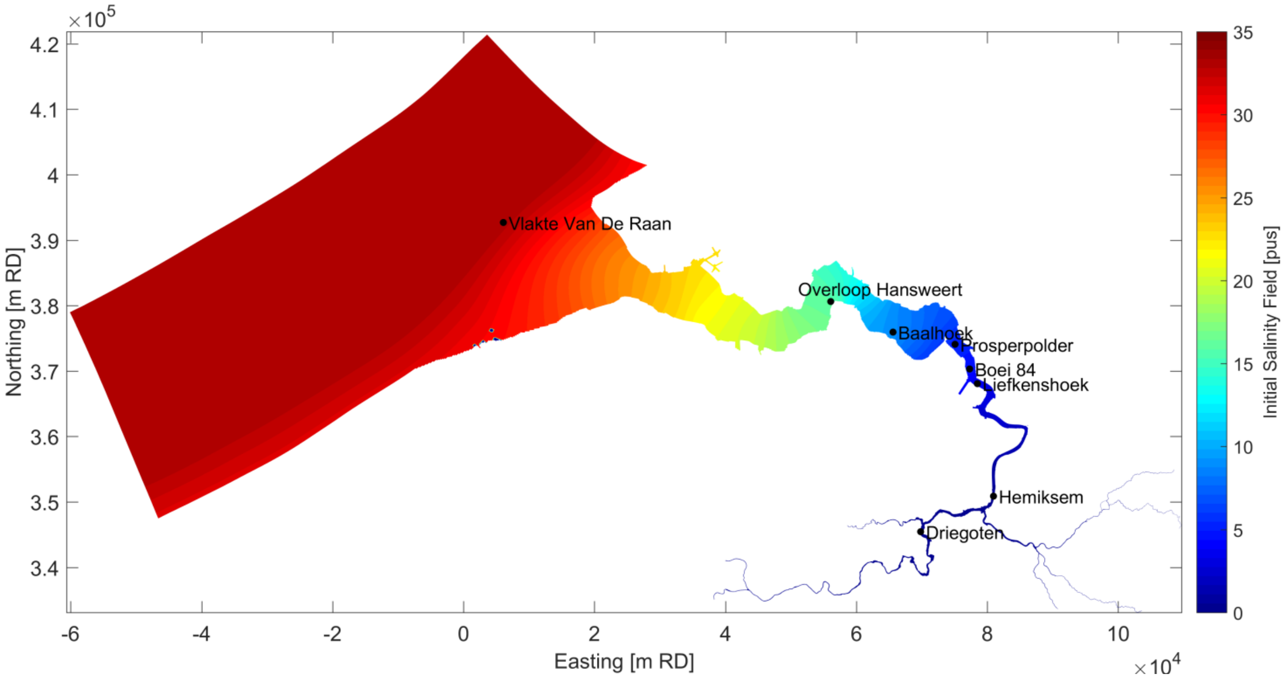


Figure 4: Initial salinity field for the NEVLA3D model and available stations with salinity measurements of 2014.

Table 3-1: Overview of available stations with salinity measurements.

Nr	Measuring station	Data source	Initial salinity at 03-01-2014 00:00 [ppt]
1	Vlakte Van De Raan	HMCZ	33.1
2	Overloop Hansweert	HMCZ	15.95
3	Baalhoek	HMCZ	8.86
4	Prosperpolder	HIC	5.15
5	Boei 84	HIC	4.7
6	Liefkenshoek	HIC	3.47
7	Hemiksem	HIC	0.33
8	Driegoten	HIC	0.3

4 RIVER DISCHARGE

River discharges are imposed at 8 stations in the NEVLA3D model (See details in Table 4-1). The instantaneous and cumulative river discharge of 2014 and 2011 are presented in Figure 5 and Figure 6 respectively. Figure 7 compares the cumulative river discharge over the entire year of 2014 and 2011 for each river.

The cumulative river discharge from Bath and Terneuzen in 2011 is about half of that in 2014, which implies that the year 2011 is relatively a dryer year.

Table 4-1: Description of river discharge data for the year 2014.

Station Names	Source	Data Type	Temporal Resolution
Bath	RWS	Measurement	10 minutes
Ternuezen	RWS	Calculated	daily
Kleine Nete	www.waterinfo.be	Measurement	daily
Grote Nete	www.waterinfo.be	Measurement	daily
Dijle	www.waterinfo.be	Measurement	daily
Dender	www.waterinfo.be	Measurement	daily
Melle	www.waterinfo.be	Measurement	daily
Zenne	www.waterinfo.be	Measurement	daily

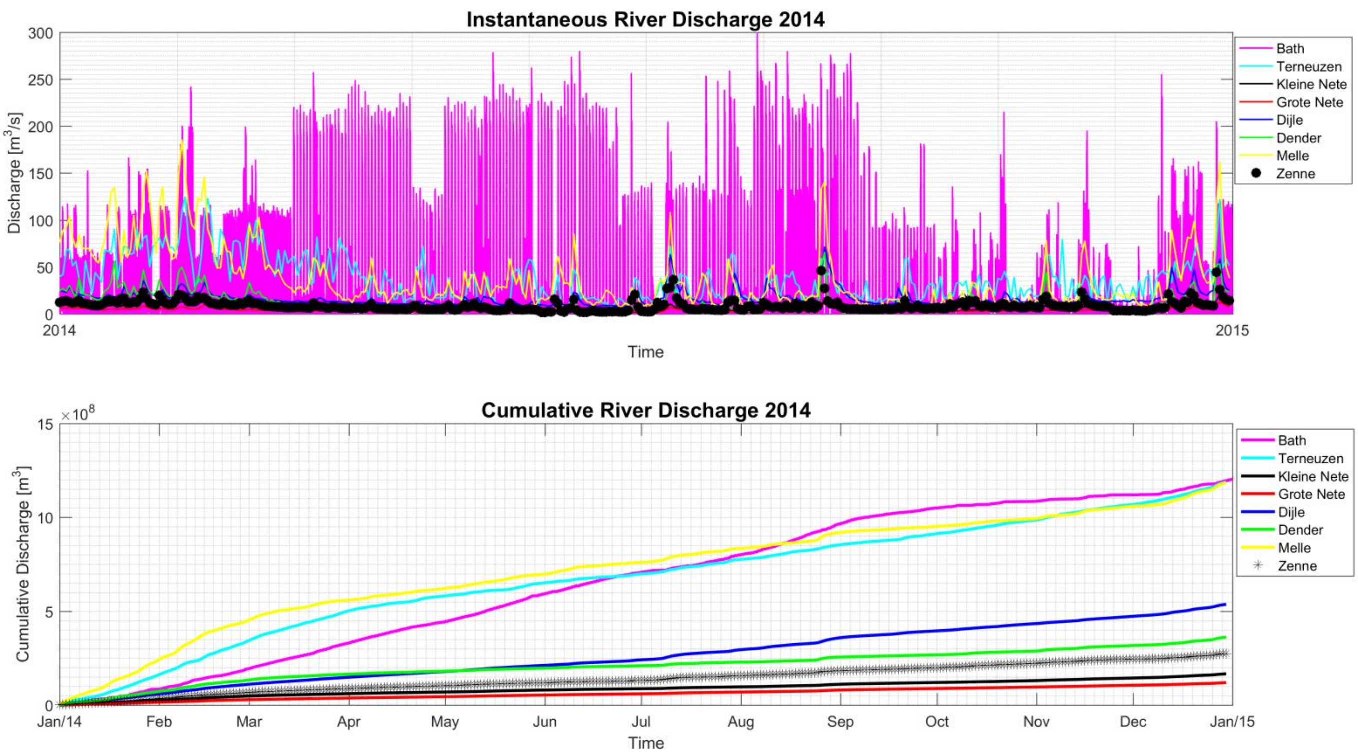


Figure 5: Instantaneous and cumulative time series of river discharge of 2014 at various locations.

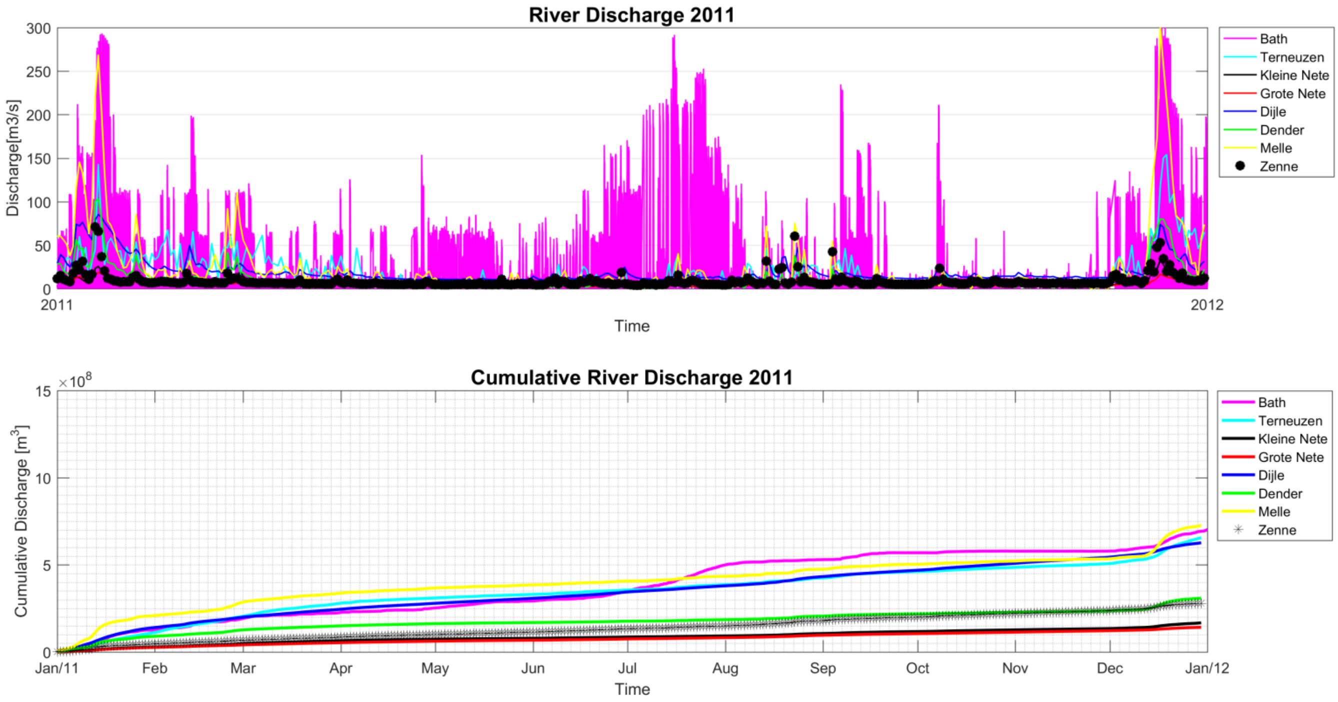


Figure 6: Instantaneous and cumulative time series of river discharge of 2011 at various locations.

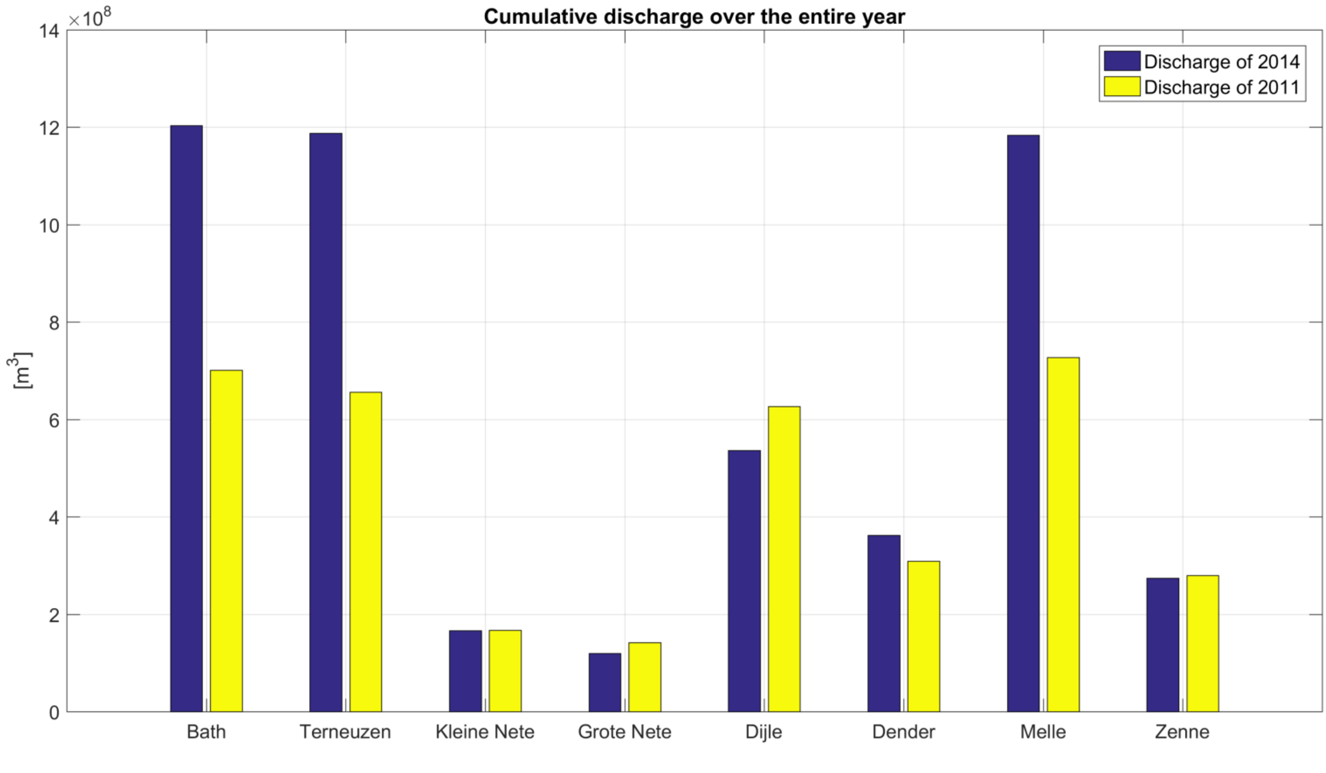


Figure 7: Comparison of cumulative river discharge over the entire year of 2014 and 2011 at 8 river branches.

5 WIND

5.1 ZUNO: Hirlam wind

The wind field data (format: Grib) are received from Hirlam (High Resolution Limited Area Model), which is a Numerical Weather Prediction (NWP) forecast system developed by the international HIRLAM programme. The Grib data are converted into a SDS-file (binary format) by means of Simona script of **waqwnd**. The spatial resolution is 1/12° latitudinal and 1/8° longitudinal, corresponding to the grid resolution of the Continental Shelf Model (CSM). The temporal resolution is 3 hours.

The Hirlam wind field data are utilized to force the ZUNO model which provides boundary conditions to the NEVLA3D model through boundary nesting.

5.2 NEVLA: Measured wind

Wind measurements are available at Hansweert with time interval of 10 minutes (RWS). Hansweert is a representative station as surge development proxy on the Scheldt. The wind rose (Figure 8) indicates that winds mostly come from the SW with magnitudes generally smaller than 20 m/s.

The time series of wind measurement at Hansweert of 2014 (Figure 9) are utilized to force the NEVLA3D model.

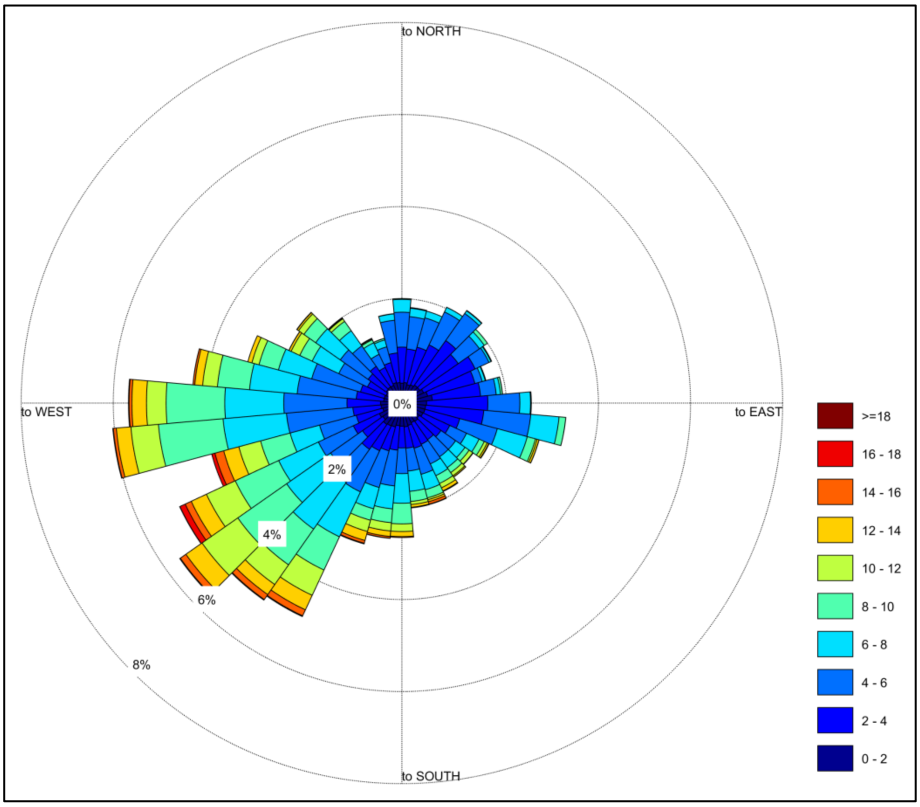


Figure 8: Wind rose at Hansweert from measurements (analysis period: 01-01-2014 to 31-12-2014).

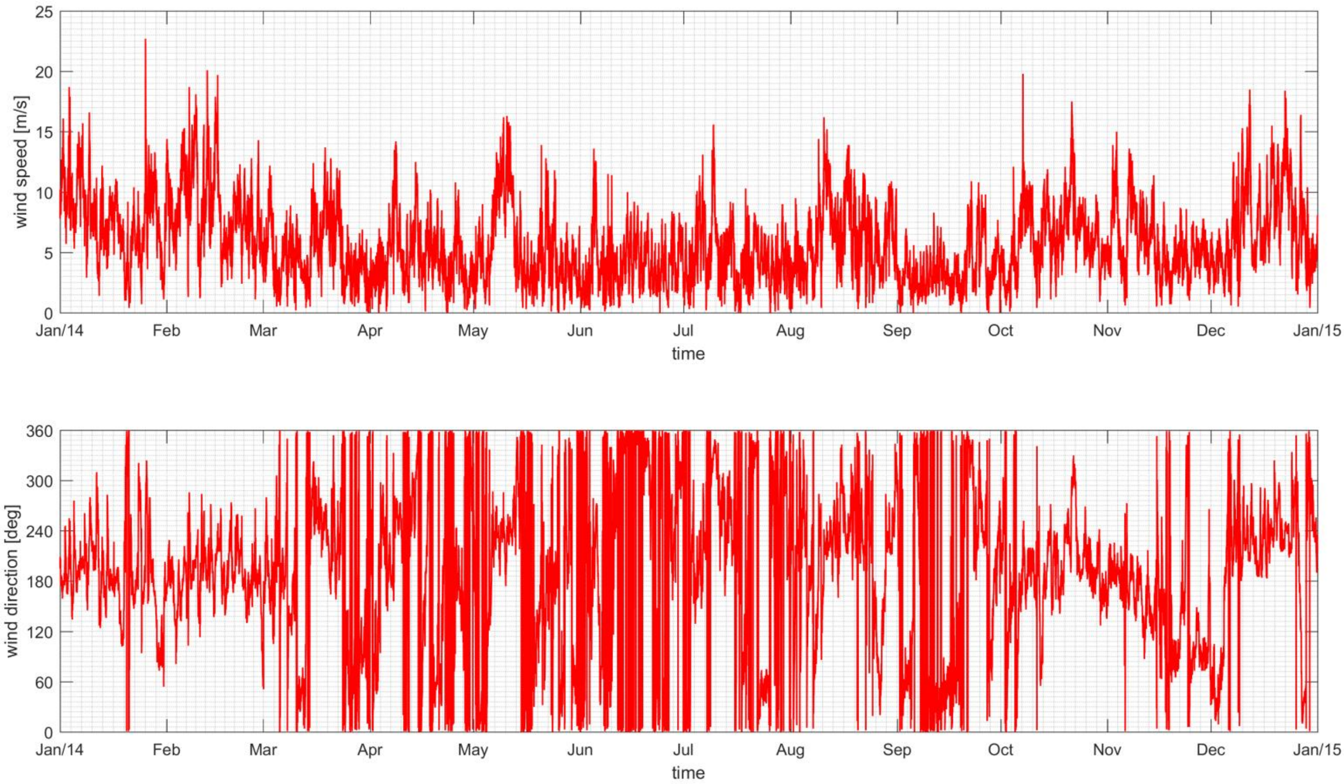


Figure 9: Time series of measured wind speed and direction in the year 2014 at Hansweert (data source: RWS).

6 MODEL SETTINGS

6.1 Modelling software

SIMONA (Simulatie Modellen Natte waterstaat) is a program developed by Rijkswaterstaat, for 2D (WAQUA module) and 3D (TRIWAQ module) modelling of water movement, particle dispersion and fluid mud transport and consists of a number of programs for preprocessing (preparation of simulations) and post processing (visualization of the model results). The **2010** version of SIMONA is used in this study.

6.2 ZUNO MODEL

The existing ZUNO 2014 model has been extensively calibrated, validated and reported by Maximova et al (2015). Therefore the ZUNO model is directly applied to provide boundary conditions for the NEVLA3D model for the year 2014.

The ZUNO model is linked to the versioning system:

https://wl-subversion.vlaanderen.be/svn/repoSpNumMod/SIMONA/ZUNO/008_ZUNO_v3_2014

6.3 NEVLA 3D

The existing NEVLA3D model was recently calibrated and validated by Vanlede et al (2015) and is used as a basis for this study. The same model settings are applied for this study (Table 6-1). The existing NEVLA3D model is updated to year of 2014 with the bathymetric measurement (see §0 and Figure 11), initial salinity conditions (see §3 and Figure 4), river discharge boundary conditions (see §4) and wind forcing (see §5.2).

In addition, the hydrodynamic and salinity boundary conditions are corrected based on analysis of model output from ZUNO model. The details are presented in the following section.

Table 6-1 Model parameters NEVLA model

Model parameter	**Value**
Global diffusion coefficient	10 m^2s^{-1}
Dynamic water viscosity	0.01 $kg.m^{-1}s^{-1}$
Water density	1023 kgm^{-3}
Air density	1.205 kgm^{-3}
Gravity	9.813 ms^{-2}
Wind stress coefficient	0.0026
Wind field	constant
Time step	0.125 min
Type of convergence criterion for the continuity equation	Water level
Convergence criterion for water levels in continuity equation	0.0005 m
Maximum number of iterations for the continuity equation	16
Maximum number of iterations for the momentum equation	32
Threshold value for drying/flooding checks at velocity points	0.3 m
Threshold value for drying/flooding checks at water level points	0.3 m
Friction formula	varying roughness field (Figure 10)
Time interval to compute Chézy values from given friction values	10 min
Eddy viscosity coefficient	1 m^2s
Vertical velocity profile in the velocity boundary points	Logarithmic
Relation for the calculation of Chezy_3D	Velocity-ratio

Time integration of the vertical terms in the mass transport equation	Central
Modeled constituents	Salinity
Turbulence model	k-ϵ model
Number of vertical layers	6

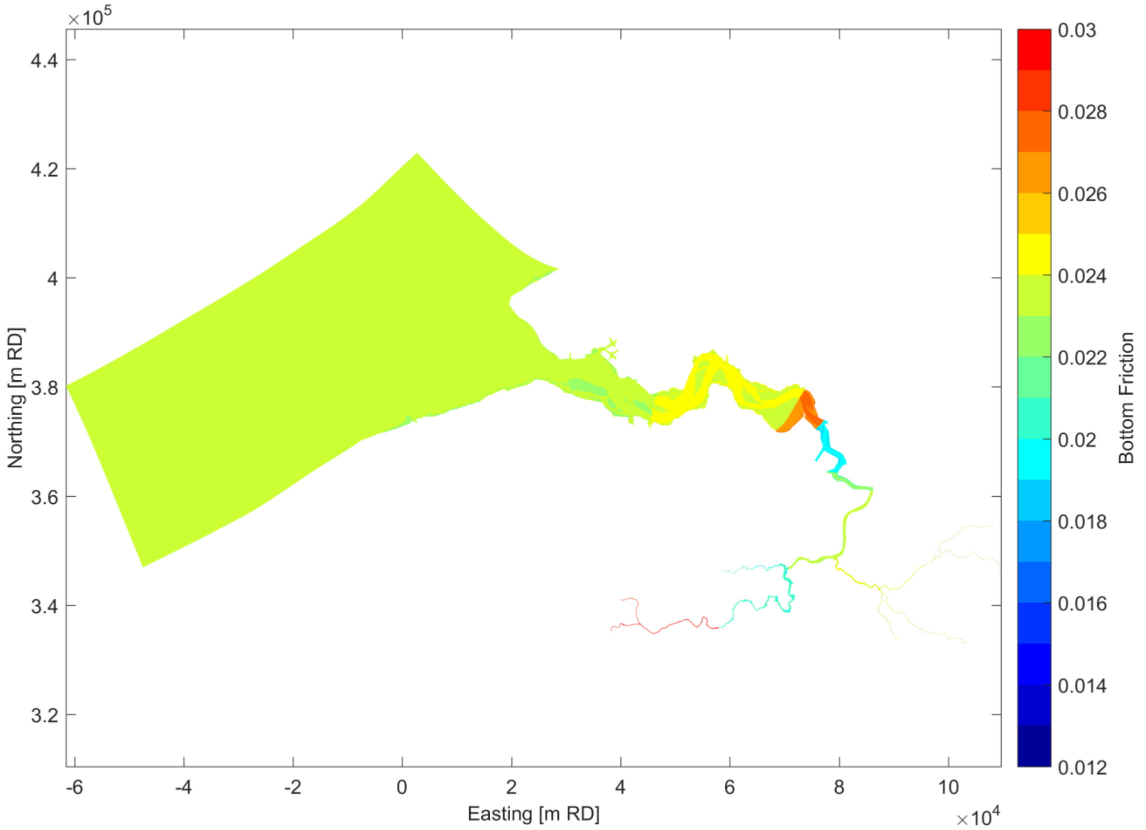


Figure 10: The bottom roughness field (Manning coefficient unit: $m^{-1/3}s$) of the NEVLA3D model (Vanlede, 2015).

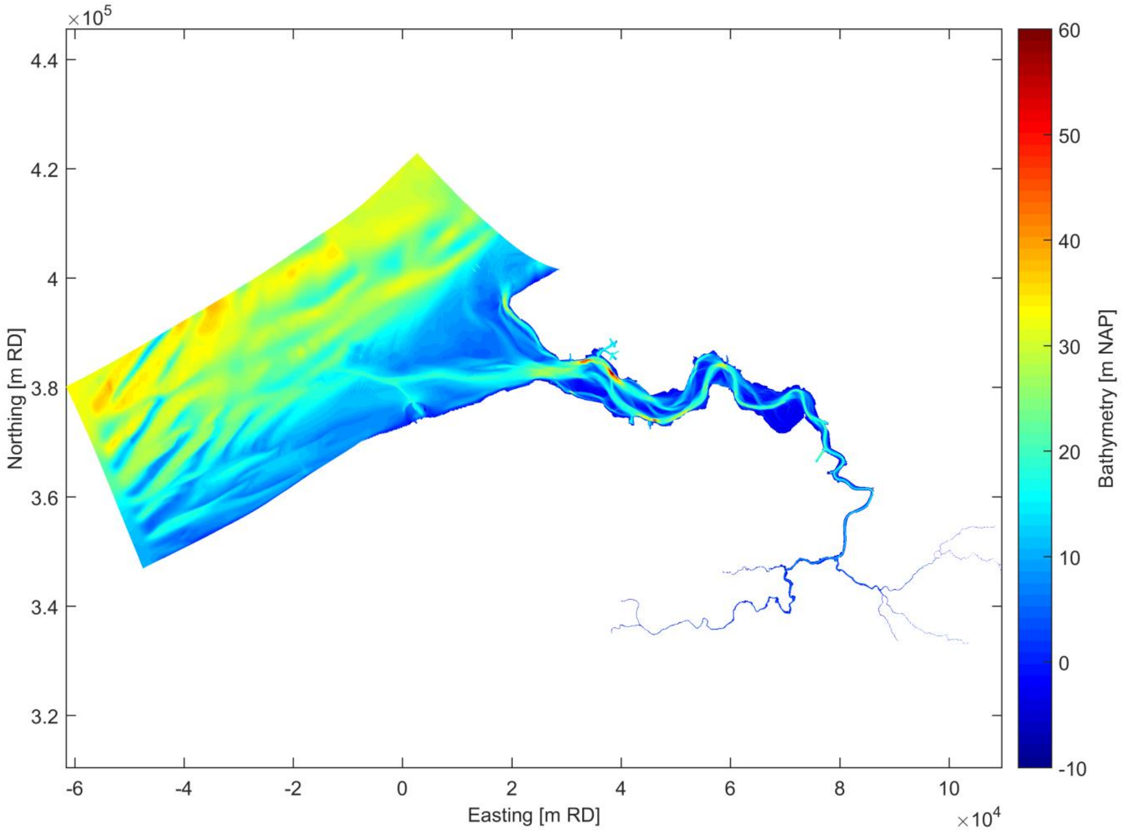


Figure 11: Bathymetry of NEVLA3D model (positive downward).

6.3.1 Correction on harmonic components

The NEVLA model is nested in the regional ZUNO model of the southern North Sea. The model validation for the entire year of 2013 (Maximova et al., 2016) shows that the ZUNO model has a bias in the phase of M2, M4 and S2 components and in the Z0 level.

Therefore a correction of the harmonic components is calculated based on the comparison of the harmonic components of the ZUNO results and measurements from 01-01-2014 to 31-12-2014.

Average differences in harmonic components (Measurements - ZUNO) are found for stations in the Belgian and Dutch Coastal zone for the M2, M4, S2 phases and Z0 component. The calculation of the corrections is presented in Table 6-2. However those correction terms are different from the findings from Maximova et al., 2016 (Table 6-3) which performs the analysis for the entire year of 2013, especially in terms of M4 phase and Z0 amplitude. This is justified because the analysis periods are different. It is therefore recommended to always carry out a new correction on the harmonic components for future studies when the simulation periods are subject to change.

Table 6-2: Correction of harmonic components (analysis period: 01-01-2014 to 31-12-2014).

	M2 PHASE [deg]					**M4 PHASE [deg]**					**S2 PHASE [deg]**					**Z0 Amp [cm]**		
Stations	Measurement		ZUNO		Measurement-ZUNO	Measurement		ZUNO		Measurement-ZUNO	Measurement		ZUNO		Measurement-ZUNO	Measurement	ZUNO	Measurement-ZUNO
	Value	Error	Value	Error	Value	Value	Error	Value	Error	Value	Value	Error	Value	Error	Value	Value	Value	Value
Cadzand	49.06	0.097	45.3	0.11	4	85.2	1.118	91.9	1.52	-7	106	0.3787	100	0.37	6	-0.42	9.93	-10.3
Vlissingen	59.51	0.092	58.9	0.09	1	113	1.2341	125	1.75	-11	118	0.3313	115	0.44	3	2.31	9.83	-7.5
Westkapelle	53.36	0.11	48.9	0.1	4	93.2	0.9911	98.6	1.42	-5	110	0.3696	103	0.41	7	0.53	9.06	-8.5
Vlakte van de Raan	46.23	0.103	40.6	0.09	6	85.9	1.0175	88.2	1.46	-2	102	0.3706	94.2	0.41	8	1.60	7.55	-6.0
Oostende	33.81	0.1	28.4	0.07	5	25.4	1.7712	38.3	1.53	-13	89.5	0.351	81.2	0.31	8	4.02	7.02	-3.0
Nieuwpoort	29.53	0.096	24.3	0.07	5	5.53	1.3245	15.3	1.42	-10	85.2	0.3824	77.1	0.26	8	3.62	6.17	-2.6
AVERAGE					**4**					**-8**					**7**			**-6.3**

Table 6-3: Correction of harmonic components.

Harmonic component	Correction for 2013 (Maximova et al., 2016)	Correction for 2014 (this report)
Phase M2	+4°	+4°
Phase M4	-6°	-8°
Phase S2	+7°	+7°
Z0	-16 cm	-6.3 cm

The time series of the boundary conditions of the NEVLA3D model are ‘harmonically corrected’ with the obtained correction terms (as shown in Table 6-3). This means that the time series at the boundary locations of the NEVLA3D model that are obtained out of ZUNO, are decomposed in harmonic components and a residual term. The harmonic components are corrected, and the signal is re-synthesized. Applying these corrected boundary conditions in the NEVLA3D model makes that the hydrodynamics in the NEVLA3D model does not have the systematic bias in harmonic components that is present in ZUNO.

6.3.2 Correction on Salinity Boundary

The salinity boundary conditions for the NEVLA3D model are generated by nesting the NEVLA3D in the CSM-ZUNO model train. Model results for salinity are highly influenced by values imposed at the boundaries. Therefore, it is very important to have accurate salinity boundary conditions.

The modeled and measured salinity at Vlakte van de Raan are compared in Figure 12. The ZUNO model underestimates the salinity values in the area of interest. Therefore, it is necessary to implement a salinity correction at the boundaries.

The correction is calculated based on the comparison of the calculated and measured daily averaged salinity time series at Vlakte van de Raan (this salinity measurement point is the closest to the boundaries). The signal of this difference is added to all the open salinity boundaries.

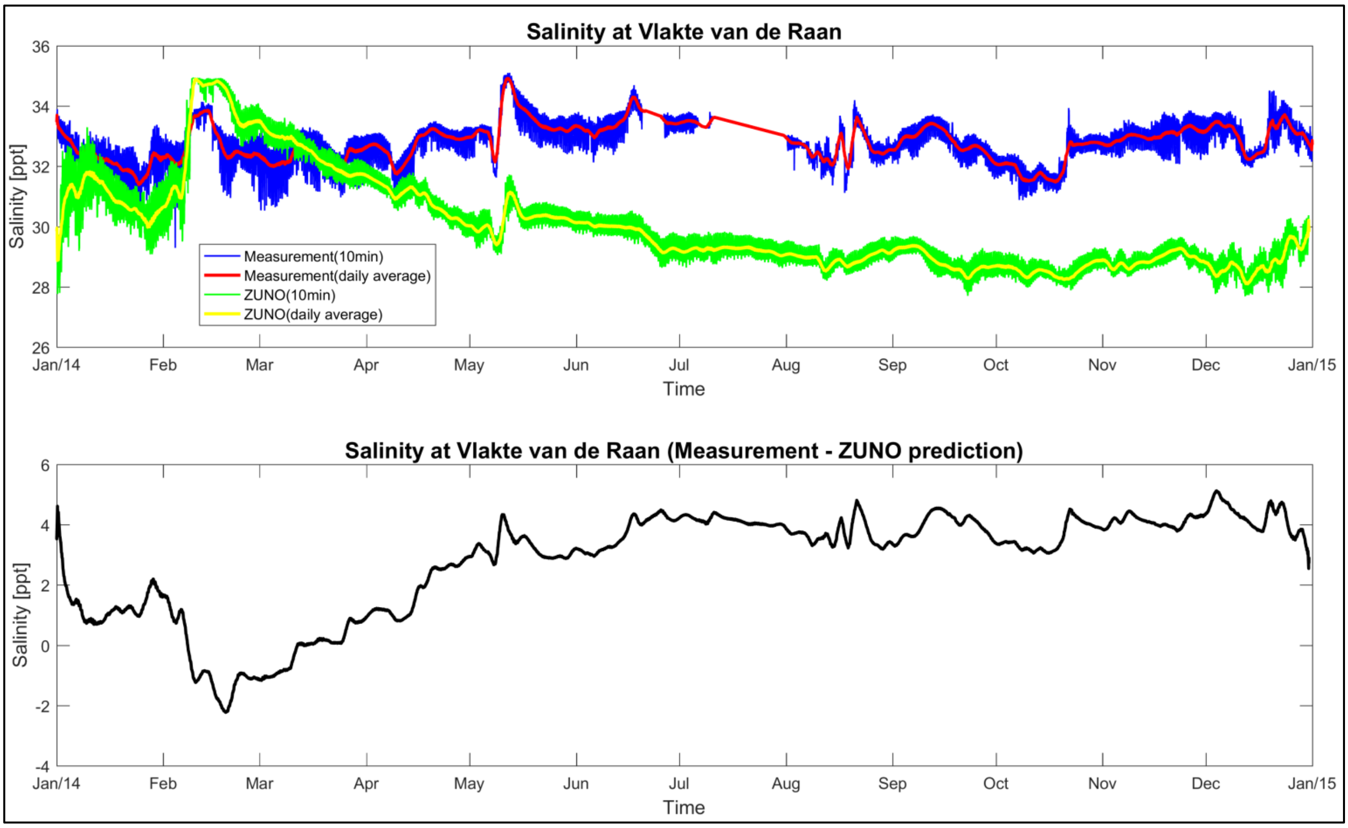


Figure 12: Comparison of salinity at Vlakte van de Raan between measurement and ZUNO predictions.

7 VALIDATION OF 2014 RUN

The full year model run was disrupted at 14/11/2014 15:30 due to unforeseen technical reasons. However it did not require any update of the model inputs and settings. With the same model setups, the model was restarted from 09/11/2014 00:00 (when a restart file was written) and finished successfully till 31/12/2014. The interruption has not affected the model results in any way.

7.1 Water Level

The water levels predicted by NEVLA2014 model are systematically analyzed along the estuary. The statistical results of bias, RMSE and RMSE0 (the definitions can be found in §Annex2) are presented as below.

Figure 13 presents the bias of the complete time series of water level along the estuary. The bias of water level is typically less than 10 cm at the Westerschelde and increases to about 15 cm at the Beneden-Zeeschelde and Boven-Zeeschelde.

Figure 14 presents the RMSE of the complete time series of water level along the estuary. The RMSE of water level is typically less than 15 cm at the Westerschelde and increases to about 25 cm at the Beneden-Zeeschelde and Boven-Zeeschelde.

Figure 15 presents the RMSE0 of the complete time series of water level along the estuary. The RMSE0 of water level is typically less than 15 cm at the Westerschelde and increases to about 20 cm at the Beneden-Zeeschelde and Boven-Zeeschelde.

Figure 16 presents the comparison of M2 amplitude between model and measurement along the river. The NEVLA model slightly underestimates the M2 amplitude in the Scheldt.

In general, the NEVLA2014 run shows reasonable predictions on water levels along the River Scheldt. The uncertainties on water level predictions are gradually increased to the upstream direction.

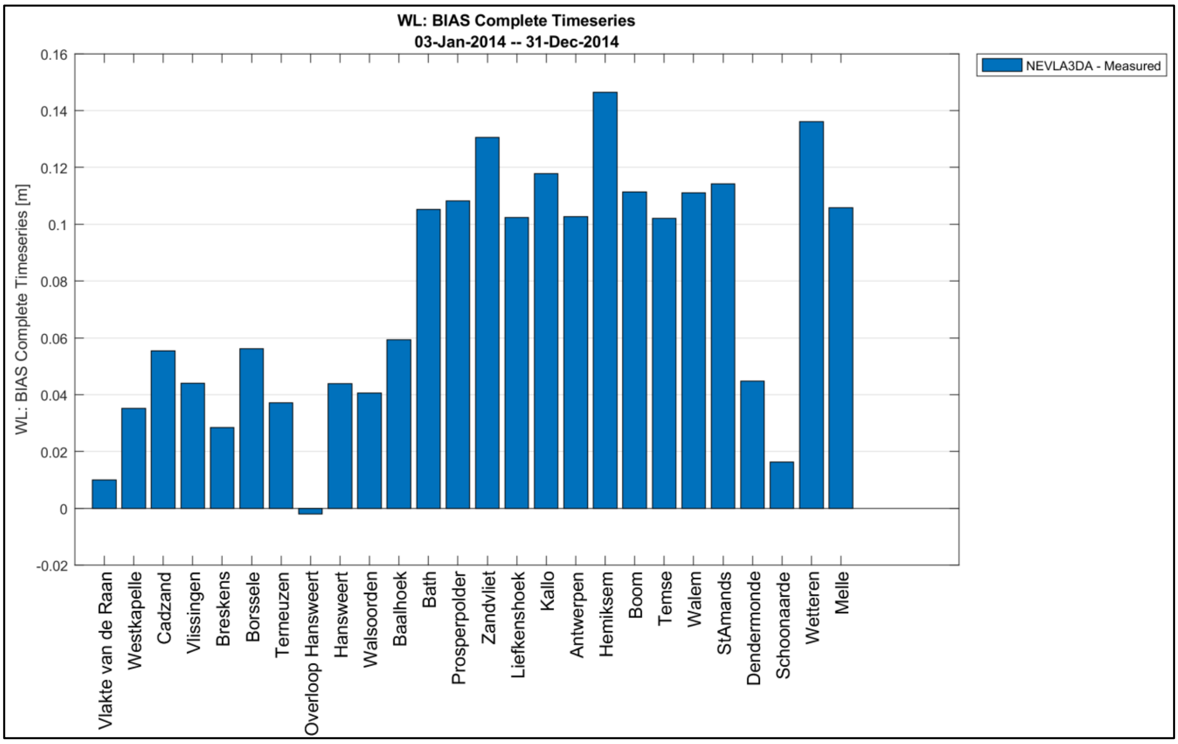


Figure 13: Bias of complete time series of water level along the estuary from NEVLA2014.

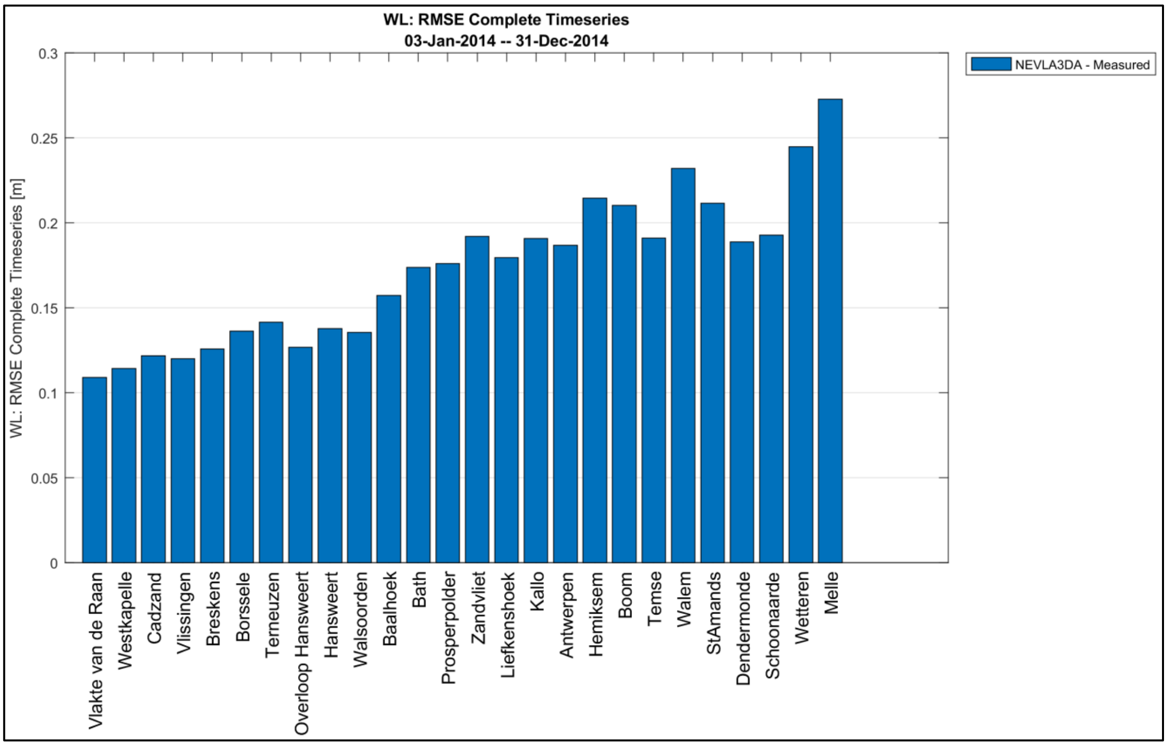


Figure 14: RMSE of complete time series of water level along the estuary from NEVLA2014.

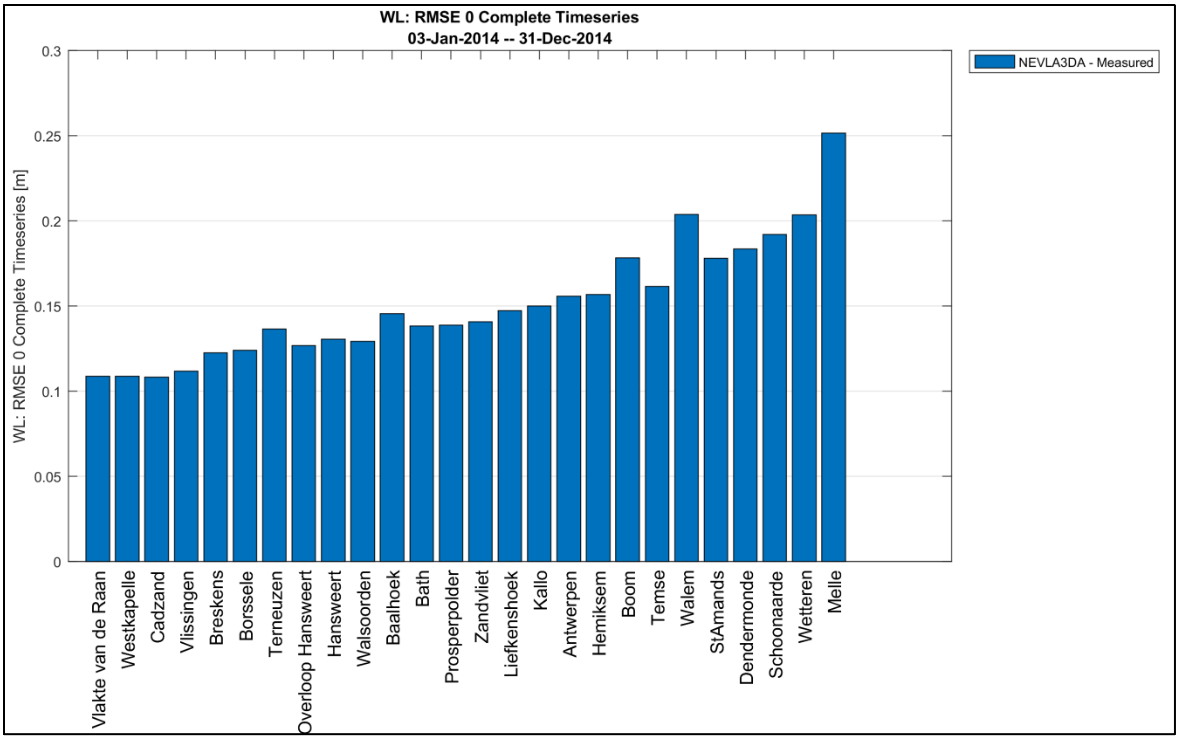


Figure 15: RMSE0 of complete time series of water level along the estuary from NEVLA2014.

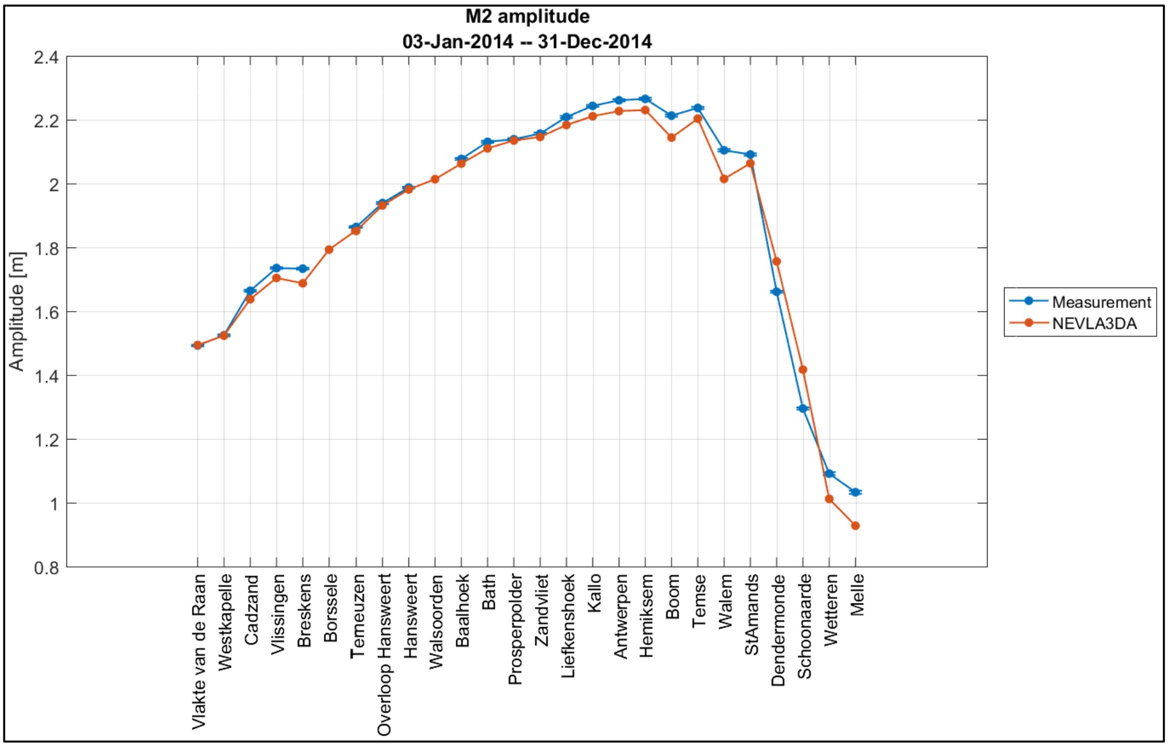


Figure 16: M2 amplitude along the estuary from NEVLA2014.

7.2 Salinity

The comparison of the modelled and measured salinity time series are presented in Figure 17 to Figure 23. With the correction on salinity boundary (§6.3.2), salinity is in general well reproduced by NEVLA2014 along the estuary. The statistical analysis results are presented in Table 7-1. The RMSE are less than 2 psu at all stations. The discrepancies can partly be attributed to the less accurate initial salinity field that is based on the interpolation of measurement (see Figure 4).

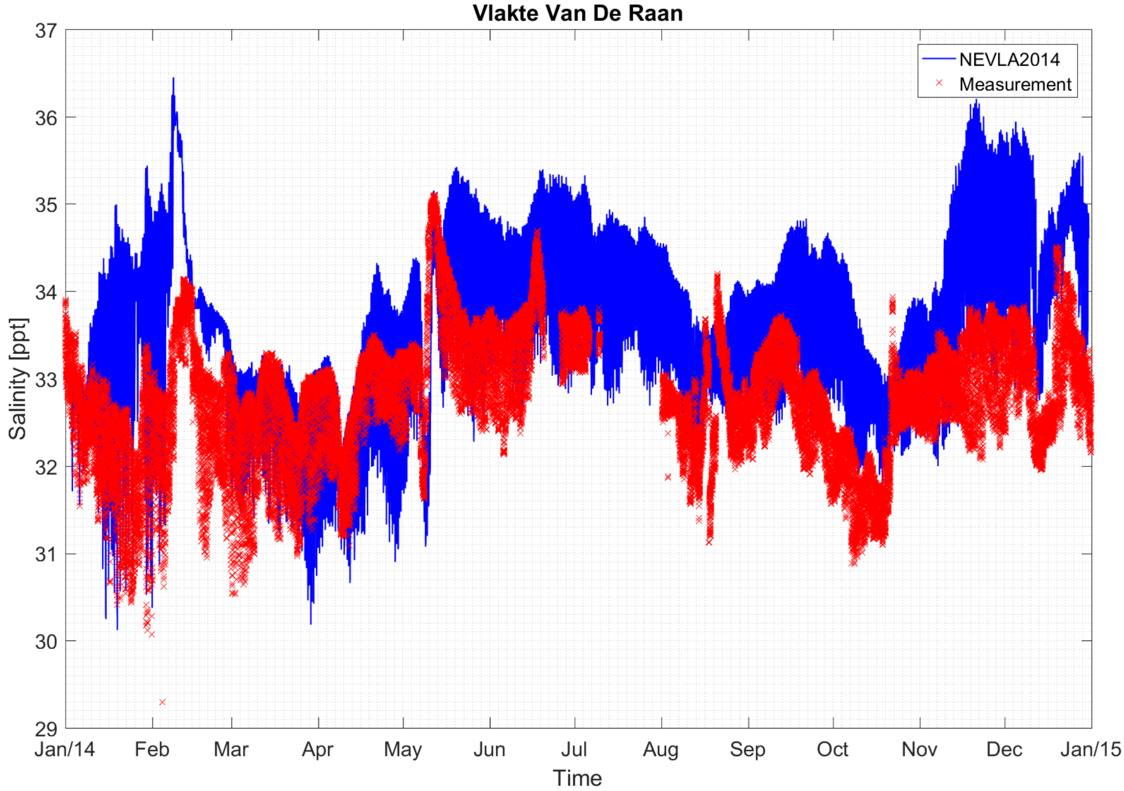


Figure 17: Comparison of salinity between measurement and NEVLA2014 at Vlakte Van De Raan.

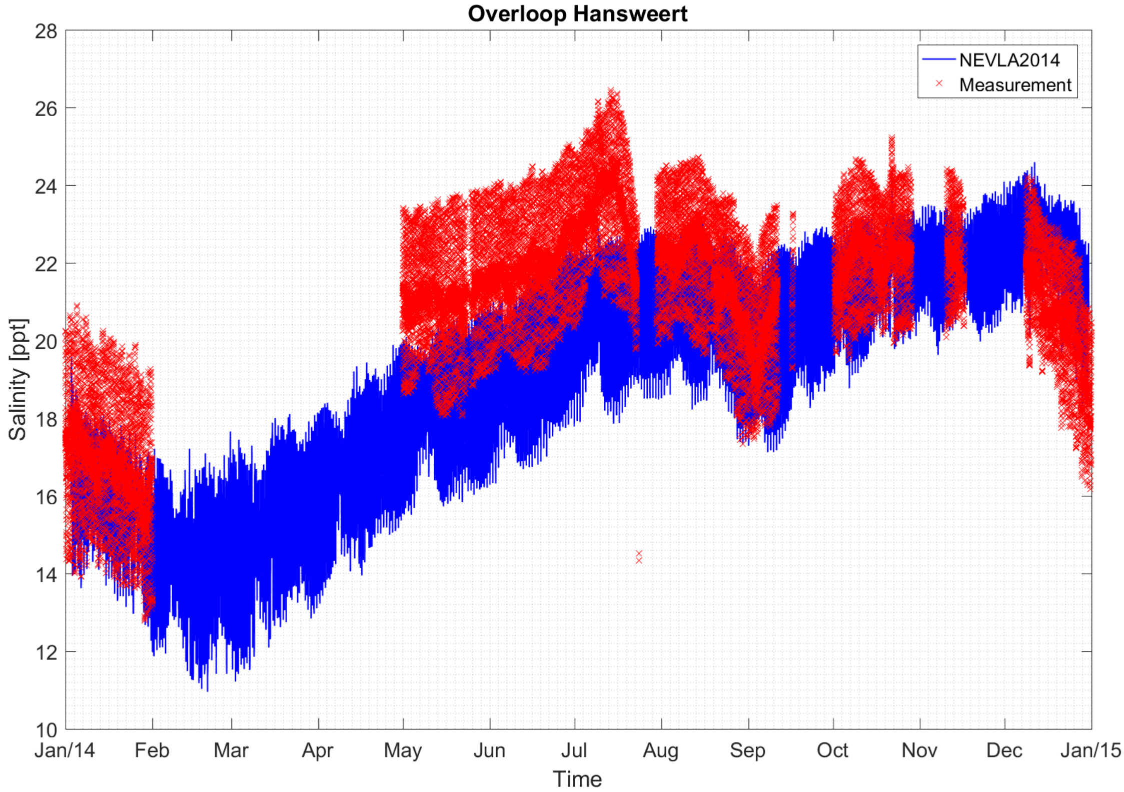


Figure 18: Comparison of salinity between measurement and NEVLA2014 at Overloop Hansweert.

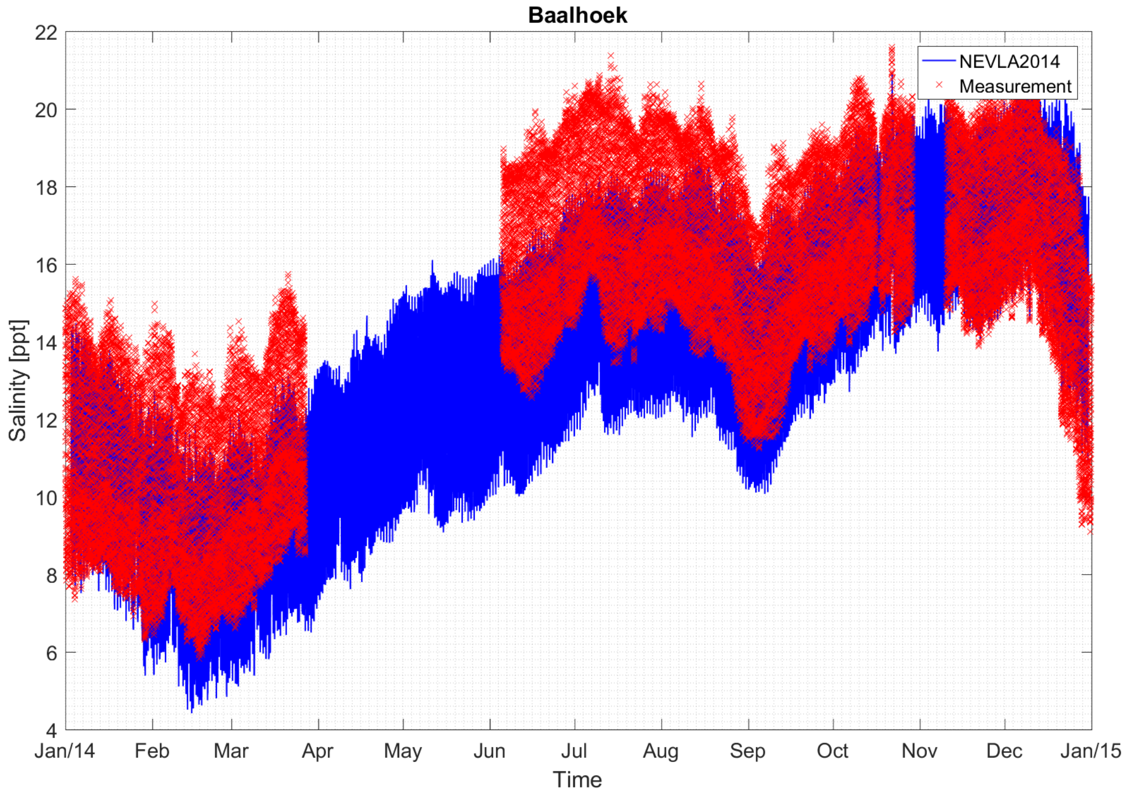


Figure 19: Comparison of salinity between measurement and NEVLA2014 at Baalhoek.

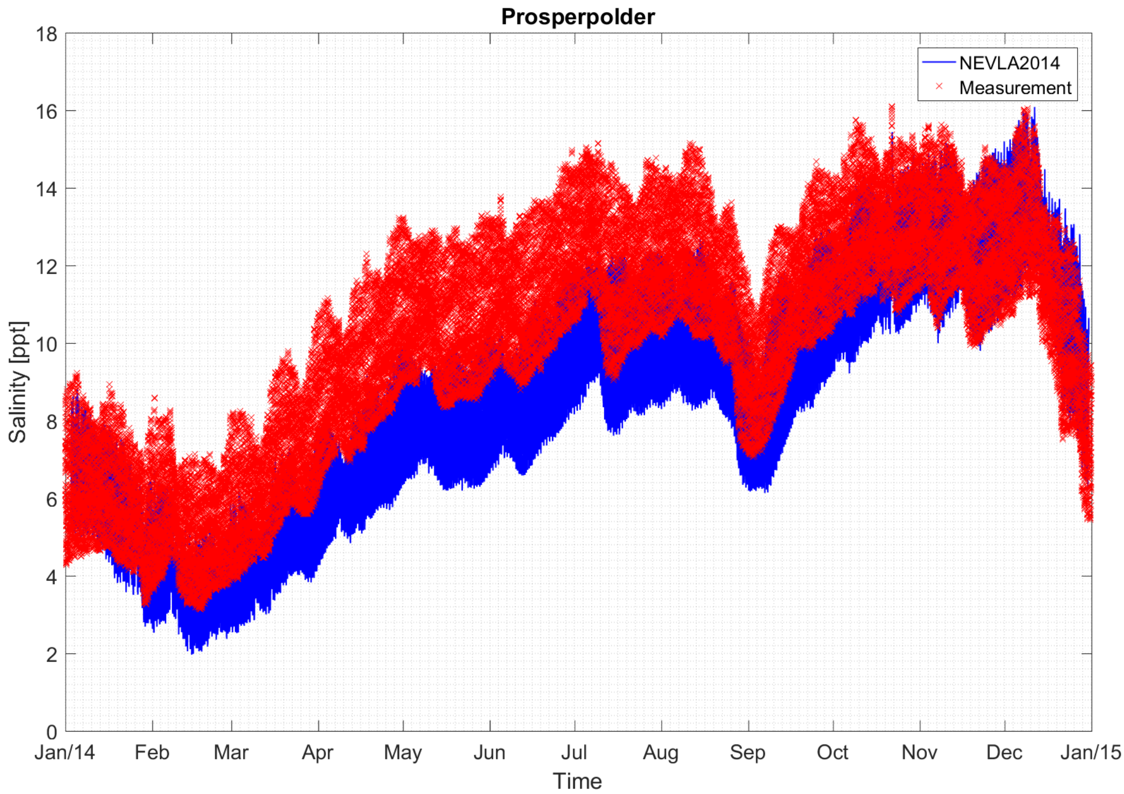


Figure 20: Comparison of salinity between measurement and NEVLA2014 at Prosperpolder.

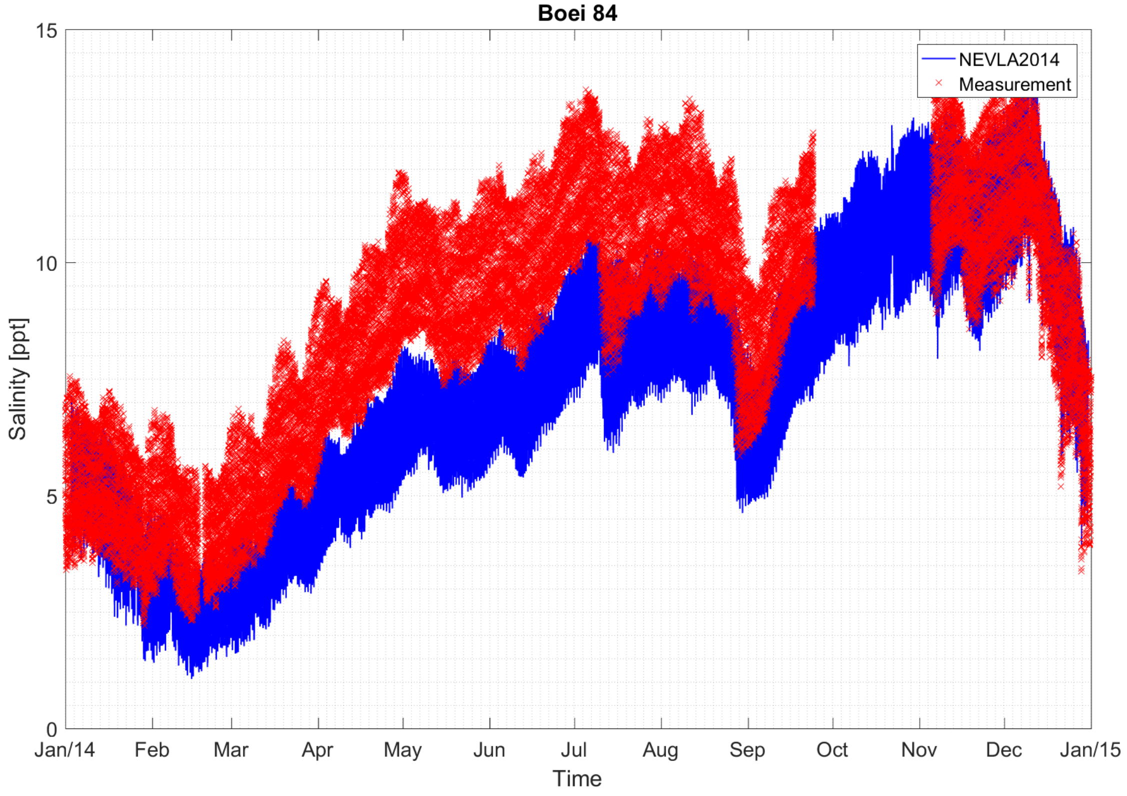


Figure 21: Comparison of salinity between measurement and NEVLA2014 at Boei84.

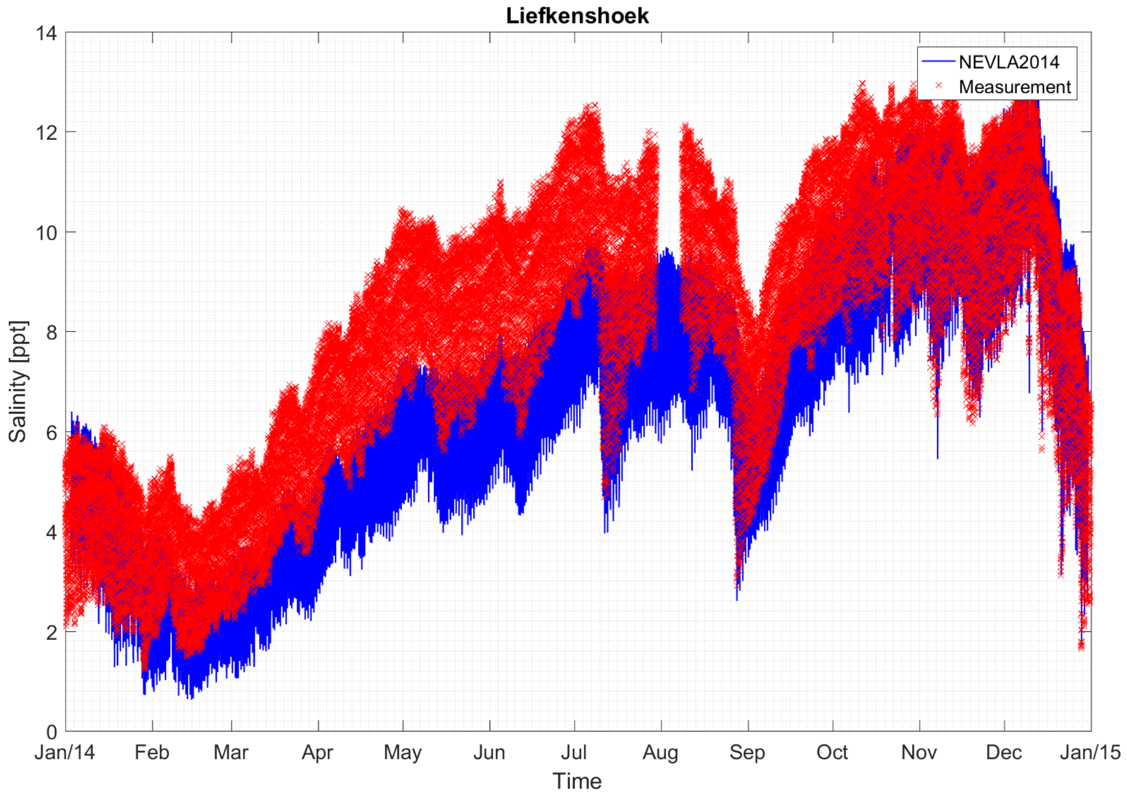


Figure 22: Comparison of salinity between measurement and NEVLA2014 at Liefkenshoek.

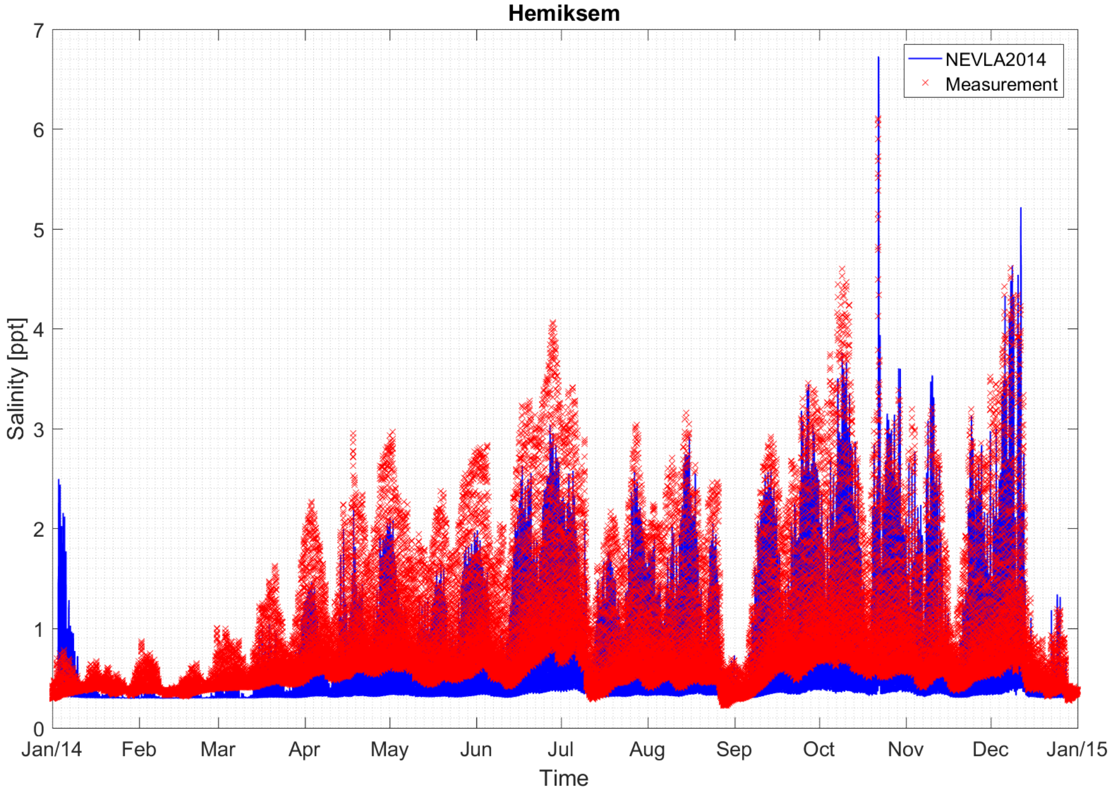


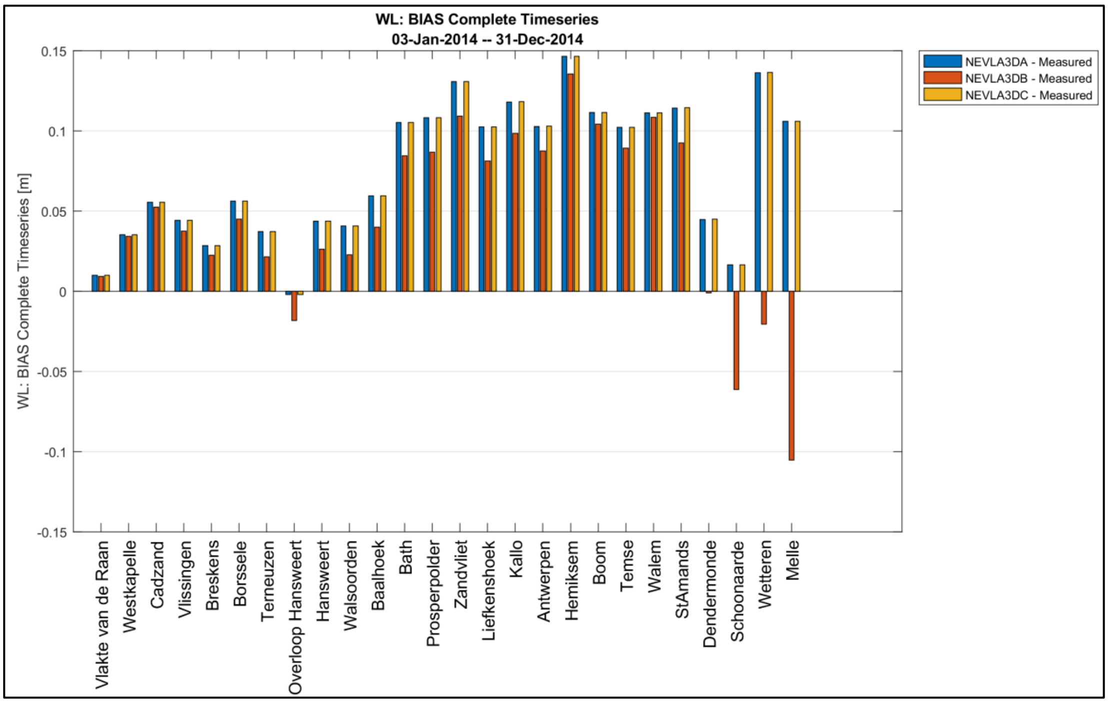
Figure 23: Comparison of salinity between measurement and NEVLA2014 at Hemiksem.

Table 7-1: Statistic analysis of salinity between NEVLA2014 and measurements.

Nr	Station	Correlation Coefficient R [-]	RMSE [psu]
1	Vlakte Van De Raan	0.95	1.3
2	Overloop Hansweert	0.62	1.1
3	Baalhoek	0.79	1.5
4	Prosperpolder	0.91	2.0
5	Boei 84	0.66	0.6
6	Liefkenshoek	0.94	1.7
7	Hemiksem	0.92	2.0

8 COMPARISON WITH SCENARIO B AND C

Figure 24 shows that changing locally the bathymetry inside DGD (Scenario C) results in very limited impact on water level predictions in the Scheldt, compared with Scenario A. However Scenario B leads to more changes on the water level, especially in the Upper Sea Scheldt (StAmands to Melle). This is not surprising because the river discharge from Melle in 2011 (Scenario B) is only half of the discharge in 2014 (Scenario A), see Figure 7. The lower discharge of 2011 at Bath and Terneuzen however leads to less impact on the water levels in the Western Scheldt.



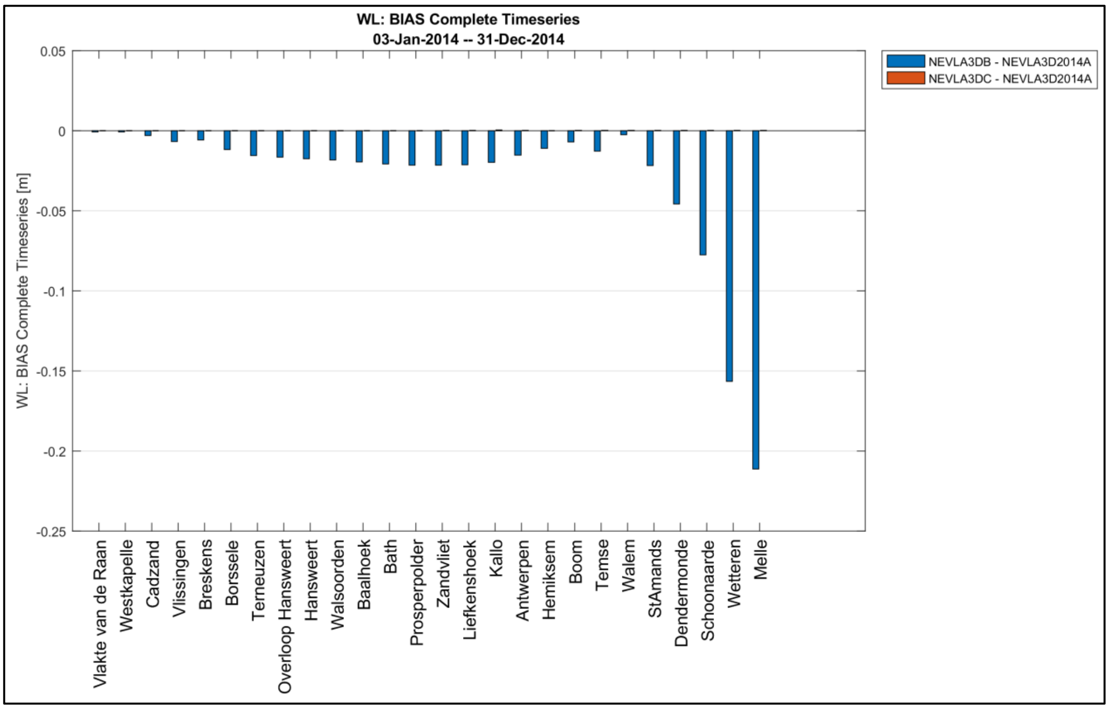


Figure 24: Bias of the complete time series of water level along the River Scheldt (upper panel: compare with measurement; lower panel: compare with Scenario A).

Figure 25 to Figure 31 present the comparison of salinity between the 3 different scenarios at the 7 stations. Changing local bathymetry inside DGD (Scenario C) provide very limited impact on salt transport along the Scheldt. With reduced discharge (Scenario B), the salinity is increased from Hansweert to upstream stations.

Figure 32 compares the depth averaged salinity along the navigation channel in the Scheldt in December when there are peaks in river discharges. Compared with Scenario A, Scenario B shows more pronounced saline intrusion in the first half of December, followed by retreat of saline in the second half of December. This is corresponding to the changes of river discharge at Melle in December as shown in Figure 33. The river discharge in the second half of December of 2011 is larger compared to the normal year of 2014, eventually leading to a reduction of saline intrusion. The salt transportation shows logical response to river discharges.

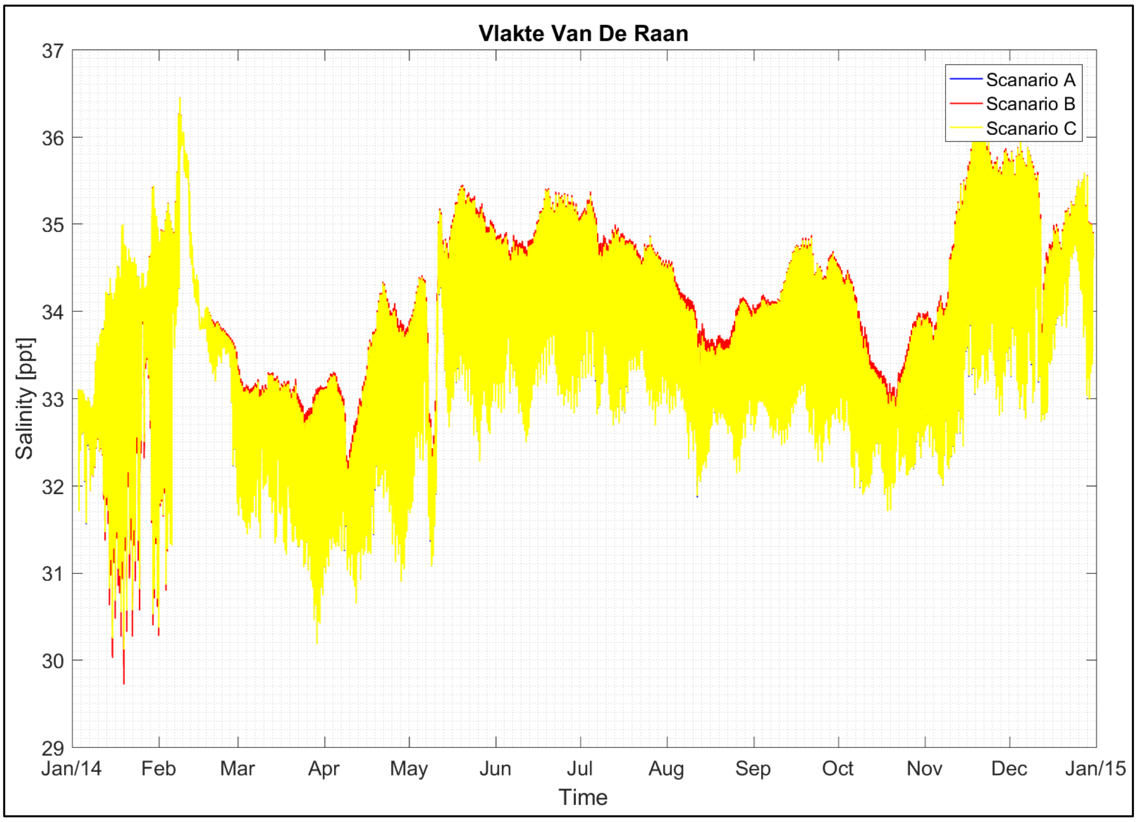


Figure 25: Comparison of salinity between the 3 different scenarios at Vlakte Van De Raan.

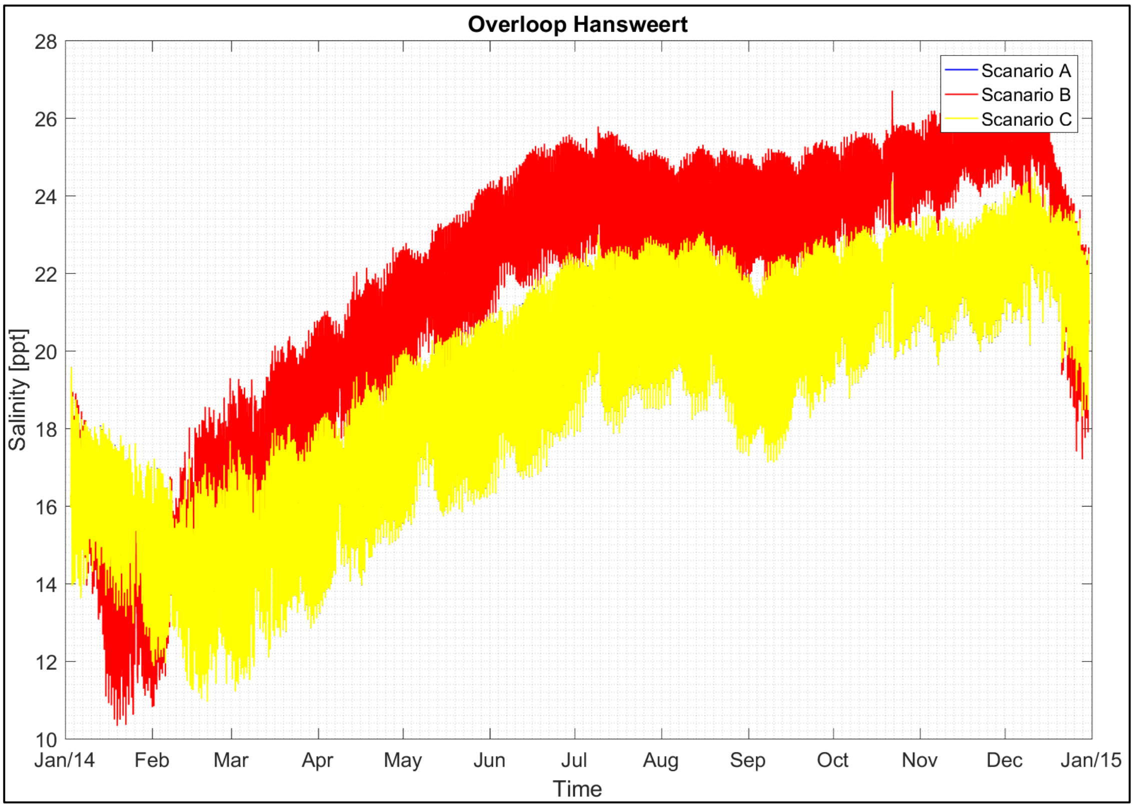


Figure 26: Comparison of salinity between the 3 different scenarios at Overloop Hansweert.

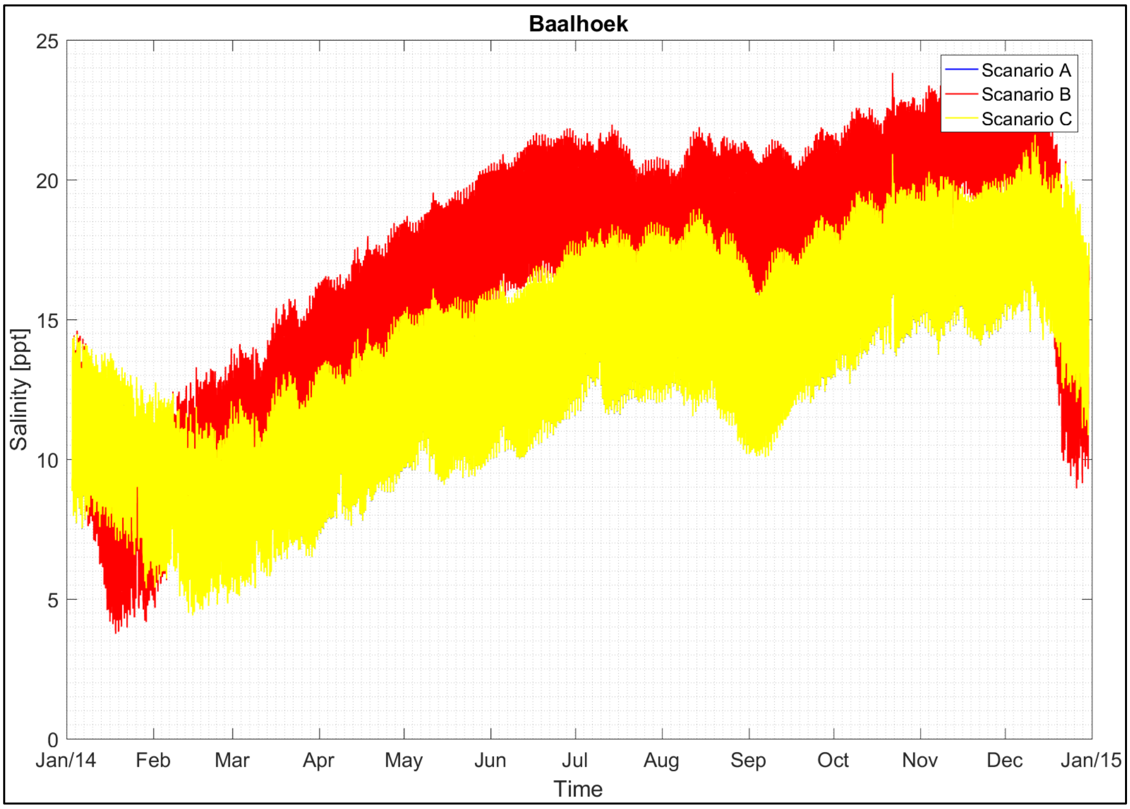


Figure 27: Comparison of salinity between the 3 different scenarios at Baalhoek.

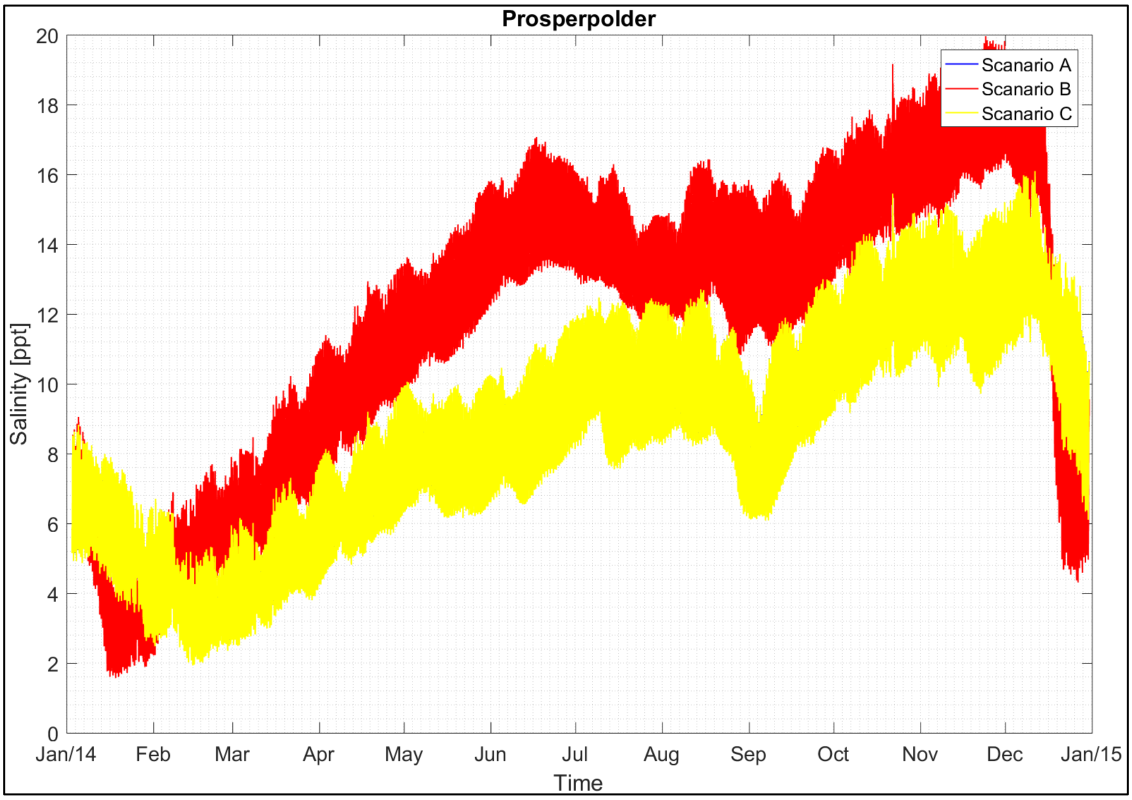


Figure 28: Comparison of salinity between the 3 different scenarios at Prosperpolder.

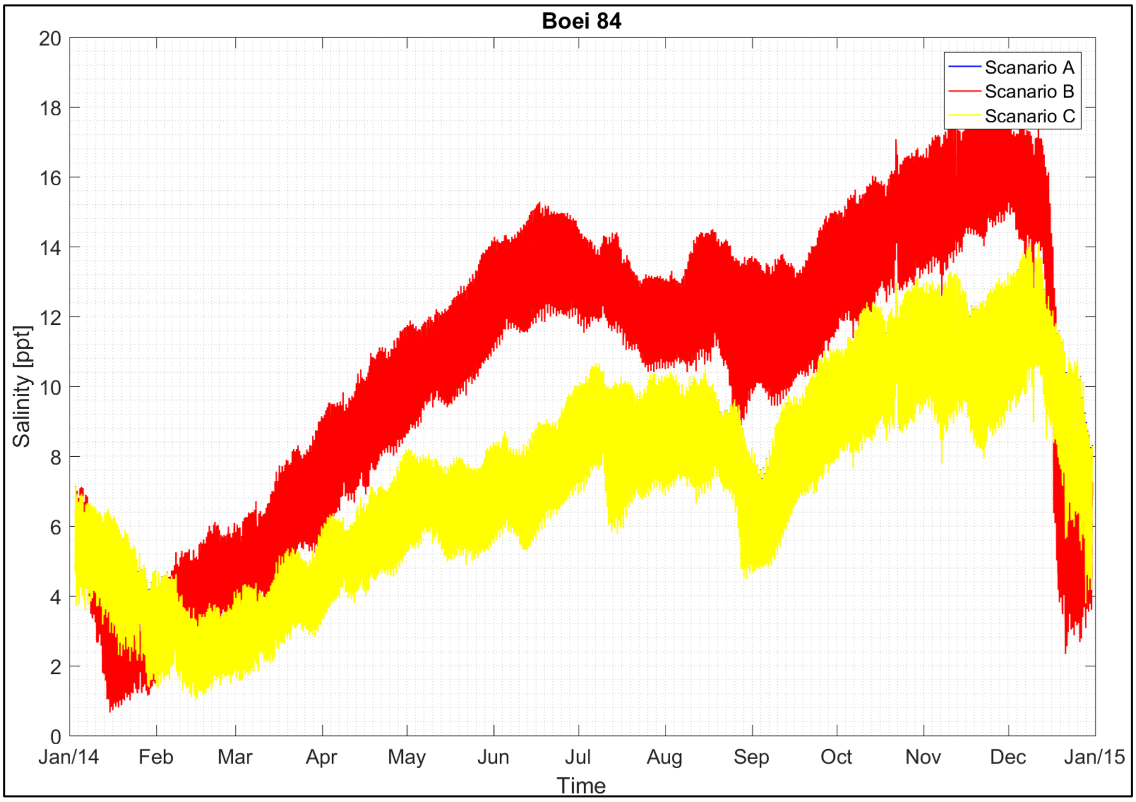


Figure 29: Comparison of salinity between the 3 different scenarios at Boei84.

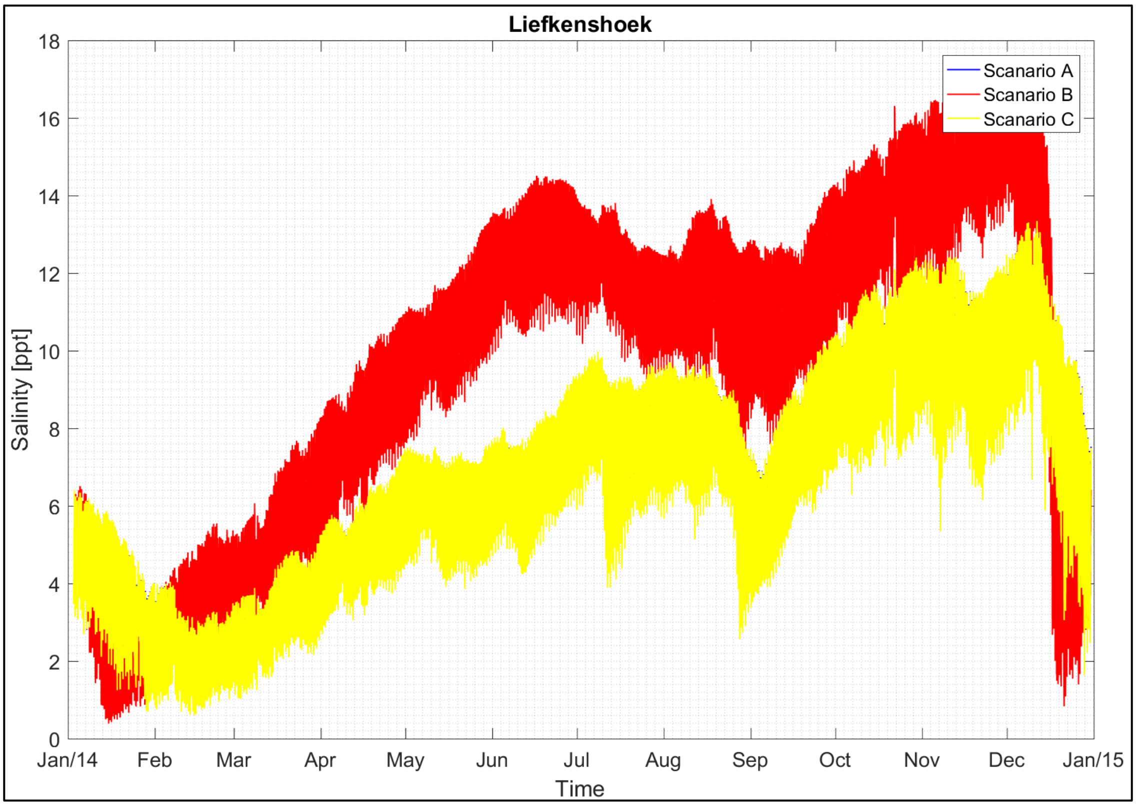


Figure 30: Comparison of salinity between the 3 different scenarios at Liefkenshoek.

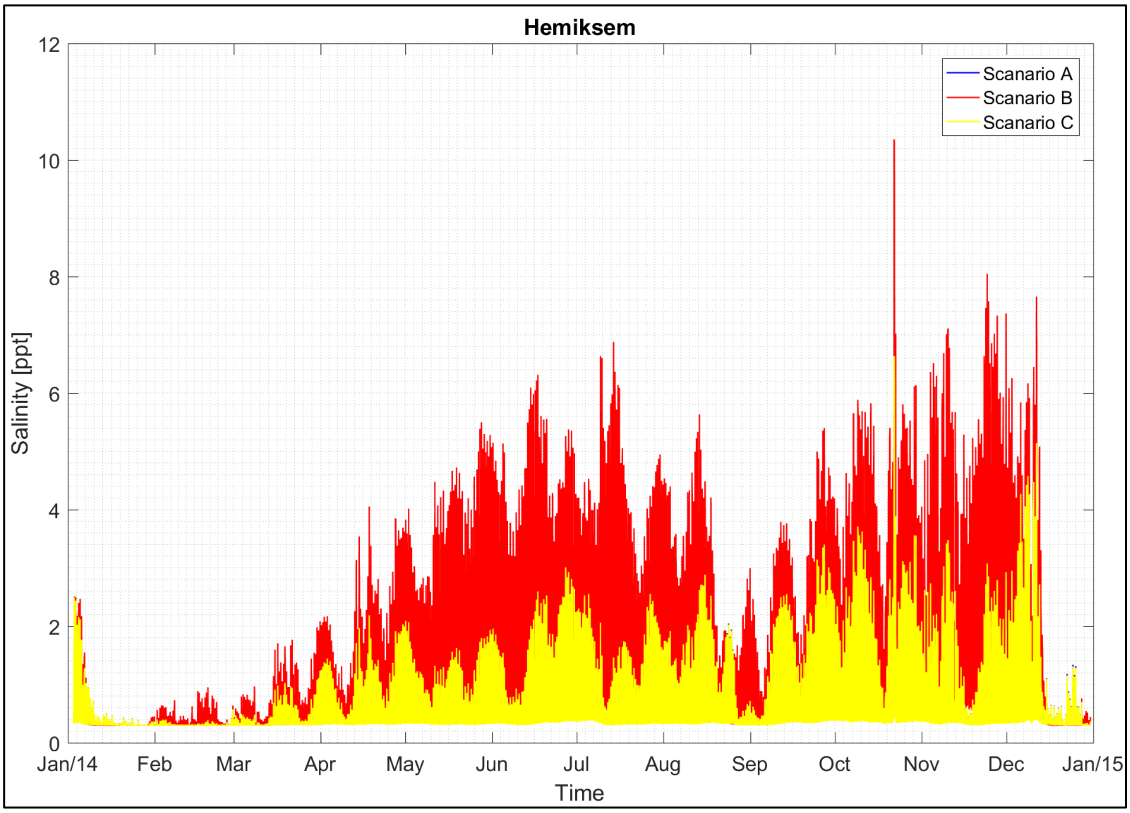


Figure 31: Comparison of salinity between the 3 different scenarios at Hemiksem.

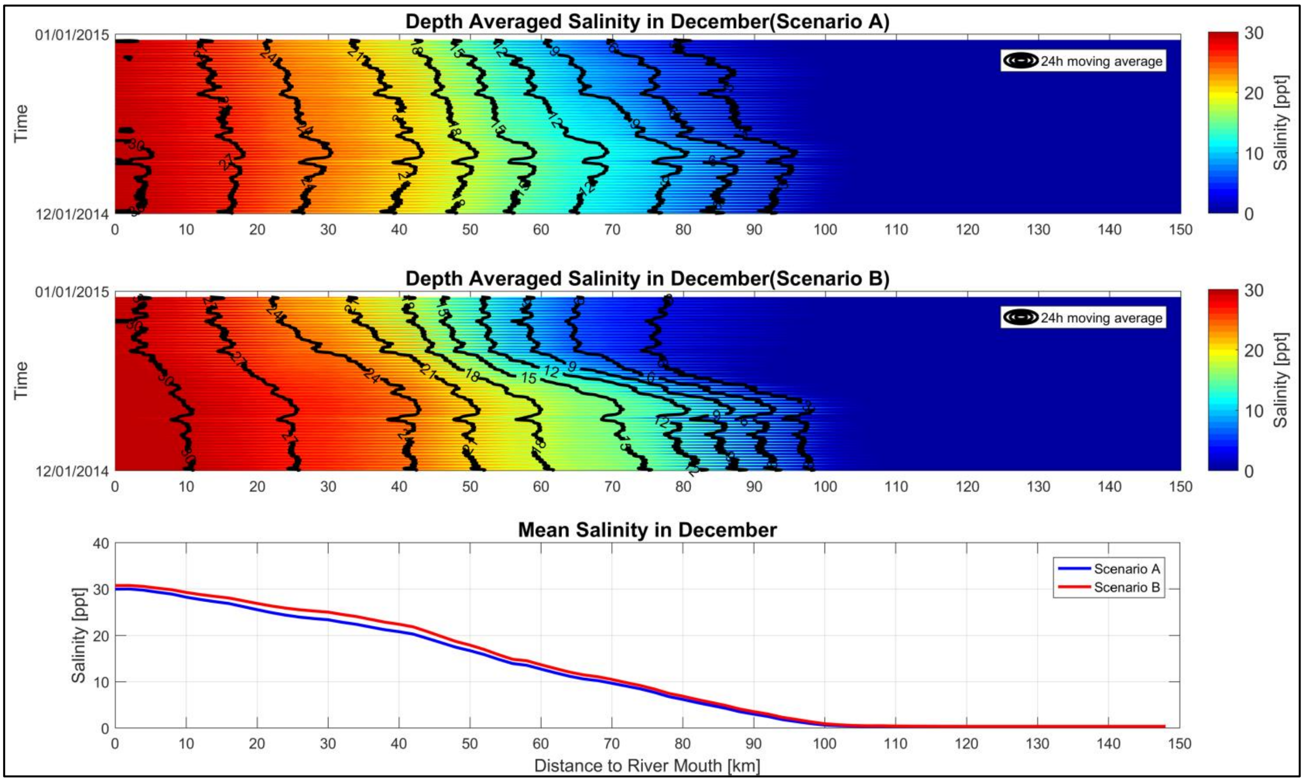


Figure 32: Depth averaged salinity in December along the navigation channel of Scheldt. (Upper panel: Scenario A with 'normal-year' river discharge; Middle panel: Scenario B with 'dry-year' discharge; Lower panel: Time averaged salinity in December between Scenario A and B).

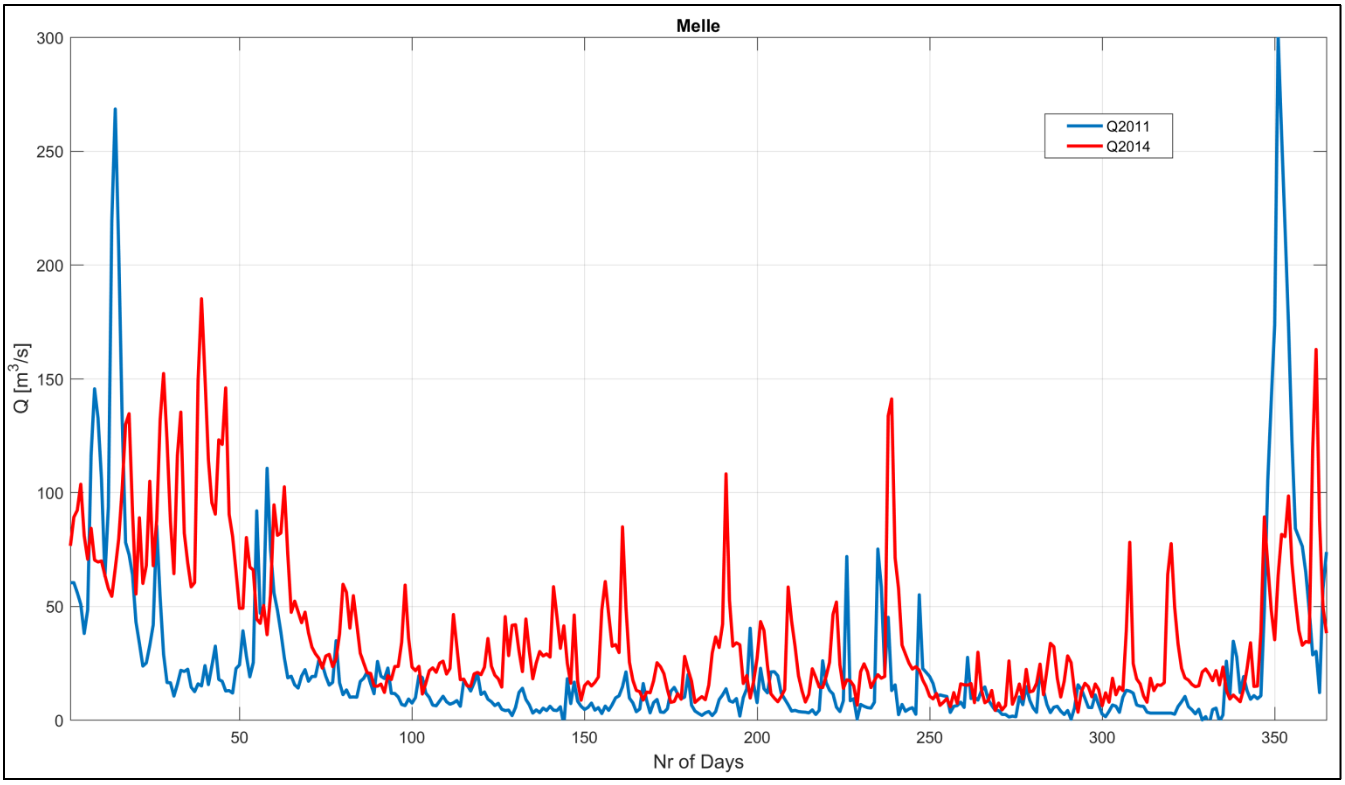


Figure 33: River discharge at Melle for the year 2011 and 2014.

Figure 34 shows the comparison of the maximum and yearly averaged velocity along the Scheldt. The maximum velocity is the velocity ever occurred during the simulation period of one year. The most influential area is the Upper Sea Scheldt, where Scenario B leads to increase of the maximum velocity by about 10 cm/s and the yearly averaged velocity is decreased by about 2-6 cm/s.

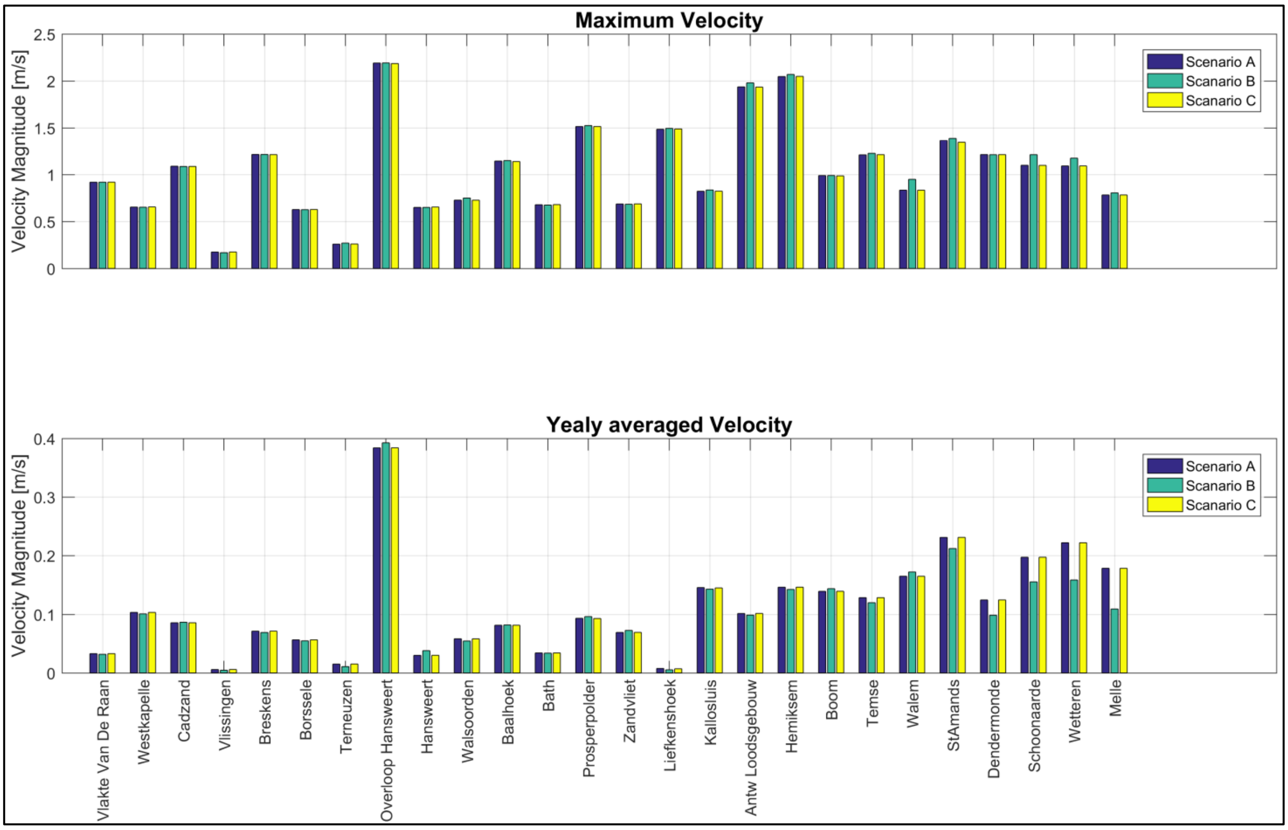


Figure 34: Comparison of maximum velocity ever occurred during the simulation period at various stations (upper panel) and the yearly averaged velocity (lower panel) between the 3 different scenarios.

9 LIST OF REFERENCES

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ANNEX 1: VERTICAL TRANSFORMATION BETWEEN NAP, TAW AND LAT

The vertical reference level used by this project is NAP which is about 2.35 m above TAW level (http://www.vliz.be/imisdocs/publications/130099.pdf).

The difference between LAT and TAW is spatially different while near DGD LAT is about 0.72 m below TAW. Figure 35 sketches the vertical transformation between LAT, TAW and NAP.

To conclude the vertical transformation near DGD is:

NAP = +2.35 m TAW = +3.07m LAT

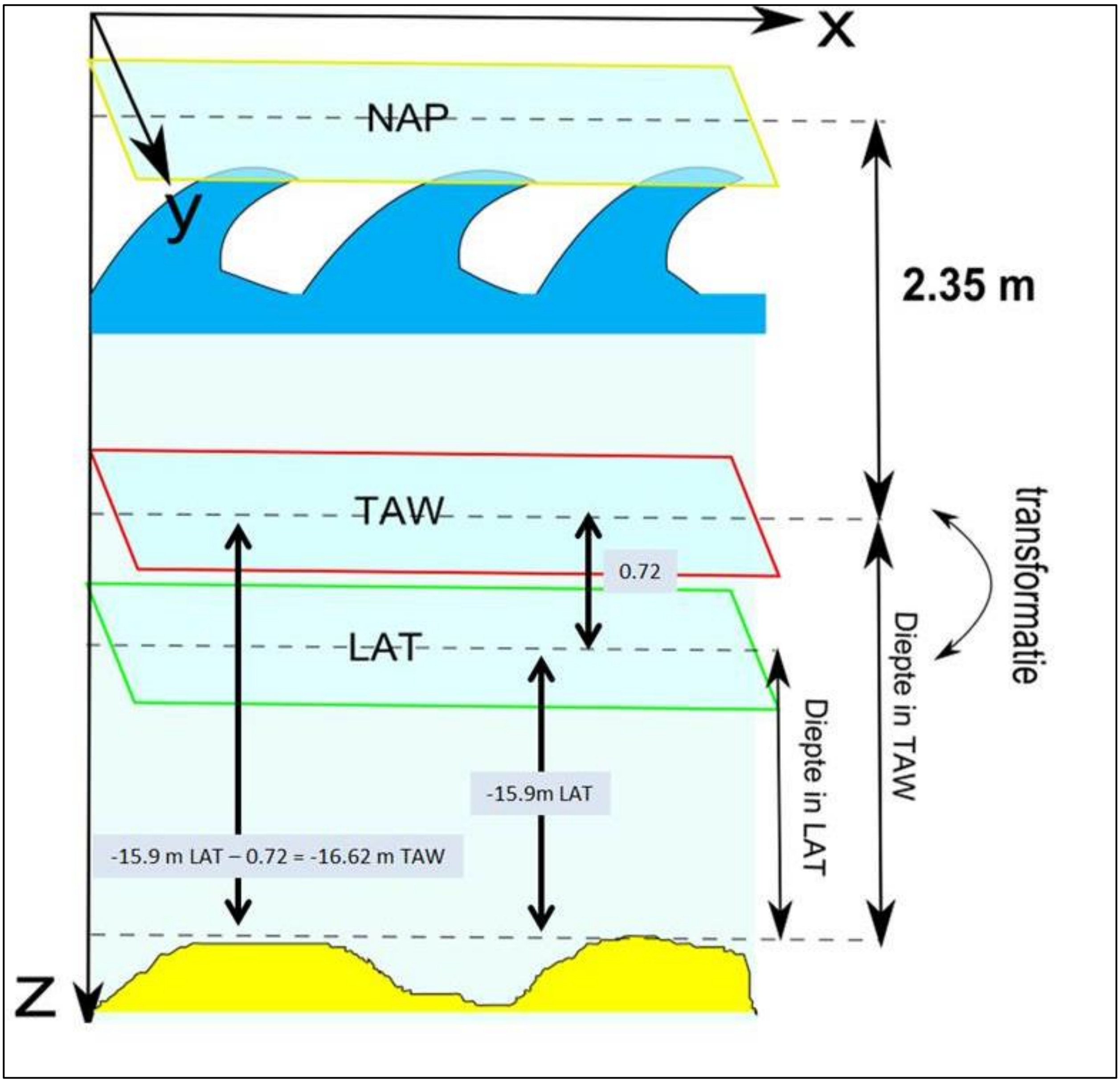

Figure 35: Sketch of vertical transformation between LAT, TAW and NAP near DGD.

ANNEX 2: DEFINITION OF STATISTICS

The **Bias** of water level represents the average deviation of the differences between model predicted water level and measurement.

The **RMSE** of water level represents the sample standard deviation of the differences between predicted water level and measurement.

The **RMSE0** is the bias corrected root mean square error which describes the forecast errors not associated with the bias.

The mathematical expressions are listed below. *y* and *x* represent modeled and measured values respectively and *n* is the number of samples.

$$Bias = \overline{y} - \overline{x}$$

$$RMSE = \sqrt{\frac{\sum_{1}^{n} (y_i - x_i)^2}{n}}$$

$$RMSE0 = \sqrt{\frac{\sum_{1}^{n} ((y_i - x_i) - (\overline{y} - \overline{x}))^2}{n}}$$