Local mud dynamics and sedimentation around the Maasmond

Deltares

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Summary
Siltation of mud in the ports and access channels of the Port of Rotterdam is of great interest to both the Port Authorities and to Rijkswaterstaat as both are responsible for maintenance dredging to maintain navigable depth. Siltation (amounts and location) is currently determined with field surveys. However, given the timescales for siltation processes, models can also be an important tool in the management of port siltation. Therefore, the aim of this work is to make a first step towards the development of a high-resolution fine sediment/mud transport model of the Maasmond and port basins. The high resolution and inclusion of density coupling (fluid mud) will make it suitable for operational management.

In order to calculate the mud dynamics in the harbour area of the Rhine Meuse Delta, a sequence of models is used to capture mud dynamics over both shorter (tidal) and longer (monthly) time periods. First the OSR model (in Delft3D) provides the hydrodynamic conditions for a full month, including wave effects. This hydrodynamic model is used to force the sediment transport model. Sediment transport modelling is done over a longer period (May) using Delft3D-WAQ. The Delft3D-WAQ model is suitable for computing long term sediment dynamics and therefore allows the simulated sediment distribution in the water column and in the bed to reach a dynamic equilibrium. The effect of dredging in the harbours and waterways is also included. The model was used to perform a number of sensitivity tests which helped determine optimum settings but also gave information into the processes that are important for mud dynamics in the area. In general, it was found that water-column processes are most dominant in determining the distribution of near-surface sediments and near-bed sediments. However, in certain harbours the parameters determining the exchange between water column and the bed gave more realistic results. The settings and sediment concentrations from the longer-term simulation is then fed back into a Delft3D short term sediment model to investigate the generation and distribution of fluid mud. First tests with density coupling showed that high concentrations of fluid mud spread over a larger area while without density coupling the sediment remains more concentrated. The detailed behaviour of the fluid mud layer needs to be studied further, as well as its sensitivity to the choice for number of layers in the vertical and the horizontal grid resolution.

A first comparison has been made with observations on suspended sediment concentration and harbour siltation. The model outcomes are consistent with typically observed concentration levels and sedimentation volumes. However, the available data and the simulation period of one month is too short to allow for a quantitative validation. For this more field observations should become available (a field survey is anticipated) and the model should be re-run for longer time intervals, including the periods with field observations.

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final

Contents

1 Introduction and context

1.1 Background

Sediment dynamics and specifically, the siltation of mud, in the ports and access channels of the Port of Rotterdam is of great interest to both the Port Authorities and to Rijkswaterstaat. Both are responsible for the maintenance of the harbours and access channels. The amount of siltation determines the frequency and amount of maintenance dredging to maintain navigable depth. However, significant siltation can occur in a short time, even between surveys, as a result of the transport and deposition of fluid mud layers.

In addition to field surveys, numerical models can be an important tool for the port maintenance. The simulation and determination of water levels, flow rates and salinity through models is already done in practice, but not yet for fine sediment dynamics. One of the reasons is that, in the past sediment models, especially fine cohesive sediment models were less developed and still very computationally expensive. Recently these limitations have been largely overcome, although cohesive sediment models remain complex and appropriate calibration data is often lacking.

In the recent past, a fine sediment transport model has been developed for the Dutch coastal zone (ZUNO-DD) that calculates the large-scale fine sediment dynamics around the outflow of the Rhine. However, this model is not suitable for the inner area around the Rhine mouth and into the harbours, as the resolution is limited. This model was also only developed to take salinity and temperature gradients into consideration and not sediment-driven density currents. In addition to suspension transport, density driven mud transport is also an important transport mechanism in the ports and access channels.

The aim of this work is to make a first step towards the development of a high-resolution fine sediment/mud transport model of the Maasmond and port basins. The high resolution and inclusion of density coupling (fluid mud) will make it suitable for operational management.

1.2 Mud dynamics in the Port of Rotterdam

The mud supply towards the Maasvlakte harbours is thought to be mainly of marine origin, driven by near-bed landward transport. However, the mud supply toward Botlek harbour is thought to be mainly of fluvial origin. For a detailed description of the mud dynamics in the Port of Rotterdam is referred to the PhD-thesis of De Nijs (2012). De Nijs et al. (2010) remark that:

“The estuarine turbidity maximum (ETM) is […] maintained by the trapping of fluvial SPM at the head of the salt wedge. The trapping process is associated with the raining out of fluvial SPM from the upper, fresher part of the water column, into the layer below the pycnocline. The dominant mechanisms responsible are baroclinic shear flows and the abrupt change in turbulent mixing characteristics due to damping of turbulence at the pycnocline.
The SPM transport capacity of the tidal flow is not fully utilized in the ETM, and the ETM is independent of a bed-based supply of mud. This is explained by regular exchange of part of the ETM with harbor basins, which act as efficient sinks, and that the Rotterdam Waterway is not a complete fluvial SPM trap.”

1.3 OSR model

The OSR-model (Operationeel Stromingsmodel Rotterdam) will be used as the basis for setting up a 3D model for mud dynamics. This model from the Port of Rotterdam (PoR) is used for calculating flow velocities and salinity concentrations for operational use in the Rhine Meuse Delta and runs with the SIMONA software[1]. The model system consists of two model components:

1 The 2DH model (OSR-Harbour), which covers the full Rhine Meuse Delta and a large part of the ocean (see Figure 1.1, dark blue grid);
2 The 3D model (OSR-NSC), which covers a smaller domain (see Figure 1.1, light blue grid).

To save computational time, the Harbour model is used to generate the boundary conditions for the NSC-model, with which more detailed 3D flow computations can be carried out. There are two versions of the NSC-model, a model with a coarse schematization for fast computations (NSC-coarse, with grid resolution identical to the Harbour model) and a model with a finer schematization for more detailed computations (NSC-fine, with grid resolution 3x as fine with the Harbour model). Further details about the models can be found in Kranenburg (2015a, 2015b) and Kranenburg and Schreuder (2015).

Figure 1.1 Overview of the domains from the OSR model. In dark blue the large domain (Harbour model) and in light blue the smaller domain (NSC).

[1] *Release Notes Major Release SIMONA 2012 en Release Notes Major Release SIMONA 2014; http://www.helpdeskwater.nl/onderwerpen/applicaties-modellen/*

2 Development 3D model for mud dynamics

2.1 Introducing the model chain

In order to calculate the mud dynamics in the harbour area of the Rhine Meuse Delta, a chain of models is necessary to capture the essential features of sediment dynamics over both shorter (tidal) and longer (monthly) time periods. The model chain is setup in three interconnected parts as visualized in the flow chart below in Figure 2.1.

1 Delft3D Flow Model
Using the OSR model (in Delft3D), the hydrodynamic conditions for a full month is calculated, including wave effects. This hydrodynamic model is used to force the sediment transport model.

2 Delft3D-WAQ model
This model receives the hydrodynamic conditions from the Delft3D flow model (through offline coupling i.e. no feedback from Delft3D-WAQ to FLOW). The Delft3D-WAQ model is suitable for computing long term sediment dynamics and therefore allows the simulated sediment distribution in the water column and in the bed to reach a dynamic equilibrium. The effect of dredging in the harbours and waterways is also included. Note that the WAQ model is not a morphodynamic model, i.e. bed levels are fixed. However, sedimentation and the resulting sediment distribution on the bed is included. As the sediment bed concentrations require a longer spin-up time than in the water column, the WAQ model is also used to generate initial conditions for sediment concentrations in the water column and in the bed for the simulation period with and without the effects of dredging. This information is fed back into the Delft3D short term sediment model as initial conditions.

3 Delft3D Sediment Model.
This is essentially the same as the Delft3D Flow model set-up in Step 1, but with sediment transport activated. As starting conditions, it uses the sediment concentrations in both the water column and the bed from the WAQ spin-up runs (water column and bed) described in Step 2.

In the following paragraphs more details will be given on the setup of each sub-model.

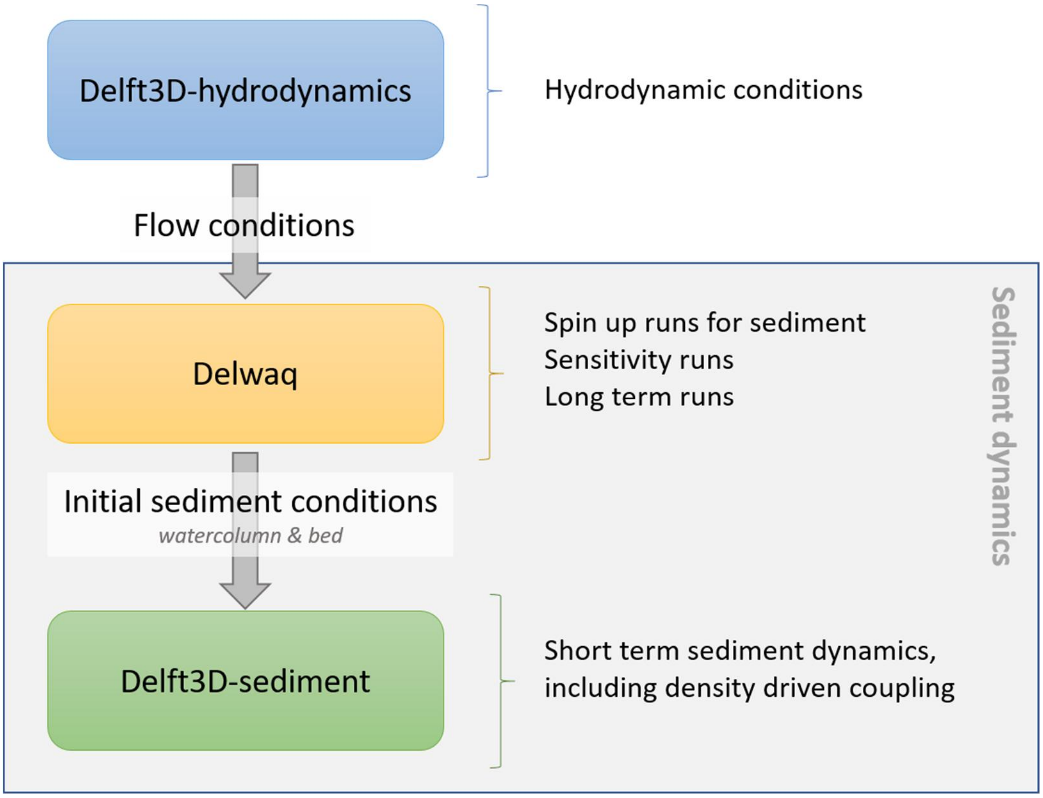

Figure 2.1 Model structure for computing mud dynamics.

2.2 Hydrodynamic model

2.2.1 Conversion of the SIMONA NSC-model to Delft3D

To construct a 3D hydrodynamic model, the existing NSC-coarse model was converted from SIMONA to Delft3D. In principle, the same schematization and settings are used for the grid, bed level, vertical schematization, roughness, viscosity and diffusivity and timestep. For some runs these settings were changed to avoid negative salinity values in the Haringvliet mouth. Details can be found in Appendix A.1. As a first test, the Delft3D model was forced with the same conditions as the received NSC-coarse model, namely January 2018. Conditions for flow and salinity were retrieved from the larger Harbour model and included salinity concentrations for all model boundaries, Riemann values for the sea boundary and discharges for the river boundaries and the Haringvliet sluices. For wind the potential wind at Hoek van Holland was used. Also, the relevant in- and outlets were included. The conversion was successful as the comparison of the water levels and salinity concentrations between both models showed only small differences, see Appendix A.2.

2.2.2 Choice of period

In order to obtain representative conditions for suspended sediment dynamics, a period with average discharge[2] and no storm events was chosen. It is furthermore important to at least model one full spring neap cycle (2 weeks) and preferably even a month. This resulted in the choice for modelling May 2016, see Figure 2.2. For this period, boundary conditions from the Harbour model were readily available from a previous project (Deltares 2018). For the wind, potential wind at Hoek van Holland was imposed.

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[2] Average Lobith discharge is about 2200 m^3/s.

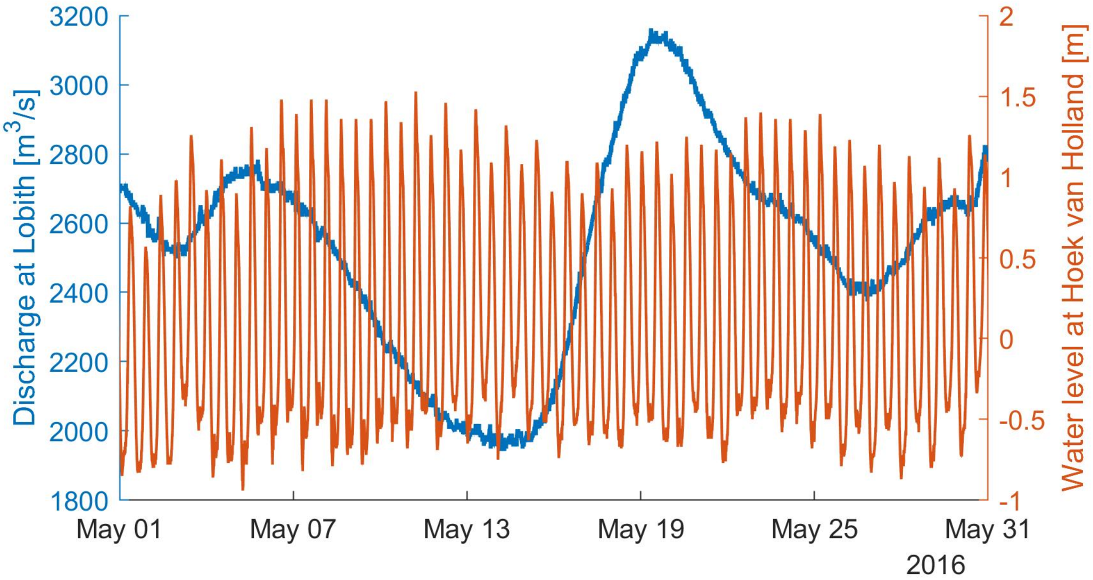


Figure 2.2 Tidal and discharge conditions during the May 2016.

2.2.3 Including waves

For the suspended sediment dynamics, it is important to include wave dynamics, as waves can stir up bottom sediment in shallower areas. The Delft3D flow model has therefore been coupled to a wave model (SWAN). Based on the flow and wind conditions a new wave field is computed and fed back to the flow module on an hourly basis. Both models share the same grid and schematization.

2.2.4 Validation of the hydrodynamic model

In order to check how well the coupled flow-wave model performs for the simulation period (May 2016), model results were compared with measured water level and salinity data. The results are shown in Appendix A.3. Water levels are generally in good agreement, but show an underestimation of the ebb levels, which increases landward. At Bernisse (along the river Spui) water levels are off and out of phase with the measurements. This artefact has also been reported for the NSC-model and is probably caused by differences in tidal propagation in the NSC-model with respect to the Harbour model (Huismans and Plieger 2019). Because the Spui river is not in the area of interest and validation studies have shown a good agreement on the flow distribution in the Nieuwe Waterweg, Nieuwe Maas, Oude Maas, it is assumed that the model is capable of representing the correct flow conditions in the area of interest. This also follows from the validation of the chloride concentrations, which are generally in reasonable to good agreement with the measurements.

2.2.5 Alternative settings for sediment dynamics

With the current settings, negative salinity concentrations values occur in the Haringvliet ebb-tidal delta, see Appendix A.4. These are a numerical artefact caused by large salinity gradients that result from the fresh water discharge through the Haringvliet sluices into the saline ebb-tidal delta during ebb-tide. To suppress these negative concentrations, different settings have been used for the eddy diffusivity and viscosity, see Appendix A.1.2. Furthermore, the setting for interpolating the bed level values at the grid cell corners to the cell centres has changed to “MOR”. This setting is needed in case bed level changes are computed. Though in current simulations only sediment concentrations are computed, leaving the possibility open for computing bed level changes, “MOR” was chosen.

Both changes however influence the salt-dynamics. The viscosity and diffusivity influence the mixing processes and the bed level schematization changes the flow cross-sectional areas and resulting flow through the branches. Combined, it leads to an underestimation of the salinity concentrations, see A.3.2.

Though for most simulations with sediment, the alternative settings have been used, it is advised to use the original settings for the follow up project. Negative concentrations in the ebb-tidal delta can either be accepted, as they do not affect the area of interest, or be solved by using a Forester Filter or by increasing the diffusivity and viscosity values only locally in the ebb-tidal delta.

2.3 Sediment model for longer term sediment dynamics (Delft3D-WAQ)

2.3.1 Model objective

The mud transport model was set up using Delft3D-WAQ software coupled offline with hydrodynamics (including wave effects) from a Delft3D version of the NSC-coarse model. The WAQ model receives information on water levels, currents and wave stresses as well as salinity from the hydrodynamic model.

The objective of the Delft3D-WAQ (also known as Delwaq) model is twofold:

1. The model is used to perform a sensitivity study of the critical parameters influencing fine sediment transport in and around the harbour basins in the Port of Rotterdam for the whole simulation period (one month). These parameters include the settling velocity of the sediment fractions, the efficiency at which sediment can be deposited to the bed, the dominance of different processes in the water column and on the bed and the impact of dredging and dumping.
2. The model is used to spin-up the sediment bed in the study areas so that sediment concentrations in both the water column and the bed have reached dynamic equilibrium. These spatially varying concentrations can then be fed into the more computationally expensive Delft3D-FLOW model to perform short simulations including the effect of density coupling.

2.3.2 Model background

The Delft3D-WAQ model applies the buffer parameterisation developed by van Kessel *et al*., 2011 for deposition, storage and erosion of sediments (see Appendix D for more details on the formulations). 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 bed during calm conditions and released from the bed 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. 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. Due to the highly muddy nature of the system being modelled, deeper burial of fines is also activated. 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.

2.3.3 Sensitivity tests

Several sensitivity tests were designed to build an understanding of the dominant processes responsible for mud transport in the port area. These included:

1. Sediment transport in the water column only and no bed interaction, in order to understand the distribution of fine sediments in the water column as function of settling velocity.

2. Pseudo 2D runs with very high vertical dispersion and exchange with the bed, to help understand the importance of bed exchange only by neglecting the 3D mechanisms responsible for transport in the water column.

3. Runs with both settling in the water column and water-bed exchange to examine the interaction between both mechanisms and establish realistic parameter settings.

Results of these sensitivity tests shall be briefly described in the next chapter and more details are given in the Appendixes.

2.3.4 Baseline model

Based on the settings from the ZUNO-DD model (Cronin and Blaas, 2013; Cronin et al., 2013), that was calibrated and validated for fine sediment dynamics along the Dutch coastline, and the results of the sensitivity tests, the baseline settings for the new mud transport model was established. Three fractions were used, with settling velocities of 2 mm/s, 1 mm/s and 0.5 mm/s for Sediment 1, 2 and 3 respectively. At the model boundaries a sediment concentration of 10 mg/l was imposed (the same as Delft3D-FLOW) for each fraction.

The impact of dredging and relocation was also included. Eight different areas were dredged (Figure 2.3; Table 2.1) and all sediments relocated in the (Verdiepte) Loswal (X *61190, Y 451995*) (Figure 2.4). In Delwaq the dredging areas are defined using polygons in Quickin (a pre-processing tool of Delft3D) and included in the parameter file (.par) through the user interface. The parameters associated with these different dredge areas are defined in the list of constants. The user can define when dredging starts, the frequency of dredging and the critical depth to dredge to. Other parameters include the segment number in which sediment from each area should be dumped and the speed of the release. In this application the speed and frequency of dredging was set equal in all areas and each area was dredged at a staggered time interval.

The performance of the model compared (qualitatively) to previous measurements and estimated dredge volumes shall be examined in the next chapter.

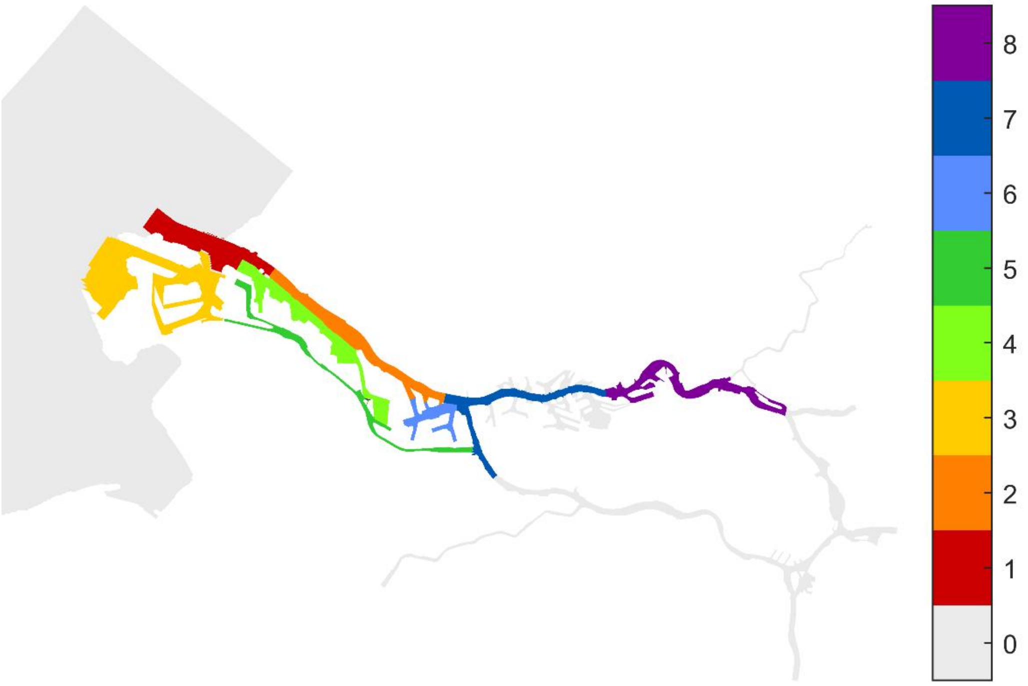


Figure 2.3 The eight dredging areas assigned to the baseline model

Table 2.1 Index of dredging areas

Area	Name
1	Maasmond
2	Nieuw Waterweg
3	Maasvlakte
4	Calandkanaal
5	Hartelkanaal
6	Botlek
7	Inner Area West
8	Inner Area East

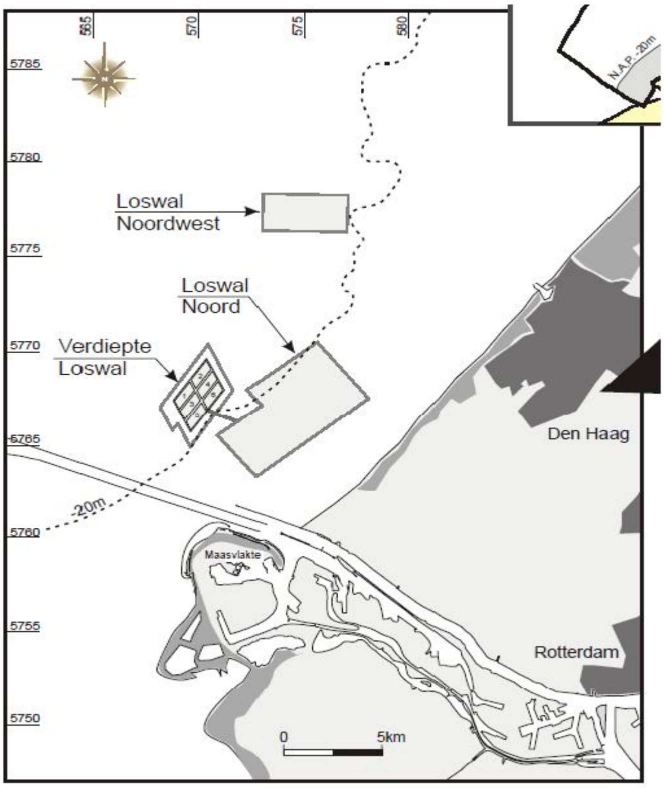


Figure 2.4 Location of the dumping grounds

2.4 Sediment model for short term sediment dynamics (Delft3D-sediment)

For the short-term sediment dynamics, two types of simulations have been carried out:

1. Test simulations to check the performance of the model and the occurrence of fluid mud;
2. Simulations with realistic settings for the sediment dynamics (identical to Delwaq settings) and with initial sediment concentrations from Delwaq, in order to compare Delft3D and Delwaq and to check the model outcomes for more realistic settings.

Below, details of both types of simulations are given. For simulating the relevant sediment exchange dynamics with the bed, all model runs include a fluff- and buffer layer, like in Delwaq. See Appendix D for an explanation of these concepts.

2.4.1 Method and settings for the test simulations

For the test simulations five fractions were used, with settling velocities of 2 mm/s, 1 mm/s, 0.5 mm/s, 0.1 mm/s and 0 mm/s. At the model boundaries a sediment concentration of 10 mg/l for each fraction was imposed. Initial concentrations in the water column and bed (fluff and buffer layer) were set to zero. It therefore requires some time for the model to reach dynamic equilibrium. Similar to the Delwaq set-up, three types of sensitivity tests have been performed:

- no exchange with the bed, to assess the transport of the sediment through the system in the water column only;
- exchange with the bed, to assess water-bed exchange and where different fractions settle;

- exchange with the bed, including the effect of the density on the flow (density coupling), in order to test whether fluid mud can be generated in the model.

Details on the precise settings for the sediment parameters, and the exchange with the bed can be found in Appendix B.1.1.

2.4.2 Method and settings for simulations with realistic settings and Delwaq input

For the realistic simulations, three fractions were used, with settling velocities of 2 mm/s, 1 mm/s and 0.5 mm/s. At the model boundaries a sediment concentration of 10 mg/l for each fraction was imposed. Initial concentrations in the water column and bed (fluff and buffer layer) were input from the Delwaq simulations. The same settings for sediment dynamics and exchange with the bed were transferred from the Delwaq runs (see Appendix B). In addition, runs with and without density coupling were carried out, to check for the occurrence of fluid mud.

3 Model insights

3.1 General

In order to understand sediment dynamics in the system, in particular the processes responsible for suspended mud and fluid mud transport, a range of spatial and temporal scales have been analysed. In Figure 3.1 an overview is given of the locations used for assessing the timeseries (model to model analysis) of suspended sediment concentrations.

Figure 3.1 Overview of the mouth area of the Rhine-Meuse Delta. In red the locations used for analysing the timeseries are shown.

3.2 Sediment dynamics in the longer term (month of May)

3.2.1 Sensitivity tests

As described in Section 2.3.3, a set of sensitivity tests were performed to evaluate the dominant processes responsible for the transport of mud in and out of the harbour basins. A description of the main findings is given here with further details in Appendix E.

The dominance of different processes was tested by comparing the distribution of suspended sediments for two sensitivity tests in particular, compared with a simulation in which full water-bed exchange was included.

The importance of three-dimensional settling and transport of fine sediments in the water column was examined using a simulation without water-bed exchange i.e. sediments could not deposit. In estuarine environments, sediment concentrations are typically higher near the bed and transport of these higher concentrations may be subject to circulation patterns driven by salinity stratification or sediment-induced density currents. The mean surface suspended sediment concentrations (for all fractions) over the entire simulation period without water-bed exchange (month of May) is shown in Figure 3.2 and the mean near bed suspended sediment concentrations is shown in Figure 3.3. See Appendix 0 for more results of runs with no water-bed exchange, including sensitivity to settling velocity.

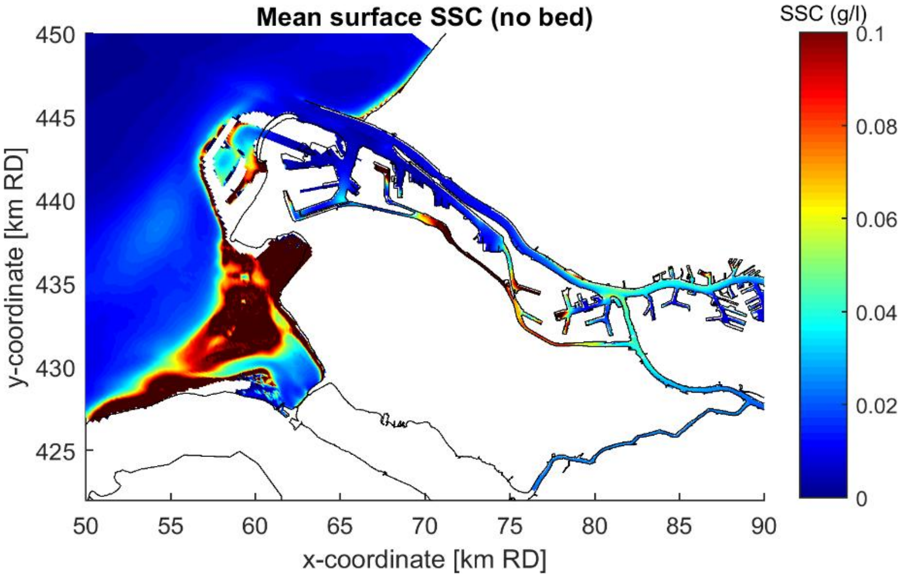


Figure 3.2 Mean surface suspended sediment concentration May 2016 without water-bed exchange

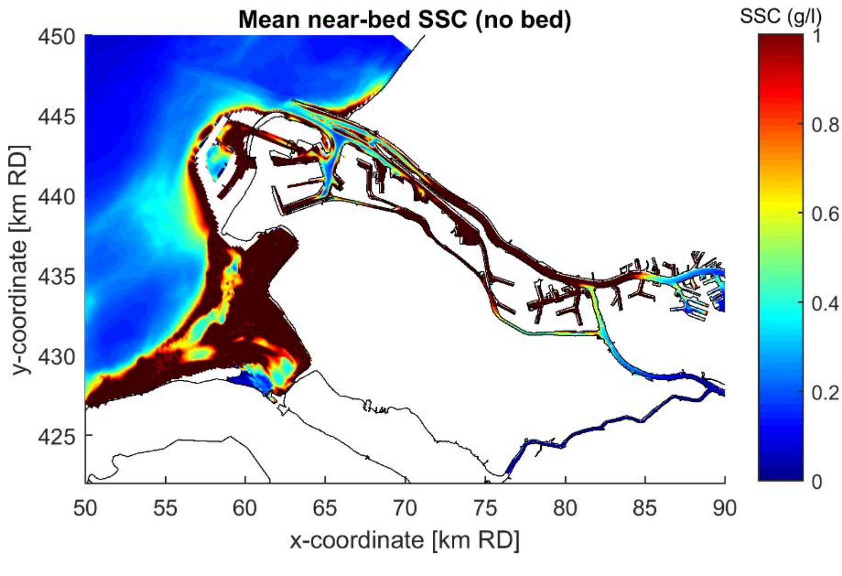


Figure 3.3 Mean near-bed suspended sediment concentration May 2016 without water-bed exchange

Conversely a simulation with a very high vertical dispersion in the water column was set up to mimic a 2D simulation by ensuring that water column processes were suppressed, and suspended sediment concentrations were therefore well mixed from the surface layer to the bed layer. The mean surface suspended sediment concentrations (for all fractions) over the entire simulation period (month of May) is shown in Figure 3.4. Note that the colour scale for the near-bed suspended sediment concentrations is different to Figure 3.3. This is because the concentrations are lower due to the well mixed nature of the water column compared to the much higher concentrations in the previous test where no water-bed exchange maintains unrealistically high sediment concentrations in the water column. It is the distribution of sediments in the study area that is of interest here rather than the concentrations themselves.

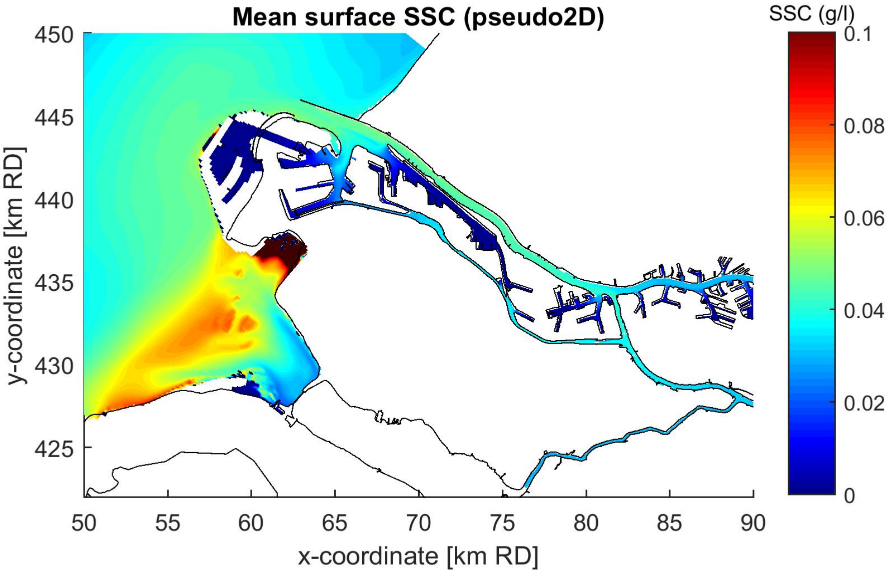


Figure 3.4 Mean surface suspended sediment concentrations May 2016 for the pseudo 2D run. The mean near-bed concentrations are identical.

The outcome of these two sensitivity tests could be compared with a realistic setup including 3D processes in the water column and full water-bed exchange. The mean surface suspended sediment concentrations (for all fractions) over the entire simulation period (month of May) is shown in Figure 3.5 and the mean near bed suspended sediment concentrations is shown in Figure 3.6.

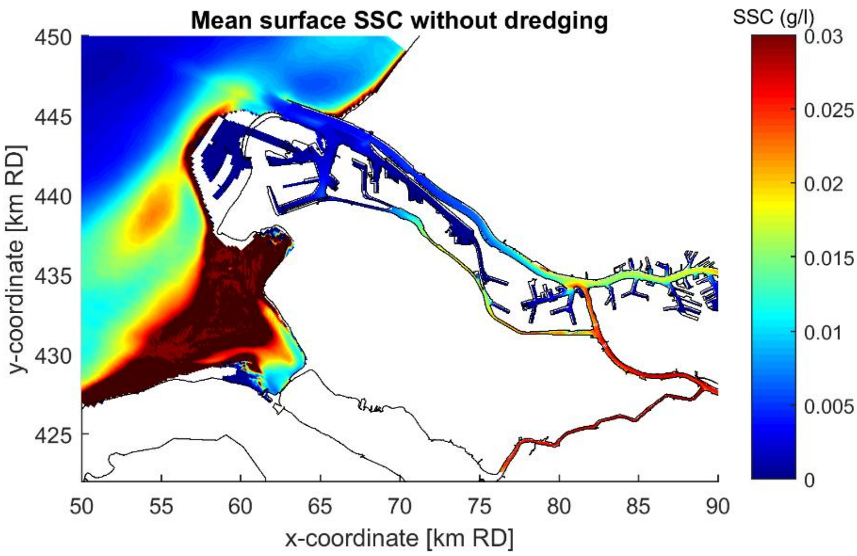


Figure 3.5 Mean surface suspended sediment concentrations May 2016 for realistic settings with full water-bed exchange

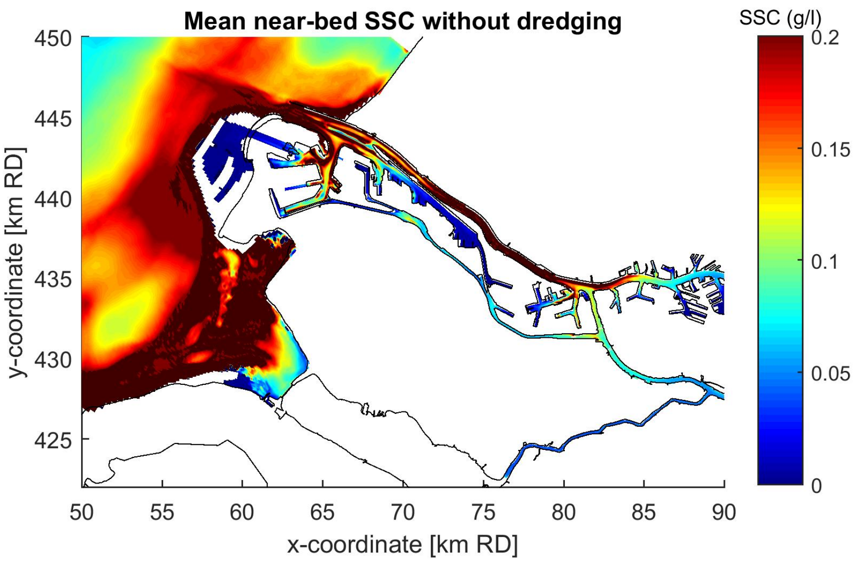


Figure 3.6 Mean near bed suspended sediment concentrations May 2016 for realistic settings with full water-bed exchange

Comparing the distribution of the three near surface suspended sediment concentrations, similarities and differences can be observed. In general the distribution of near-surface sediments in the simulation neglecting water-bed exchange (Figure 3.2) is most similar to the realistic set-up (Figure 3.5). Similarly, for the near-bed concentrations the simulation neglecting water-bed exchange (Figure 3.3) can be considered most similar to the realistic settings (Figure 3.6), although in certain harbours (e.g. Maasvlakte and Calandkanaal) it may be water-bed exchange processes that dominate deposition processes.

Given these insights, further simulations were carried out with the realistic settings including typical dredging activities and due to a lack of data, qualitative comparisons were made with historical data.

3.2.2 Realistic settings (with and without dredging)

Timeseries for three stations, the Maas-C buoy offshore, the Maeslantkering River station in the main channel and for a location further upstream near Botlek are given in Figure 3.7-Figure 3.9. For all stations concentrations are higher near the bed. Results for both the short-term flow simulations and the WAQ simulations are shown here to demonstrate the sediment dynamics are similarly captured in both runs. The hydrodynamic processes influencing the signal of SSC can also be seen. Whereas offshore the signal is marked by resuspension peaks due to wave energy, further upstream the signal is more influenced by river discharge.

The influence of dredging can clearly be seen in the bed concentrations (Figure 3.10-Figure 3.11) where sediments that had accumulated, particularly in the Maasmond, the Nieuw Waterweg and parts of the Maasvlakte have been removed through dredging. The simulations without dredging give a good indication of where sediments would accumulate if no dredging occurred and this can be qualitatively compared to reality to assess whether the model correctly captures the distribution of fine sediments in the system. A more qualitative assessment is presented in the next section where dredging volumes in the model are compared to the amount dredged in reality.

Dredging also impacts the near-bed suspended sediment concentrations more than surface concentrations (Figure 3.12). This is not only due to less sediment being available for resuspension, but concentrations offshore are also influenced through the dumping of the dredged sediment at the Verdiepte Loswal.

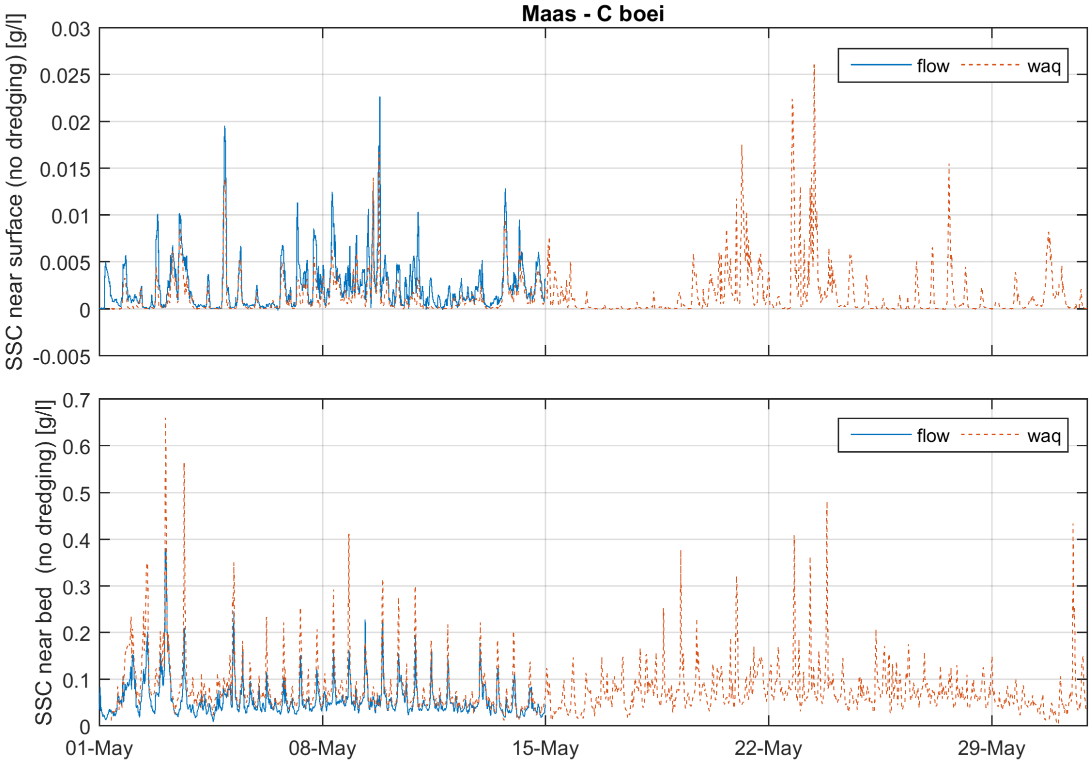


Figure 3.7 Timeseries of suspended sediment concentrations at the Maas-C buoy offshore. The flow timeseries stops as the simulation period was shorter than WAQ

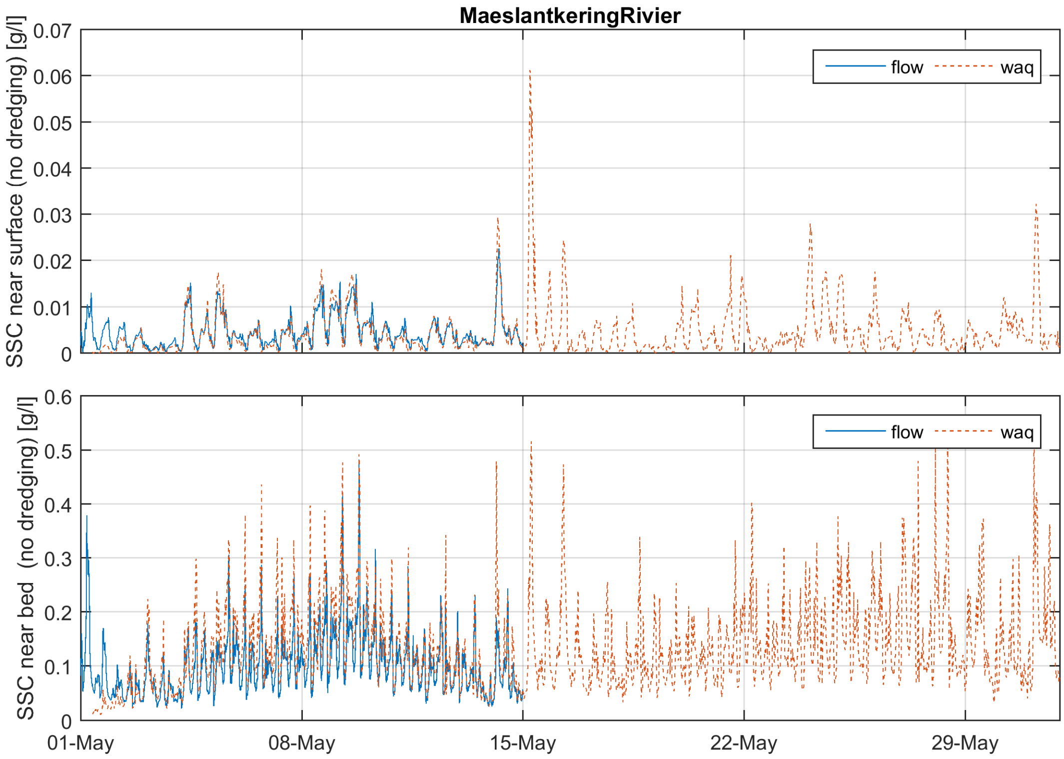


Figure 3.8 Timeseries of suspended sediment concentrations at Maeslantkering Rivier. The flow timeseries stops as the simulation period was shorter than WAQ

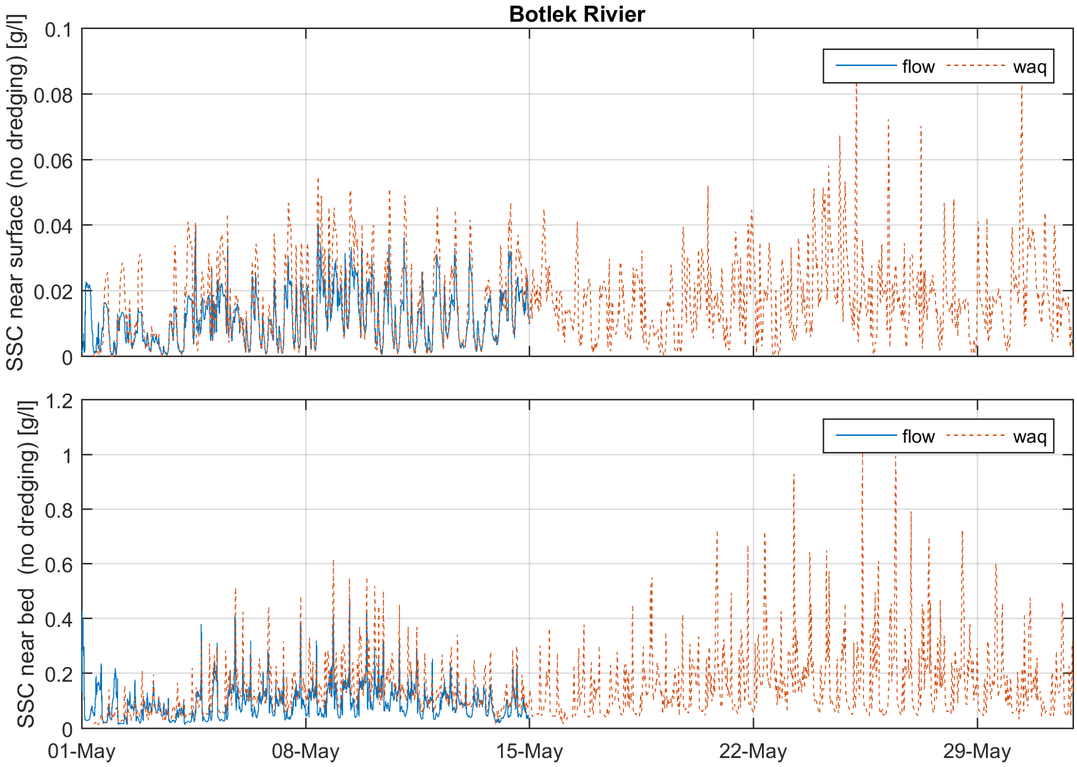


Figure 3.9 Timeseries of suspended sediment concentrations at Botlek Rivier. The flow timeseries stops as the simulation period was shorter than WAQ

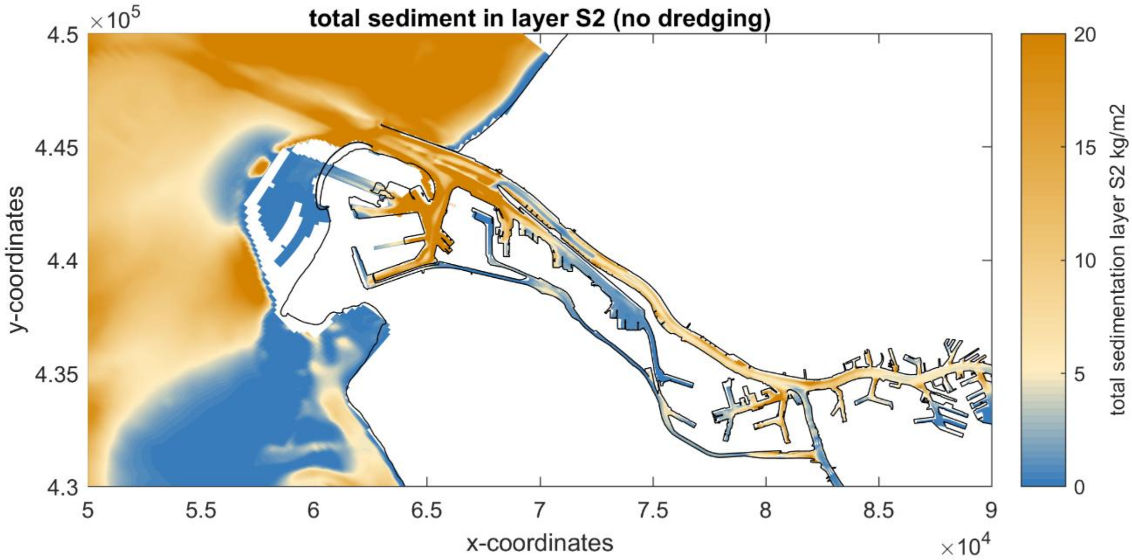


Figure 3.10 The total amount of sediment accumulated in the bed layer at the end of the simulation for the realistic simulation with no dredging

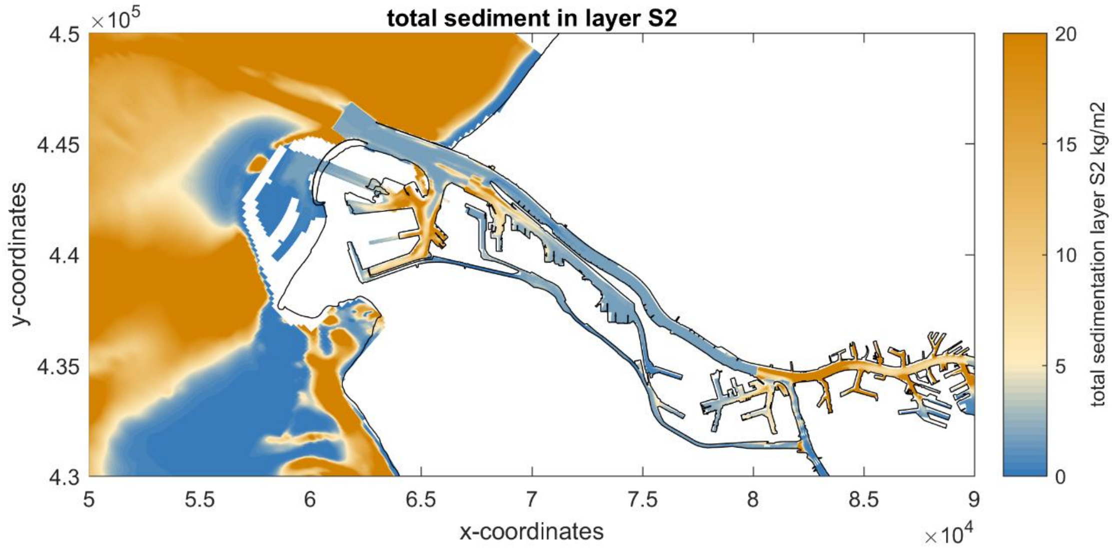


Figure 3.11 The total amount of sediment accumulated in the bed layer at the end of the simulation for the realistic simulation with dredging

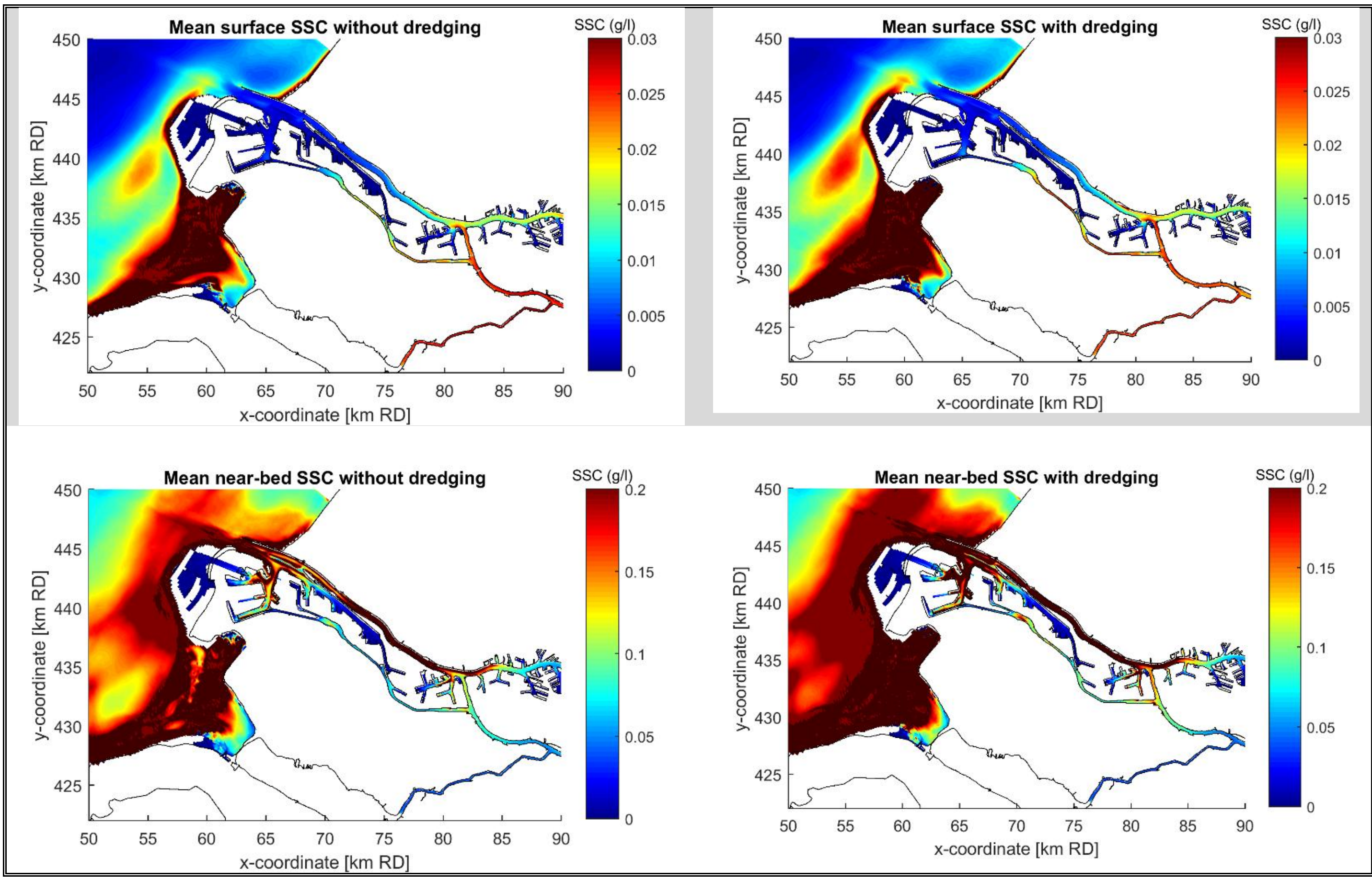


Figure 3.12 Mean surface and near bed concentrations for the May 2016 simulation without dredging (left top and bottom) and with dredging (right top and bottom)

3.2.3 Dredging volumes

Estimated dredging volumes relocated into the Verdiepte Loswal are in the order of 3 megatons per year (Table 3.1). Based on the month-long simulation for May 2016 a yearly estimate of ~ 9.3 megatons per year would be relocated into Loswal if May was repeated 12 times. Sedimentation rates would of course vary throughout the year and the volumes dredged are likely to be less in certain months so this can be considered an over estimation.

Table 3.1 The seven dredging areas implemented in the model and the total amount relocated (in tons and megatons) from each area at the end of the simulation (May 2016)

Areas	**Total sediment (tons)**	**Total sediment (megatons)**
Maasmond	155260,3	0,155
Nieuw Waterweg	55801,3	0,056
Maasvlakte	357517,1	0,358
Calandkanaal	115225,3	0,115
Hartelkanaal	20923,1	0,021
Botlek	65782,3	0,066
Inner area	76,1	-
SUM	**770585,5**	**0,77**

3.2.4 First comparison with data

Presently, there is not sufficient high-resolution data available on suspended sediment concentrations within the Port of Rotterdam to make a detailed comparison with model output. To give a qualitative impression of model performance suspended sediment concentrations are compared with two data sources, de Nijs (2012) who performed near surface and near bed SSC observations in the Nieuwe Waterweg and near-bed data from Siltman (De Kok, 2000) in the area of the Maasmond.

For the simulation with realistic settings and dredging mean modelled surface SSC concentrations are in the right order of magnitude (Figure 3.13) but overall lower than the data measured by de Nijs on 11 April 2006 (Figure 3.14). Modelled near-bed concentrations are also in the right order of magnitude (Figure 3.15) compared with measured data (Figure 3.16). A little further downstream, data by Siltman shows average values of between 90 and 500 mg/l at Station B and average values of between 50 and 270 mg/l at Station I. Maximum values at Station B go up to 1400 mg/l and 1200 mg/l at Station I (Figure 3.17 and Figure 3.18). Near-bed concentrations in the model (Figure 3.19) are on average higher than these measurements but in the right order of magnitude. The maximum concentrations observed at these stations are in line with the data. It should also be noted that the local sediment dynamics in the model with the presence of the Maasvlakte extension may also have changed with respect to the time period during which the Siltman measurements were taken 20 years previously.

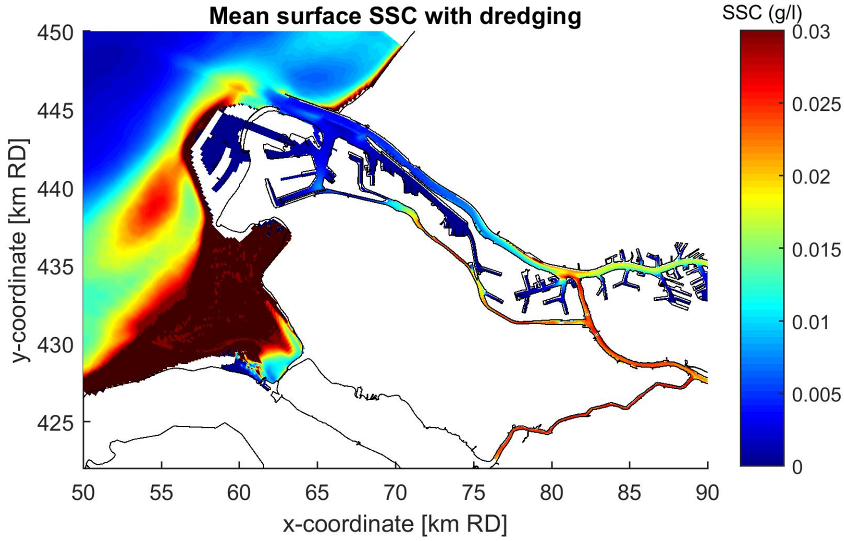


Figure 3.13 Mean (May 2016) near surface suspended sediment concentrations for a realistic simulation with dredging

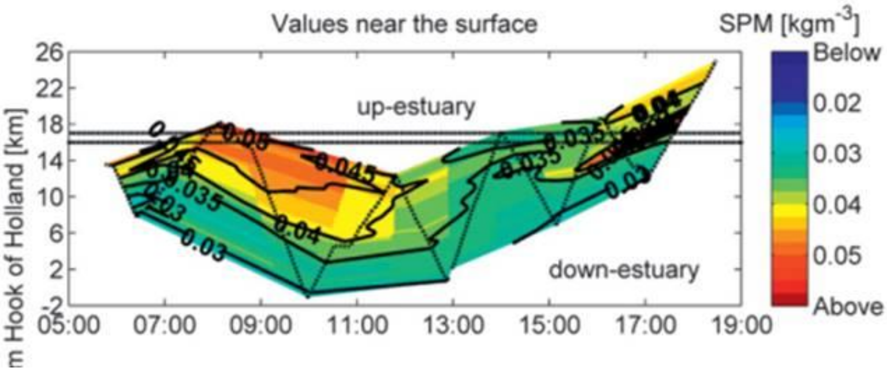


Figure 3.14 de Nijs near surface measurements across the Nieuwe Waterweg at discrete times

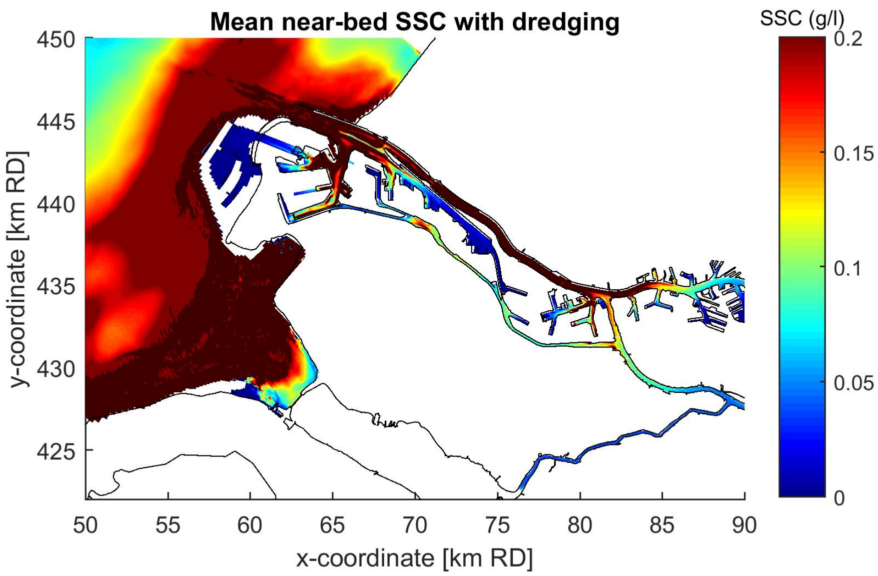


Figure 3.15 Mean (May 2016) near bed suspended sediment concentrations for a realistic simulation with dredging

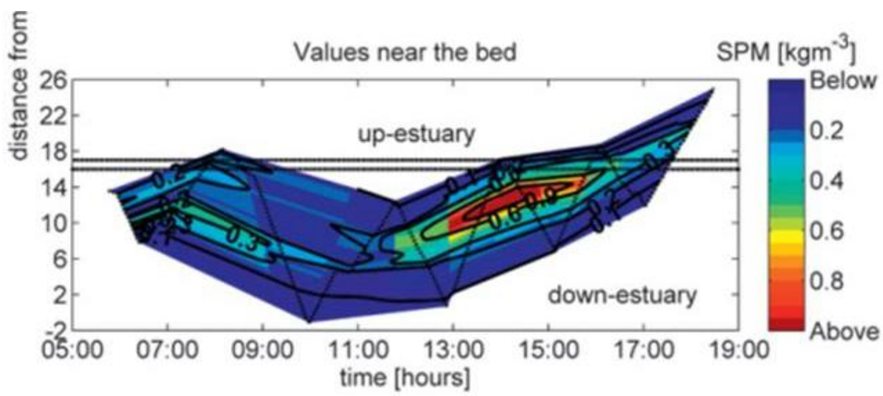


Figure 3.16 de Nijs near bed measurements across the Nieuwe Waterweg at discrete times

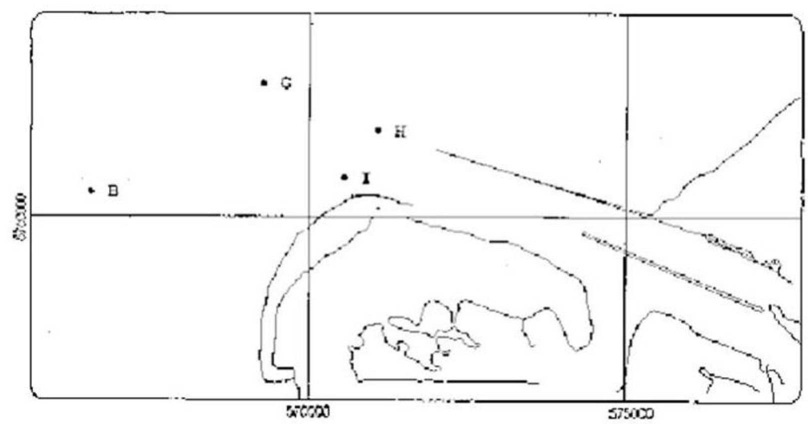


Figure 3.17 Siltman measurement locations near the Maasmond (De Kok, 2000)

maximal concentration				
	Measured			
period	18-03-97	31-03-97	20-01-97	20-03-96
position	0.55m	0.55m	0.55m	0.55m
B	400	1400	500	200
I	140	180	250	1200
G			600	120
H	250	500	300	240

average concentration				
	Measured			
period	18-03-97	31-03-97	20-01-97	20-03-96
position	0.55m	0.55m	0.55m	0.55m
B	100	500	200	90
I	50	50	40	270
G			200	35
H	100	130	130	50

Figure 3.18 Measurement data from Siltman showing maximum and average concentrations at different stations in the Maasmond. The measurements were taken 55 cm above the bed.

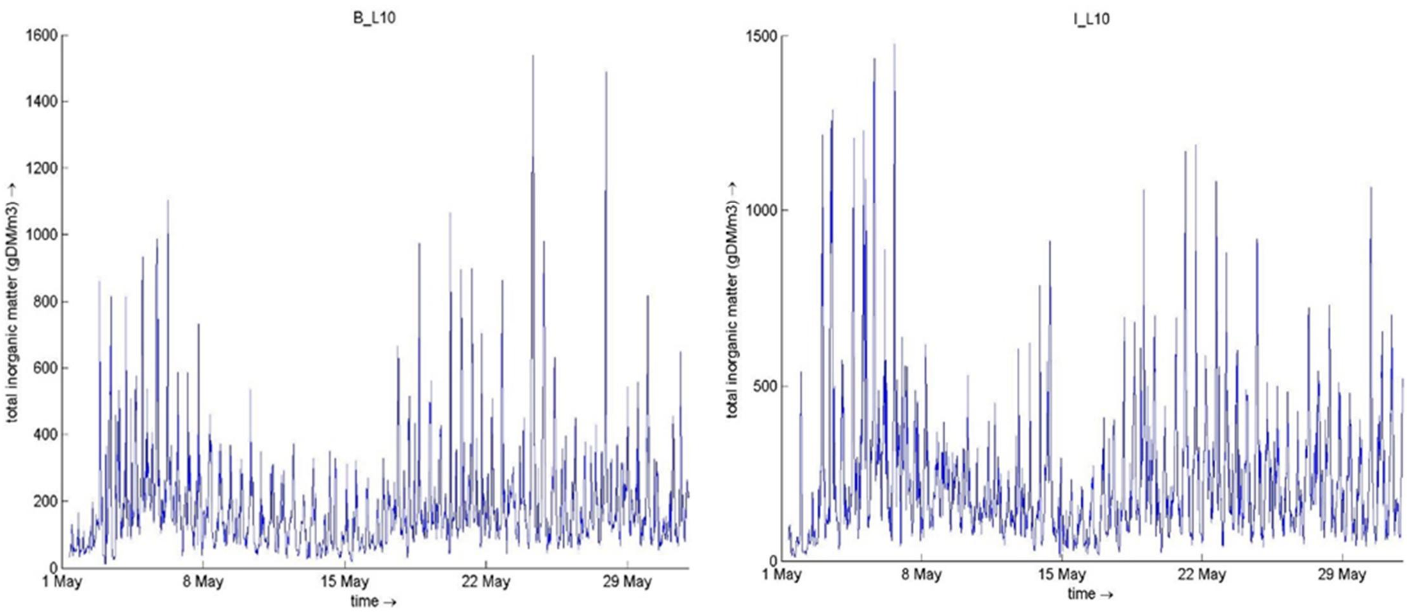


Figure 3.19 Modelled near bed total suspended sediments at Siltman stations B and I for May 2016

3.3 Short term sediment dynamics

3.3.1 Test simulations, without bed exchange

In case there is no exchange with the bed, sediment freely spreads through the system. Spatial visualization of the near surface sediment concentrations, at the end of the two-week simulation, are presented in Figure 3.20. Sediment with no settling velocity spreads nearly evenly throughout the system and reaches the at the boundaries imposed concentration of 10 mg/l. Only in the outer parts (various harbors and the Hollandsche IJssel river which does not get any river discharge) sediment concentrations are somewhat lower. For sediments with higher settling velocities, sediment starts to concentrate in certain areas. The higher the settling velocity, the stronger this concentration. These observations are in line with the expectations and with the observations in Delwaq (see Appendix E).

To quantify the comparison between Delwaq and Delft3D, timeseries of suspended sediment concentration were compared for the locations shown in Figure 3.1. The results can be found in Appendix C.1. These show that the time variation is similar, but that concentrations predicted by Delft3D are generally lower. The reason for this has not yet been explored.

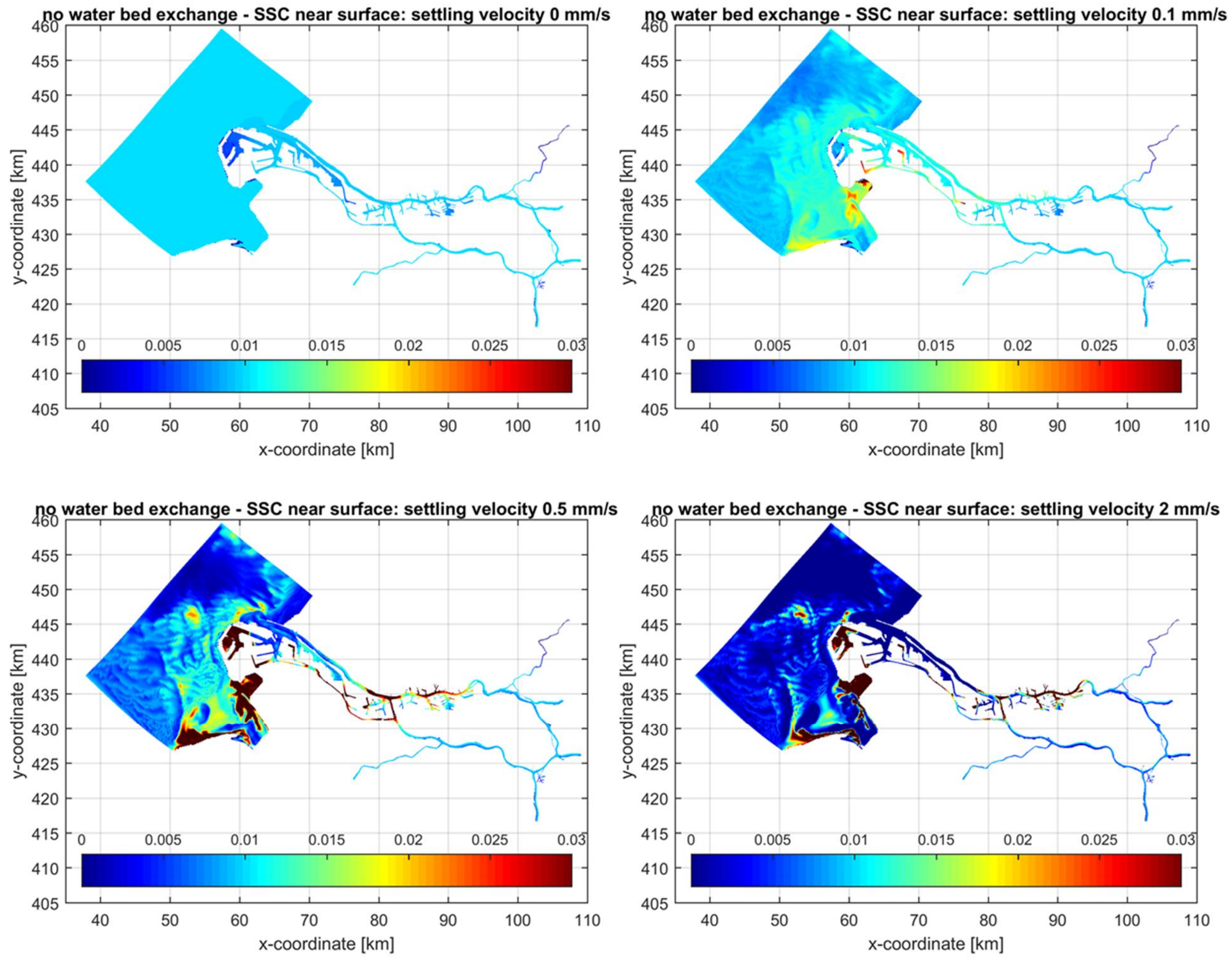


Figure 3.20 Near surface suspended sediment concentrations [g/l] for the test run without water bed interaction. Figures show concentrations for sediment fractions with four different settling velocities and indicated by the titles.

3.3.2 Test simulations, density coupling

The simulation with density coupling was instable. By using the original settings for the viscosity and diffusivity (see also explanation in paragraph 2.2.5) and a twice as small timestep (dt = 7.5 sec instead of 15 sec), a stable run was carried out. An example of the effect of the density driven coupling on the sediment concentrations is shown for Europahaven in Figure 3.21. At the end of the simulation, concentrations near the bed are about 4 times higher for the run including the density coupling. In Figure 3.22 spatial plots are given of the near bed concentrations for the final timestep in the simulations with and without density coupling. This shows density coupling leads to very different dynamics of the suspended sediment concentrations.

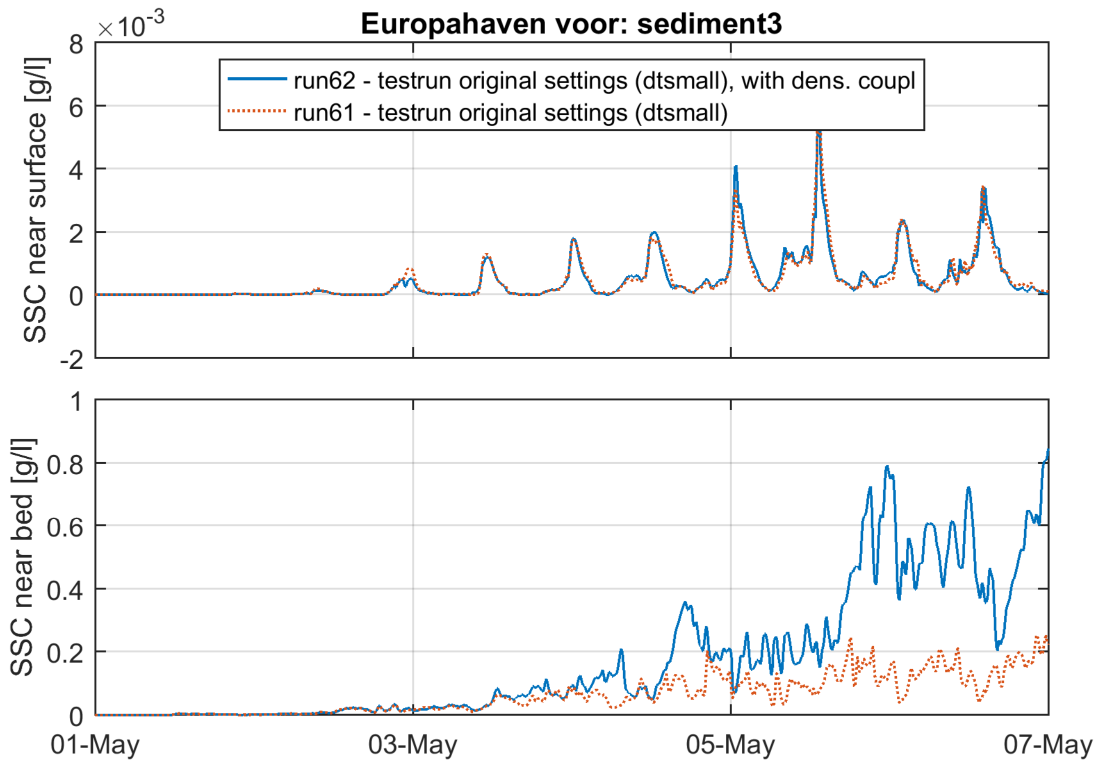


Figure 3.21 Comparison of the suspended sediment concentrations between a run with and without density coupling for the location Europahaven and sediment with velocity of 0.5 mm/s.

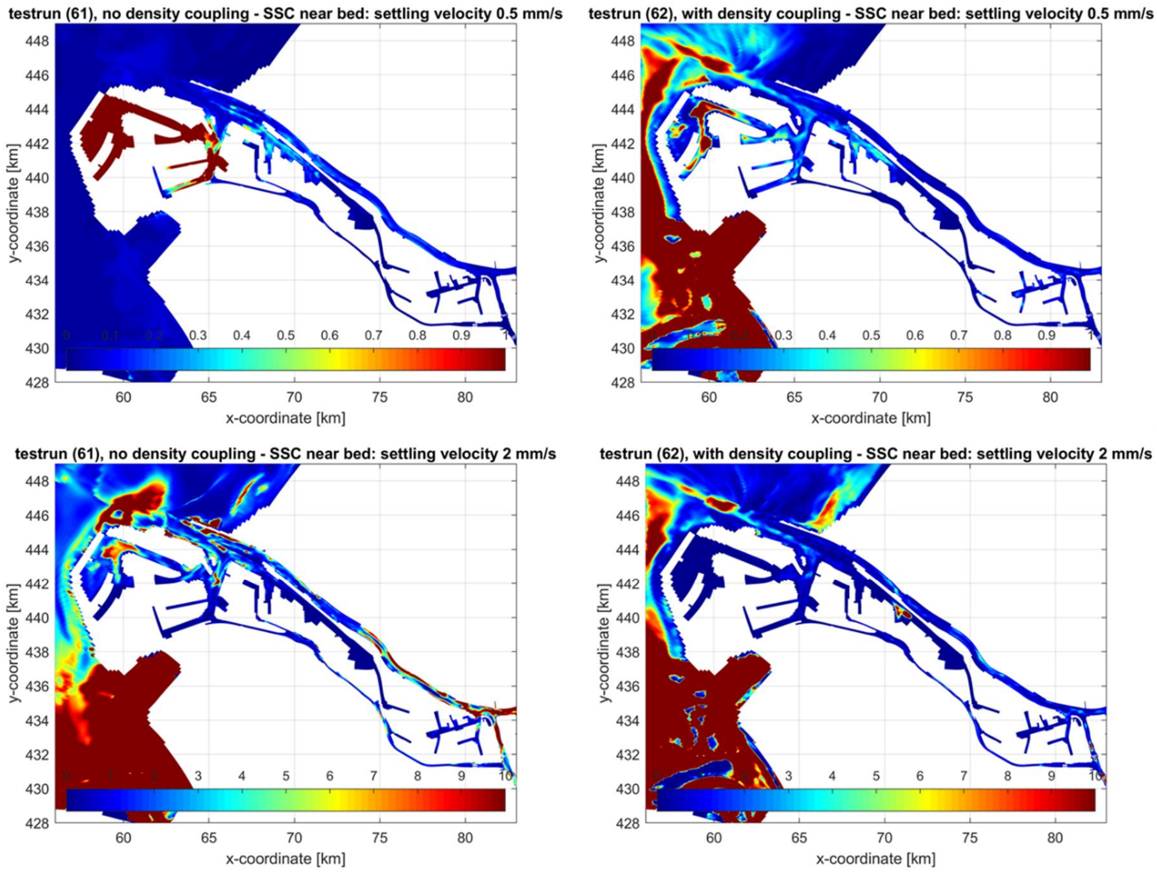


Figure 3.22 Near bed suspended sediment concentrations (g/l) for simulations without (left) and with (right) density coupling, and for sediment with settling velocity of 0.5 mm/s (top) and 2 mm/s (bottom).

3.3.3 Simulations with realistic settings, no density driven coupling

In the following step, runs with realistic settings for the sediment dynamics and with initial conditions from the spinned-up two Delwaq simulations (with and without dredging) are compared. Note that in the Delft3D run no dredging occurs, as only 2 weeks are simulated. The difference between the runs with and without dredging is only in the initial conditions, which contain higher sediment concentrations for the case with dredging.

In Figure 3.23 the time-averaged suspended sediment concentration (averaged over the first two weeks of May) are shown for the simulation with and without dredging. Both simulations show comparable distribution of the sediment, but with higher concentrations for the simulation with initial conditions from the Delwaq run with dredging. Near the surface, highest concentrations are found along the coast, in the Haringvliet eb-tidal delta in the Oude Maas and Spui. Near the bed, highest concentrations are found in the entrance area of Maasvlakte 2, in the Nieuwe Waterweg, along the coast and in the Haringvliet eb-tidal delta.

To get an indication of where most sediment settles, an overview of the sedimentation and erosion in the buffer layer is shown in Figure 3.24. This shows that most sedimentation occurs in the Maasvlakte II, Calandkanaal and Botlek harbor.

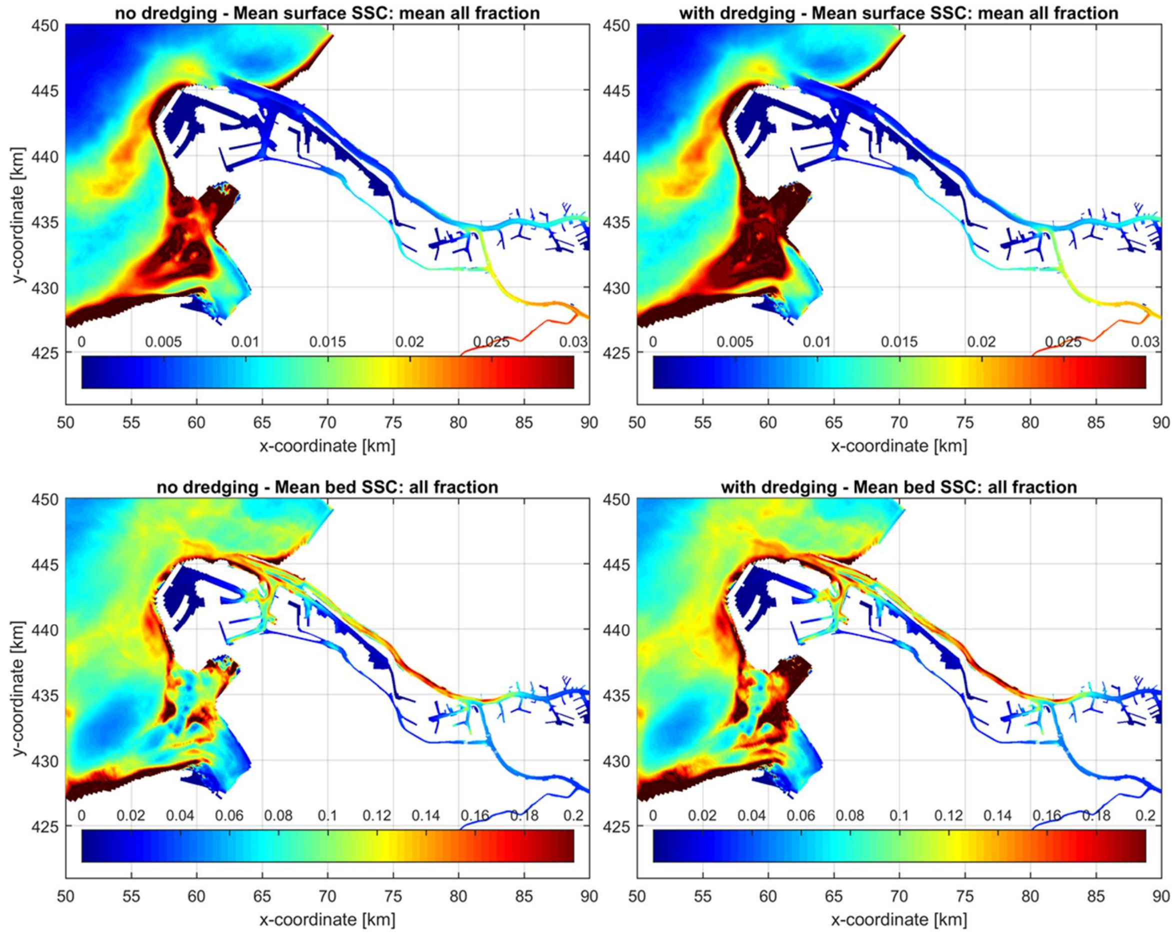


Figure 3.23 Averaged suspended sediment concentrations (g/l) for simulations with initial conditions from the Delwaq runs without (left) and with (right) dredging.

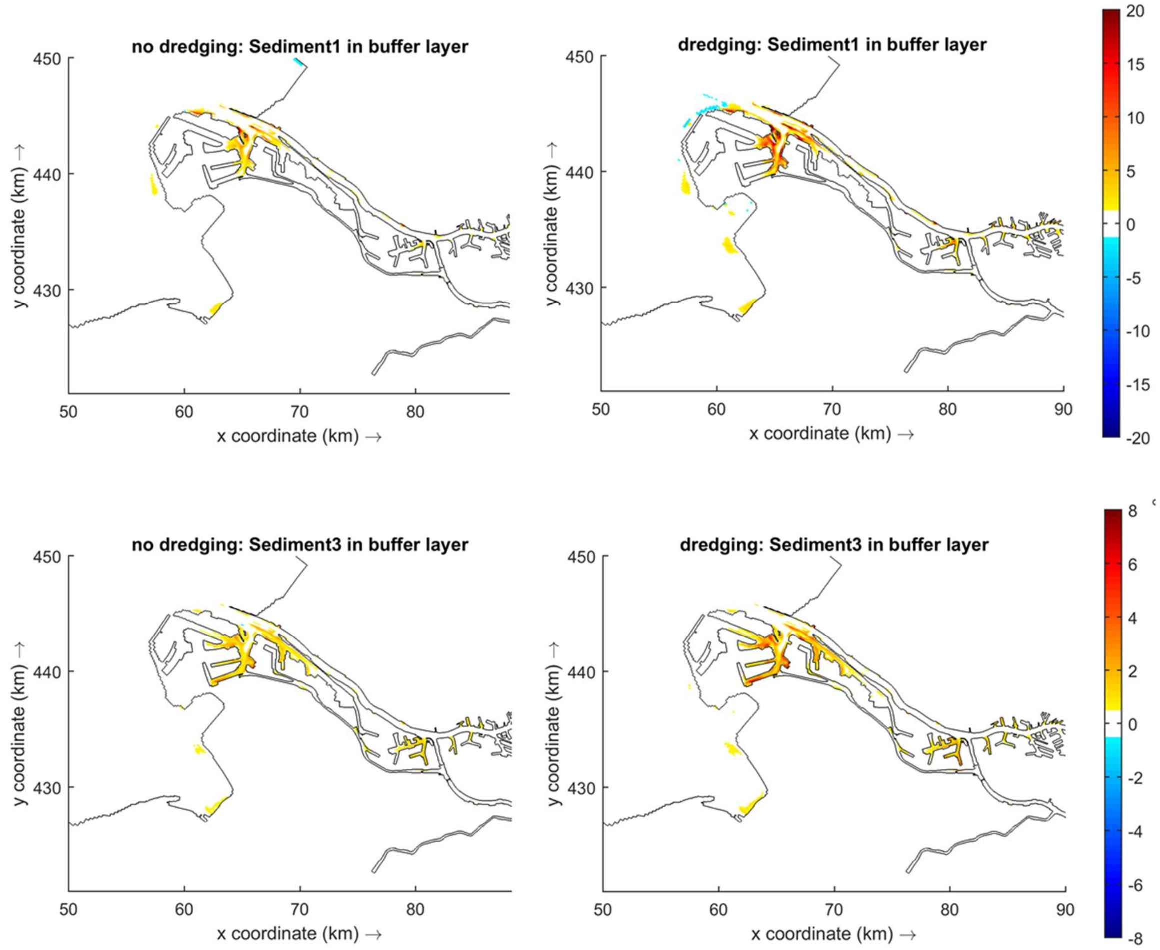
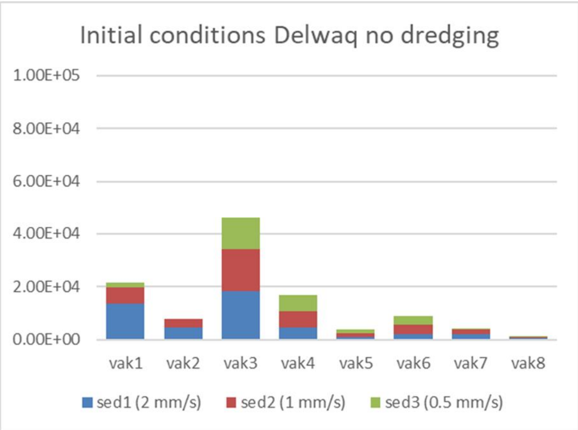


Figure 3.24 Amount of sedimentation and erosion (kg/m^2) over two week times for sediment 1 (top figures, settling velocity of 2 mm/s) and sediment 3 (bottom figures, settling velocity of 0.5 mm/s) and for the runs with initial conditions from Delwaq without (left) and with dredging (right).

The amount of deposition has also been quantified per area, as shown in Figure 3.25 and Figure 3.26. According to these number, most sedimentation happens in the mouth area (area 1), Maasvlakte II (area 3), Calandkanaal (area 4) and Botlek Harbor (area 6). To get a first impression whether the order of magnitude of sedimented mass per year is correct, the amount deposited over 2 weeks in all areas has been multiplied by 26. This leads to about 2.9 Mton/year to 5.6 Mton/year for the simulation without and with dredging. Reported dredged mass per year is about 3 Mt/year (Kirichek *et al*., 2018). This suggest that the order of magnitude is correct. Also, the distribution is in line with the experience, with most sedimentation in the mouth area, Maasvlakte II, Calandkanaal and Botlek Harbor. The number is however much lower than the ~9 Mton/year predicted by Delwaq. This difference is probably related to the observation that the suspended concentrations predicted by Delft3D-Flow are generally lower than those predicted by Delwaq (see §3.3.1). Further comparisons and interpretation of differences will be carried out in the follow up project when additional work will be undertaken to calibrate the model.

Figure 3.25 Overview of the areas for which the amount of sedimentation has been analysed.



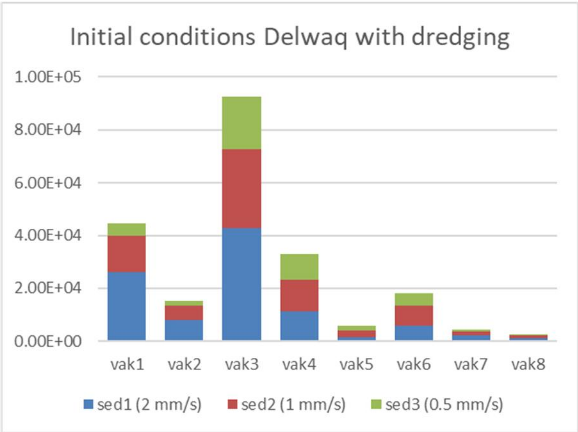


Figure 3.26 Amount of sedimentation (tons) over 2 weeks' time, per area.

3.3.4 Simulation with realistic settings, with density coupling

To check whether fluid mud occurs, runs with and without density coupling have been performed. Because concentrations in the normal runs[3] were too low (less than a few g/l), the initial concentrations in the water column and fluff layer were doubled. Even in these runs, concentrations remained too low to result in fluid mud. Therefore, an extra run was carried out with a patch sediment with high density (100 g /l for each fraction, 300 g/l total). In order to get a stable run the original settings for the viscosity and diffusivity (see also explanation in paragraph 2.2.5) and a twice as small timestep (dt = 7.5 sec instead of 15 sec) were used.

The result is shown in Figure 3.27 and Figure 3.28, in which for 0, 3 and 6 hours after the release of the sediment patch the suspended sediment concentration is shown. With density coupling the high concentrations spread over a larger area while without density coupling the sediment remains more concentrated. After about one day, only a patch of high concentration remains present in the main channel, just upstream of the original sediment patch. Inspection of the timeseries at a location in the sediment patch (Figure 3.29), shows that with density coupling, suspended sediment concentrations near the bed show a faster initial drop, but remain higher in a later stage. Near the surface negative concentrations occur. This is a

[3] *Realistic settings + initial conditions from Delwaq.*

numerical artefact that needs to be investigated. In addition, the detailed behaviour of the fluid mud layer needs to be studied further, as well as its sensitivity to the choice for number of layers in the vertical and the horizontal grid resolution. This will all be carried out in the follow up project (PRISMA).

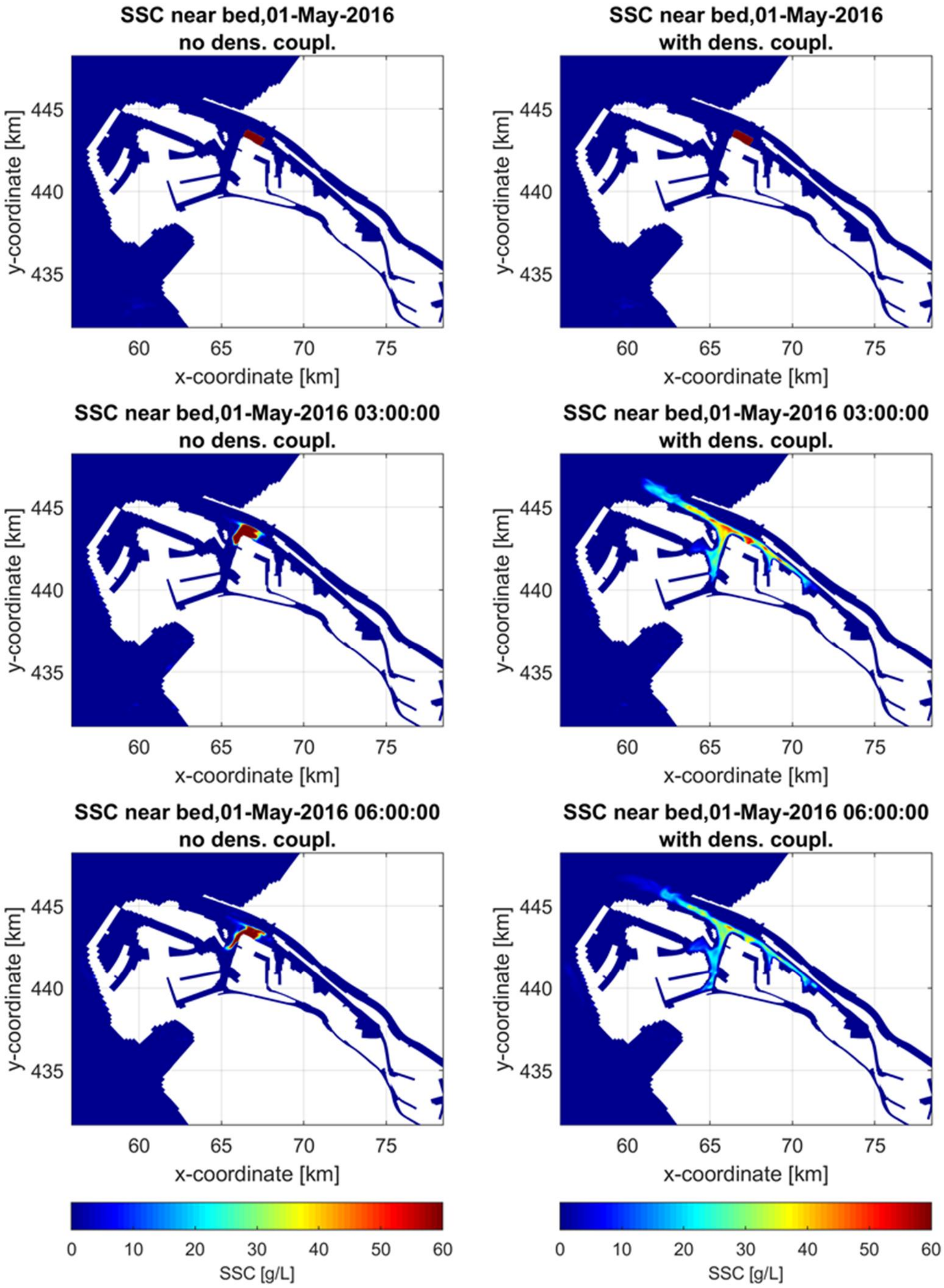


Figure 3.27 Sum of suspended sediment concentrations of all three fractions, for run without density coupling (left) and with density coupling (right), for 0, 3 and 6 hours after insertion of a patch with high sediment concentration. Note that the colour scale has been clipped at 60 g/L.

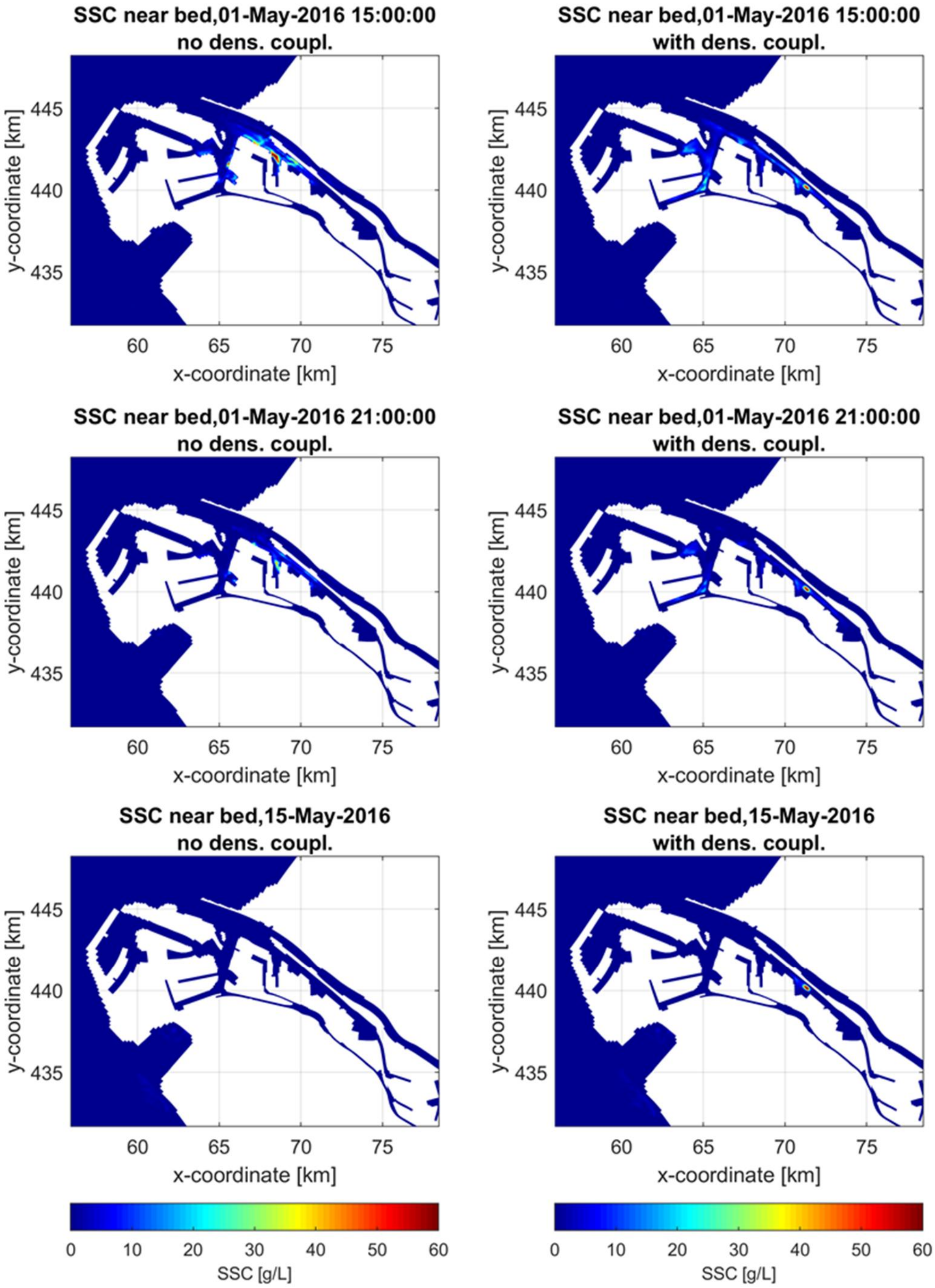


Figure 3.28 Sum of suspended sediment concentrations of all three fractions, for run without density coupling (left) and with density coupling (right), for 15 hours, 21 hours and 15 days after insertion of a patch with high sediment concentration. Note that the colour scale has been clipped at 60 g/L.

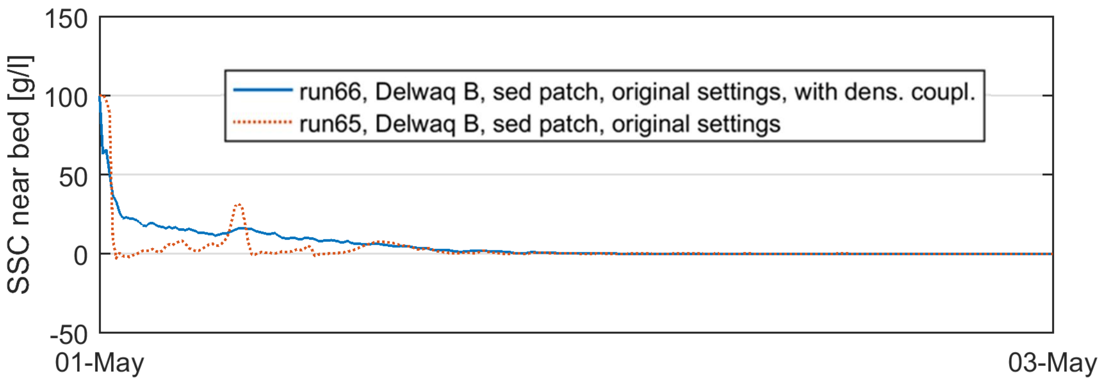


Figure 3.29 Comparison of the suspended sediment concentrations between a run with and without density coupling for sediment with velocity of 1 mm/s and at the location in the Calandkanaal where the high concentration sediment patch was released.

Conclusions and recommendations

This project has resulted in a technically operational local model for mud dynamics and sedimentation in the Maasmond area. A first comparison has been made with observations on suspended sediment concentration and harbour siltation. The model outcomes are consistent with typically observed concentration levels and sedimentation volumes. However, the available data and the simulation period of one month is too short to allow for a quantitative validation. For this more field observations should become available (a field survey is anticipated) and the model should be re-run for longer time intervals, including the periods with field observations.

The performed sensitivity study has resulted in the following preliminary conclusions:

- Sediment with a very low settling velocity does not accumulate in the harbour area, as the mechanisms steering sediment accumulation hardly act on the fraction of very fine sediment. These mechanisms are residual near-bed flow, and asymmetries in tidal forcing, vertical mixing and water-bed exchange.
- These mechanisms do act much more effectively on faster settling fractions, as these result in distinct vertical concentration gradients and water-bed exchange. Therefore, the concentration of these fractions is markedly enhanced in the Maasmond area compared to concentration levels at sea and in the river farther upstream.
- However, the concentration levels of very fast settling sediments fractions drops again as these fractions sit on the bed most of time, apart from during highly energetic conditions.
- The settling velocity at which concentration levels peak depends on several model parameter settings, but is typically within the range of 0.5 to 2 mm/s.
- In the Maasmond area, sediment accumulation appears to be caused dominantly residual transport due to vertical sediment concentration gradients. Water-bed exchange appears to play a secondary role. This may be explained as in the harbour basins the bed shear stress is very low most of the time, so resuspension is small. On the other hand, in the New Waterway the bed shear stress is very high most of the time, so little deposition of mud occurs. Necessarily, resuspension is also small, as a starved bed condition (sandy bed) is encountered for mud.

Based on model scenarios in which sediment deposited into the harbour basins was removed at a regular interval and released at the Loswal, it is concluded that concentration levels and sedimentation volumes are influenced significantly by the dredging-deposition cycle. This conclusion was already drawn earlier in a preceding large-scale model study, but it has now been confirmed with the local model. This leaves room for optimisation of dredging strategies.

Based on a comparison between model scenarios with and without sediment-induced density effects, it appears that under typical conditions fluid mud formation is limited. This conclusion still needs confirmation from field observations, as limitations in model resolution and numerical accuracy may have suppressed fluid model formation in the model.

In a scenario in which a local fluid mud is layer (e.g. as created by water injection dredging) is imposed to the model as initial condition a fast gravity-driven spreading of this layer was computed, followed by further dispersion by vertical mixing. The fluid mud layer did not persist more than a tidal cycle (12.5h). It propagated in both landward and seaward direction as a gravity-driven flow and as a result became thinner. Within the first tidal cycle it disappeared by the combined effect of advection, deposition and vertical mixing. Further investigations on the sensitivity of model resolution, numerical accuracy and assumed rheological properties of the fluid mud layer are required to draw firm conclusions.

The following recommendations are made:

1. Though for most simulations with sediment, the alternative settings have been used, it is advised to use the original settings for the follow up project.
2. Near the surface negative concentrations occur. This is a numerical artefact that needs to be investigated. In addition, the detailed behaviour of the fluid mud layer needs to be studied further, as well as its sensitivity to the choice for number of layers in the vertical and the horizontal grid resolution.

4 Literature

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A Details on the Delft3D hydrodynamic model

A.1 Model schematisation and settings

Below details on the schematisation and relevant settings as used in the Delft3D flow simulations are given.

A.1.1 Schematization

	description	File
Grid	Identical to the NSC-coarse grid.	NG03_single_2014_v501.grd
Bed level	Schematization of 2016, including the measure around the Breeddiep.	bathymetry_NG03_2016_ v505_Verbreed_Breeddiep.dep
(sub)grid features	Dry points and thin-dams, including the schematization of Maasvlakte 2.	osr_incl_MV2.dry osr3_incl_MV2.thd
Vertical	10 layers of thicknesses (from top to bottom): 12%, 12%, 11%, 11%, 11%, 11%, 11%, 9%, 6%, 6%	

A.1.2 Relevant settings

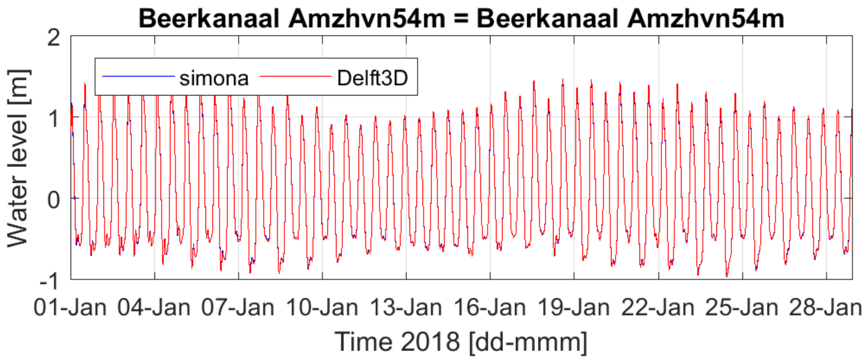
Parameter	Value	
Timestep	0.25 min	
Wind drag coefficient	Breakpoints A: coeff. 0.0026, Wind speed 0 m/s, Breakpoint B: coeff. 0.0026, Wind speed 100 m/s, Breakpoint C: coeff. 0.0026, Wind speed 100 m/s	
Roughness	Manning, spatially varying, values from NSC-coarse model	
Horizontal eddy viscosity*	1 m^2/s	(1 m^2/s)
Horizontal eddy diffusivity*	0.01 m^2/s	(1 m^2/s)
Vertical eddy viscosity*	9.7752e-007 m^2/s	(1e-5 m^2/s)
Vertical eddy diffusivity*	0 m^2/s	(1e-5 m^2/s)
Turbulence model	k-Epsilon	
Depth at grid cell faces*	Mean	(MOR)
Threshold depth	0.15 m	
Advection scheme for momentum	Cyclic	
Advection scheme for transport	Cyclic	
Wind	Uniform, timeseries from file, identical to NSC-coarse model	
Initial conditions for flow		

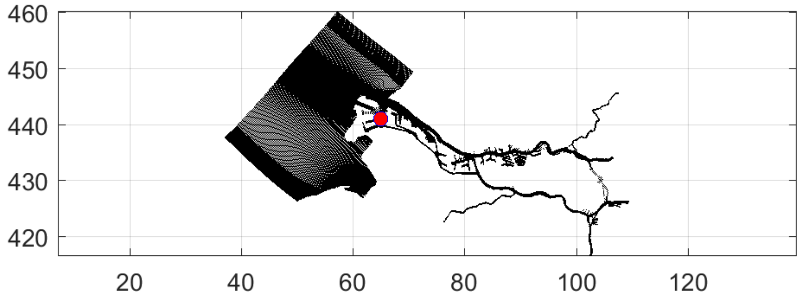
** the second value listed was used for providing the hydrodynamic conditions of most sediment runs, as with the original settings unrealistic salinity concentrations where observed in the Haringvliet mouth area and for schematization of the bed level in cell centers "MOR" is used for morphodynamic computations.*

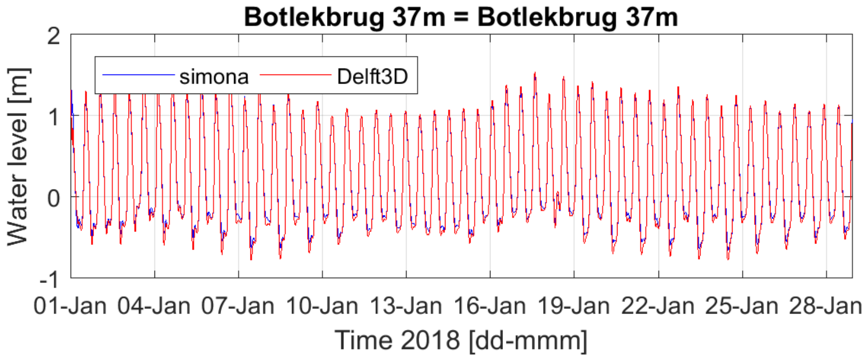
A.2 Comparison to NSC-model (SIMONA)

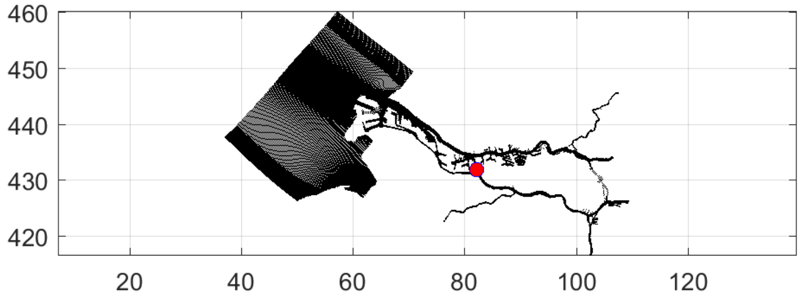
After converting the SIMONA model to Delft3D, a test run was carried out, to compare water level and salinity concentrations from both models (run 3). The results are visualized in the graphs below.

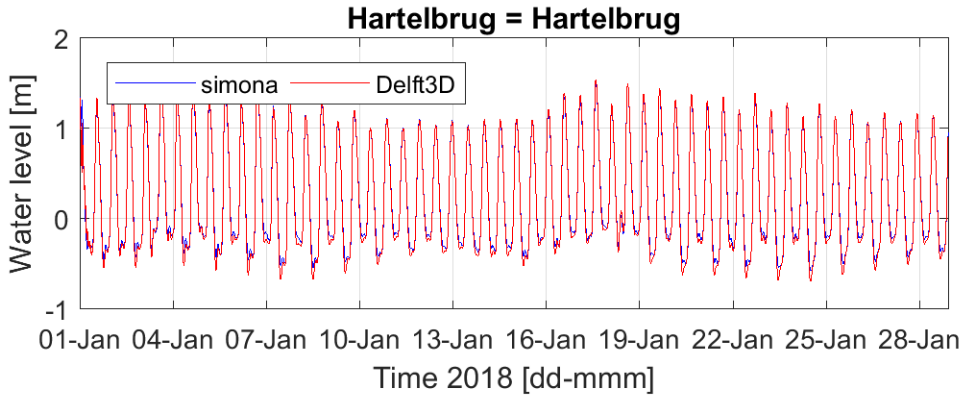
A.2.1 Water level comparison







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simona
Delft3D
Water level [m]
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0
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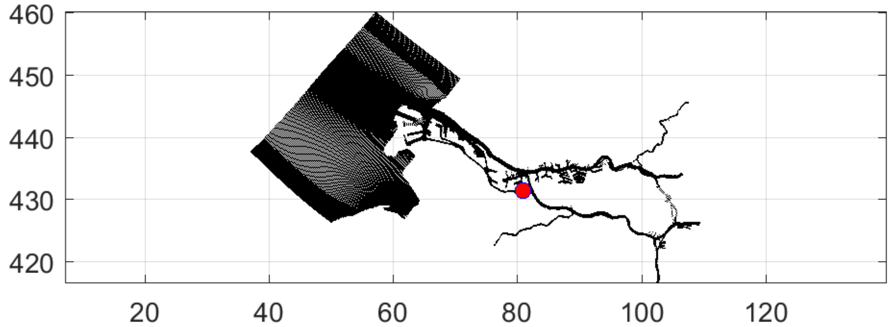
Time 2018 [dd-mmm]


460
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420
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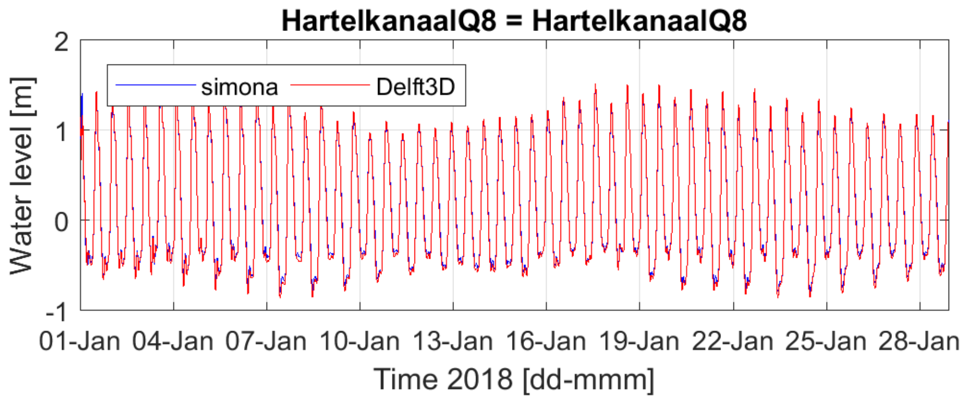
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Water level [m]
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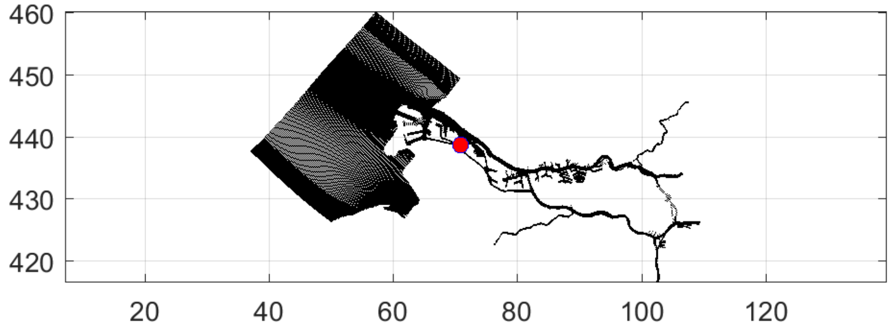
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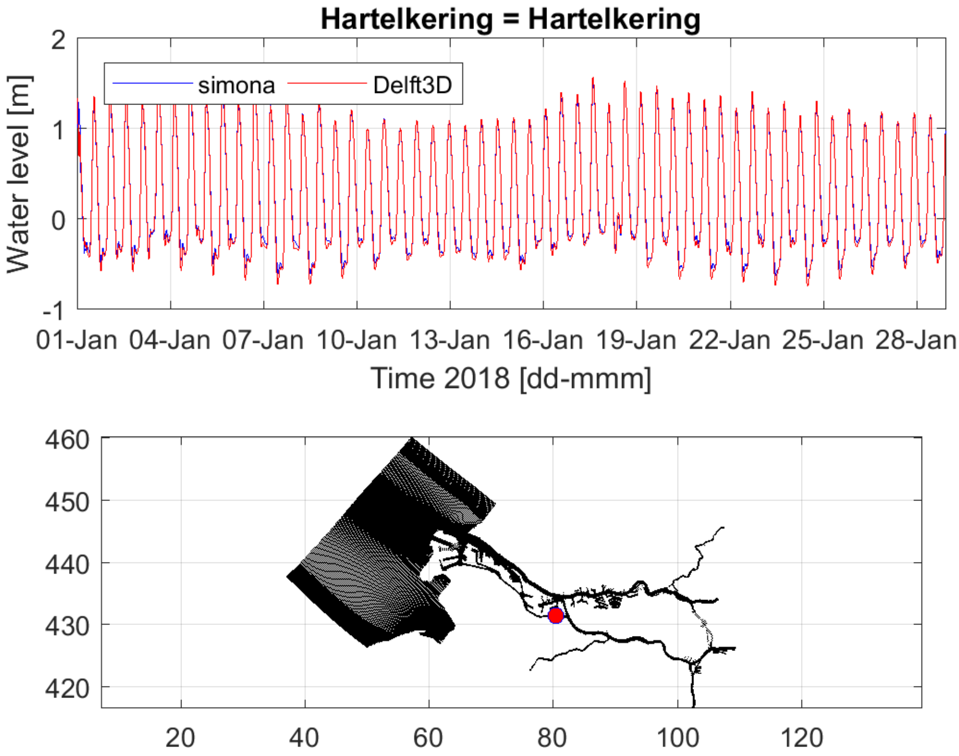
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Delft3D
Water level [m]
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01-Jan 04-Jan 07-Jan 10-Jan 13-Jan 16-Jan 19-Jan 22-Jan 25-Jan 28-Jan
Time 2018 [dd-mmm]
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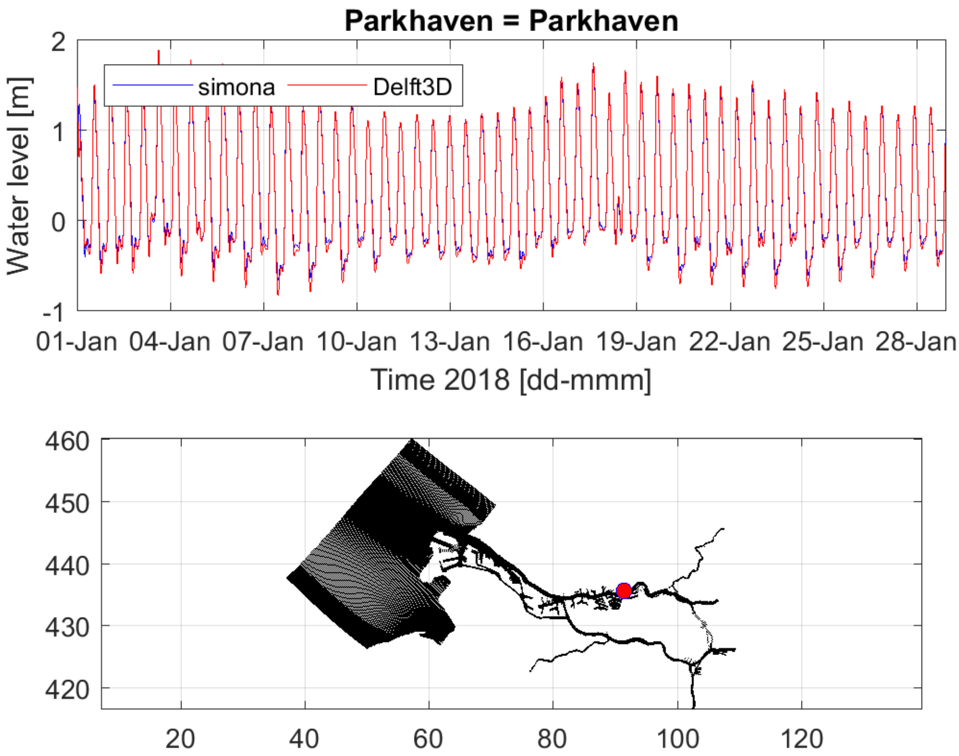
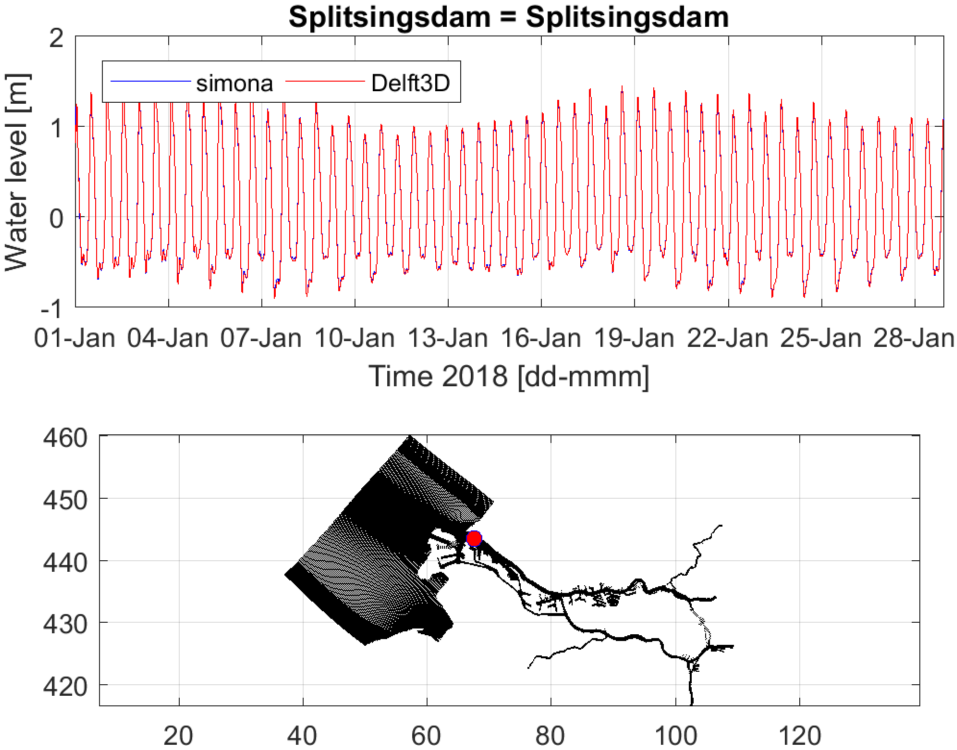
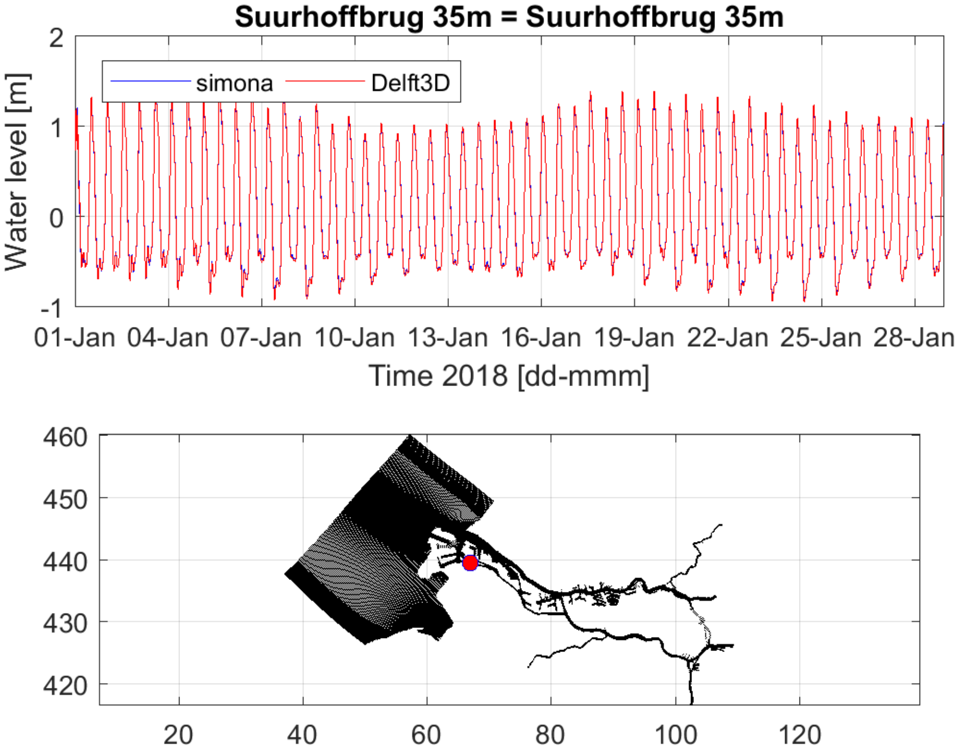
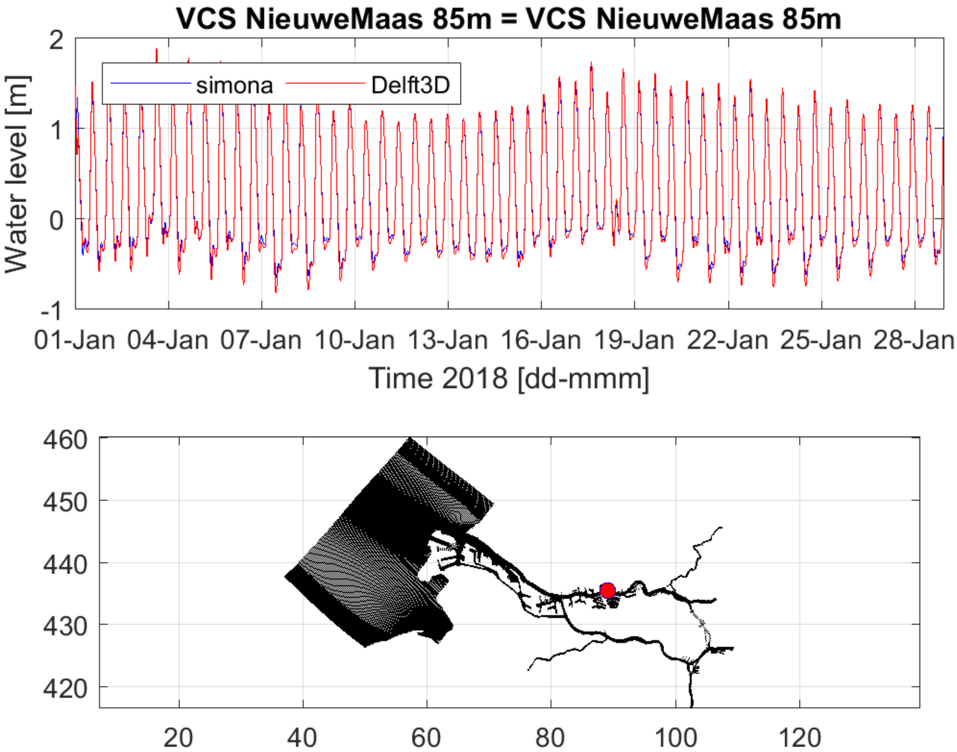
450
440
430
420
20 40 60 80 100 120

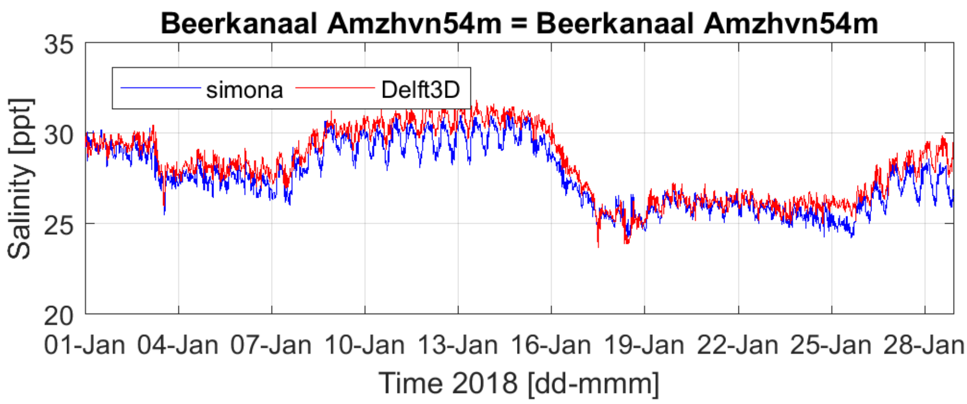

Parkhaven = Parkhaven
simona
Delft3D
Water level [m]
2
1
0
-1
01-Jan 04-Jan 07-Jan 10-Jan 13-Jan 16-Jan 19-Jan 22-Jan 25-Jan 28-Jan
Time 2018 [dd-mmm]
460
450
440
430
420
20 40 60 80 100 120

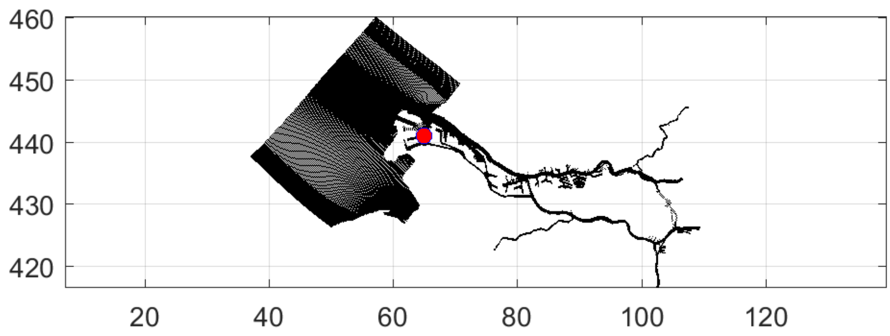

Splitsingsdam = Splitsingsdam
simona
Delft3D
Water level [m]
2
1
0
-1
01-Jan 04-Jan 07-Jan 10-Jan 13-Jan 16-Jan 19-Jan 22-Jan 25-Jan 28-Jan
Time 2018 [dd-mmm]
460
450
440
430
420
20
40
60
80
100
120

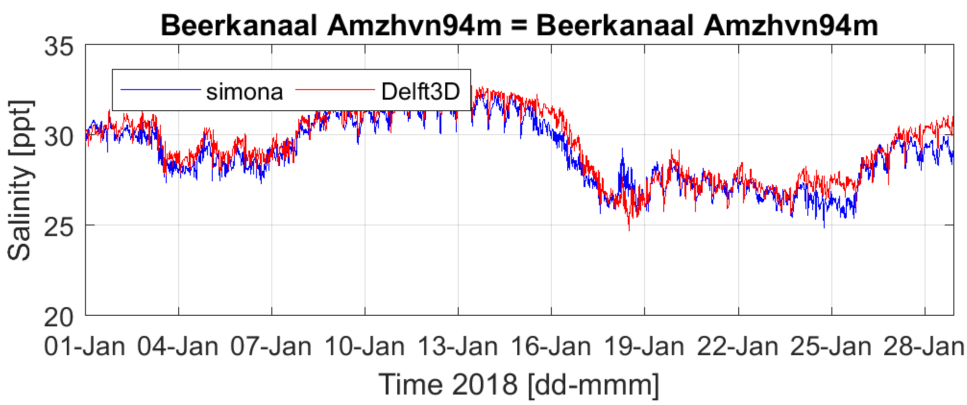

Suurhoffbrug 35m = Suurhoffbrug 35m
simona
Delft3D
Water level [m]
2
1
0
-1
01-Jan 04-Jan 07-Jan 10-Jan 13-Jan 16-Jan 19-Jan 22-Jan 25-Jan 28-Jan
Time 2018 [dd-mmm]
460
450
440
430
420
20
40
60
80
100
120

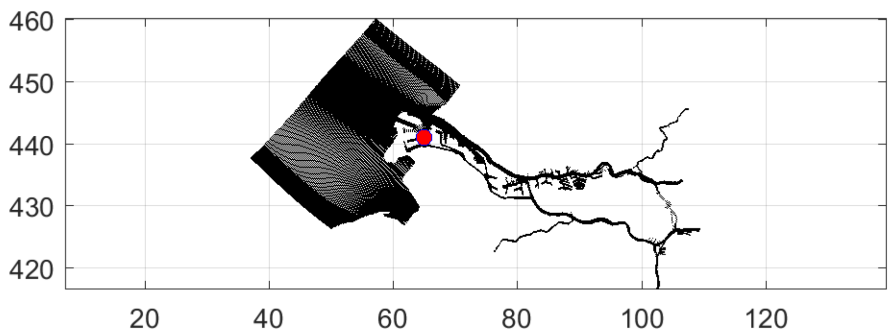

VCS NieuweMaas 85m = VCS NieuweMaas 85m
Water level [m]
simona
Delft3D
2
1
0
-1
01-Jan 04-Jan 07-Jan 10-Jan 13-Jan 16-Jan 19-Jan 22-Jan 25-Jan 28-Jan
Time 2018 [dd-mmm]
460
450
440
430
420
20
40
60
80
100
120

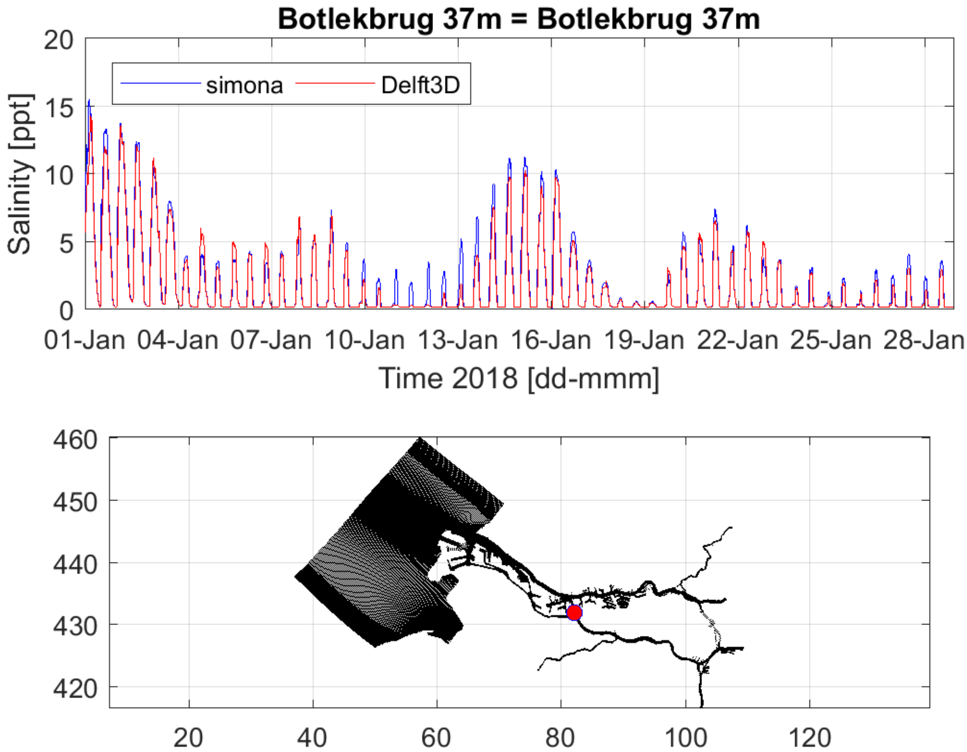
A.2.2 Comparison salinity concentrations (surface)

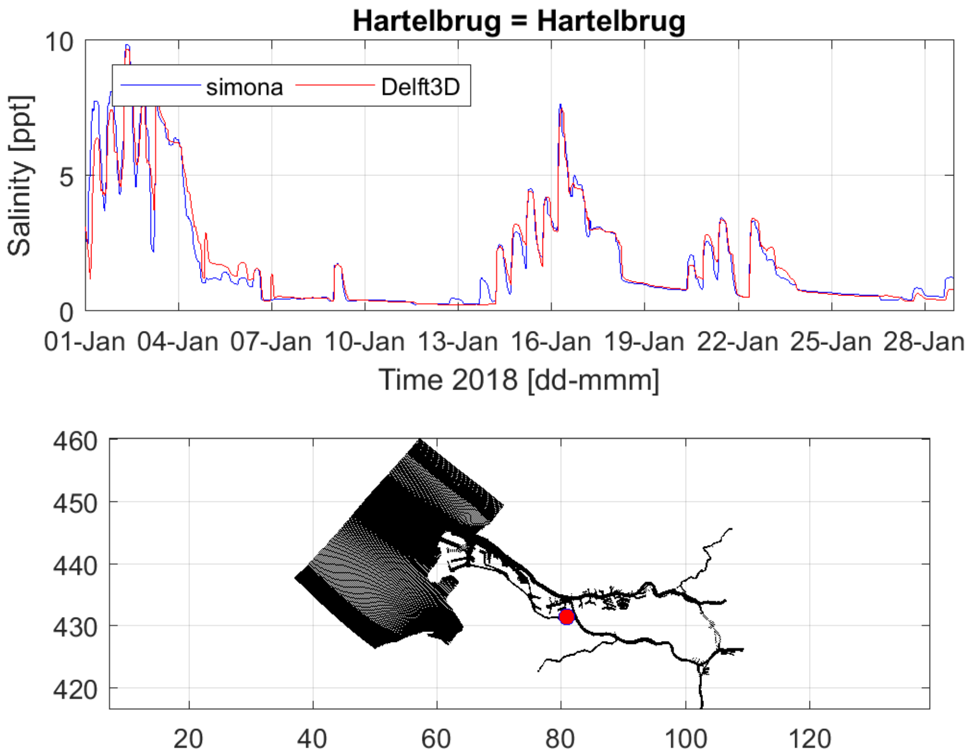


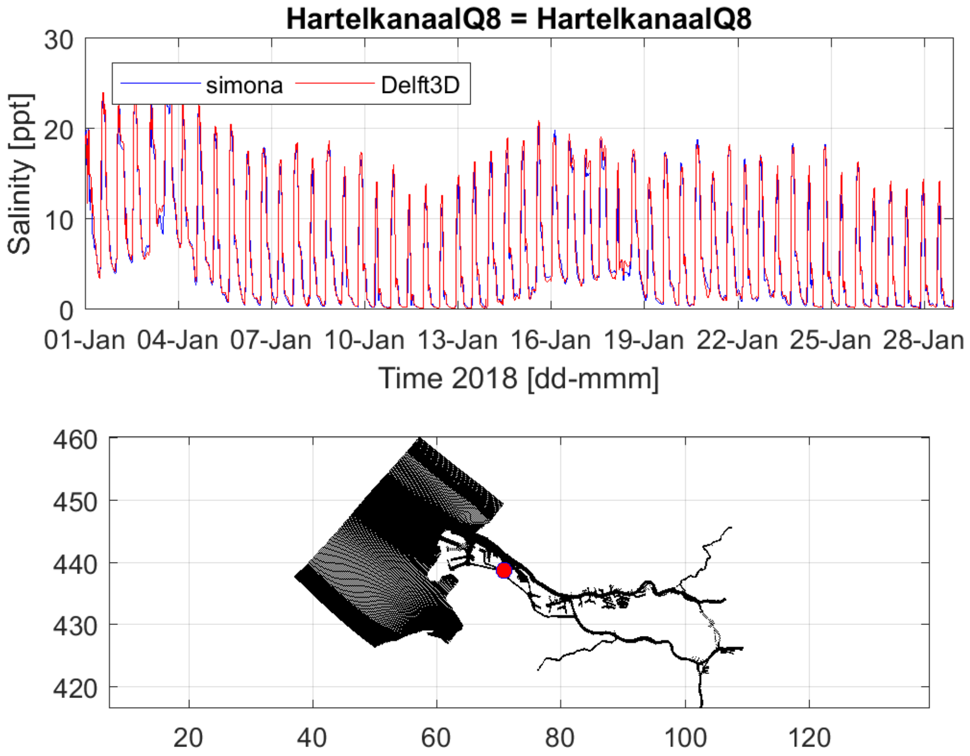


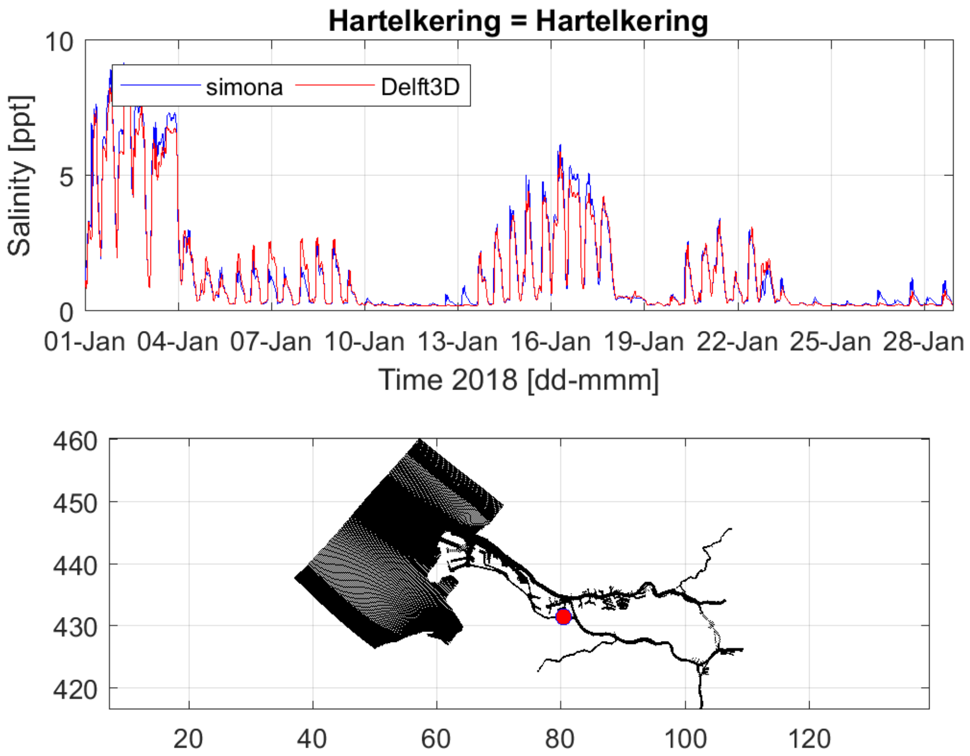


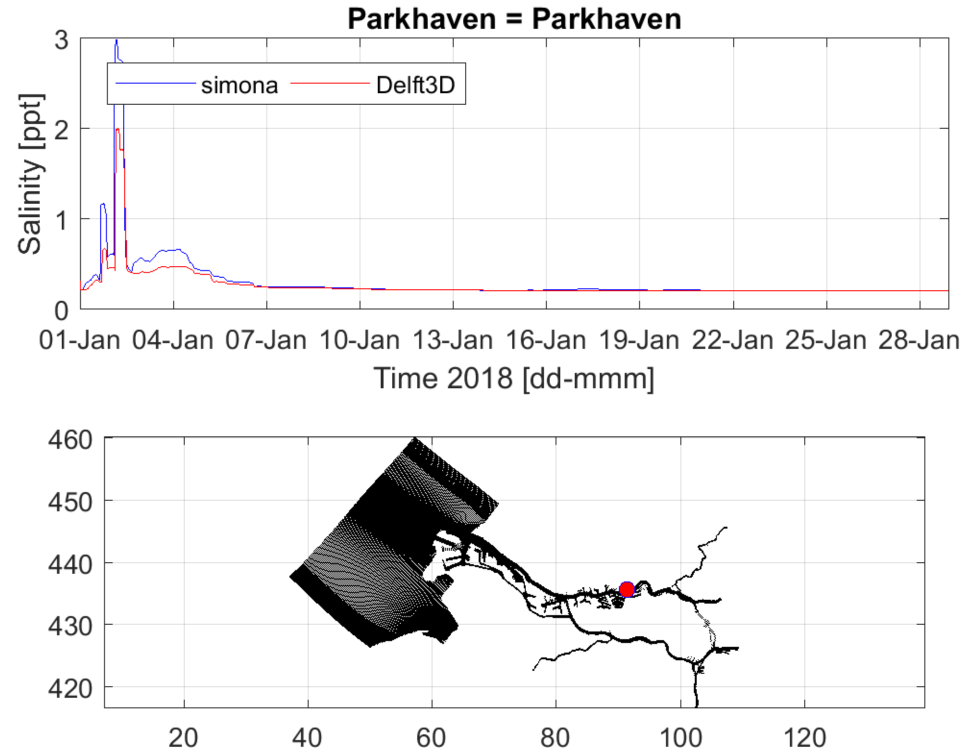


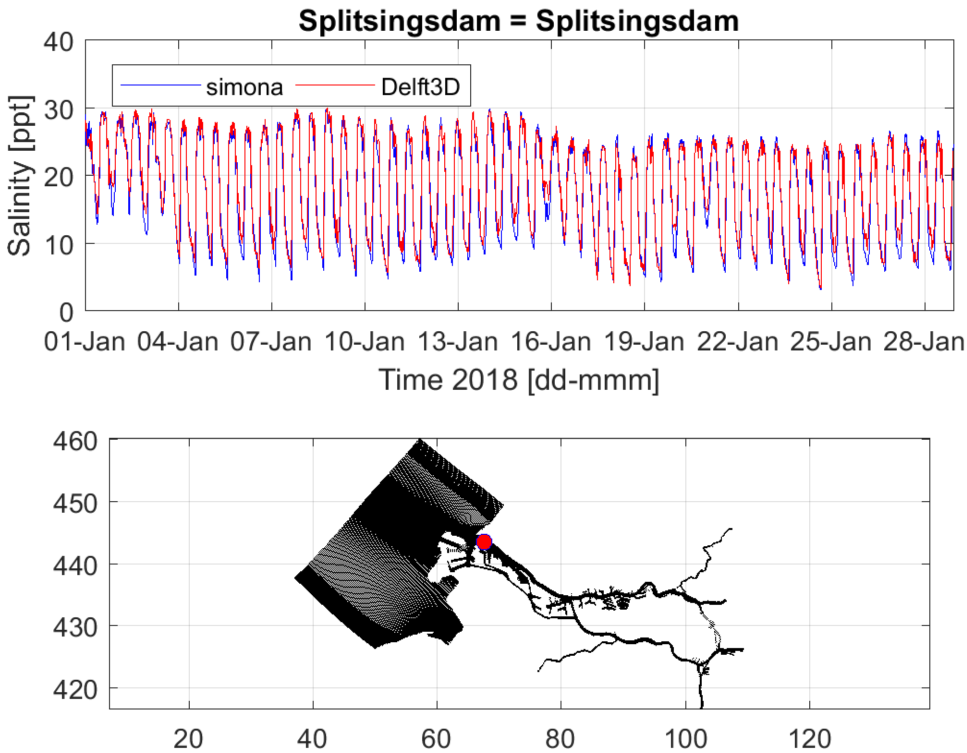

Botlekbrug 37m = Botlekbrug 37m
simona
Delft3D
Salinity [ppt]
20
15
10
5
0
01-Jan
04-Jan
07-Jan
10-Jan
13-Jan
16-Jan
19-Jan
22-Jan
25-Jan
28-Jan
Time 2018 [dd-mmm]
460
450
440
430
420
20
40
60
80
100
120

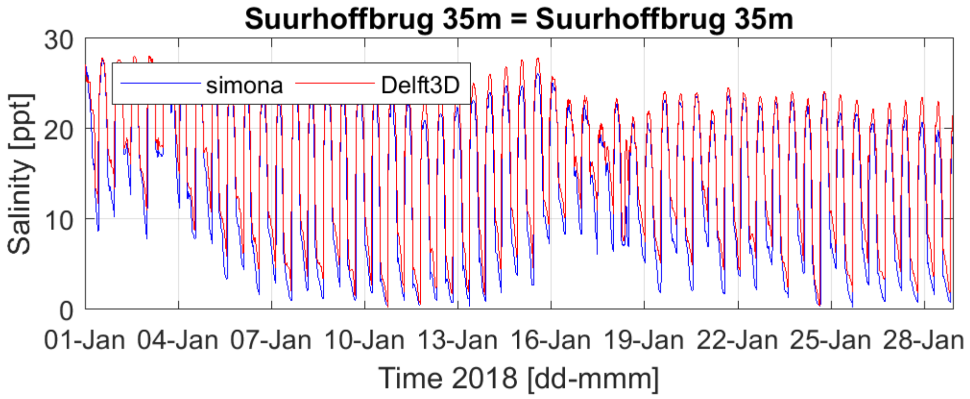

Hartelbrug = Hartelbrug
simona
Delft3D
Salinity [ppt]
10
5
0
01-Jan
04-Jan
07-Jan
10-Jan
13-Jan
16-Jan
19-Jan
22-Jan
25-Jan
28-Jan
Time 2018 [dd-mmm]
460
450
440
430
420
20
40
60
80
100
120

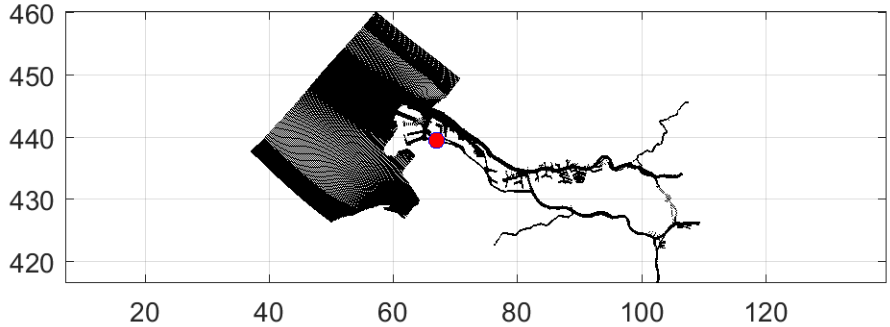

HartelkanaalQ8 = HartelkanaalQ8
simona
Delft3D
Salinity [ppt]
30
20
10
0
01-Jan 04-Jan 07-Jan 10-Jan 13-Jan 16-Jan 19-Jan 22-Jan 25-Jan 28-Jan
Time 2018 [dd-mmm]
460
450
440
430
420
20 40 60 80 100 120

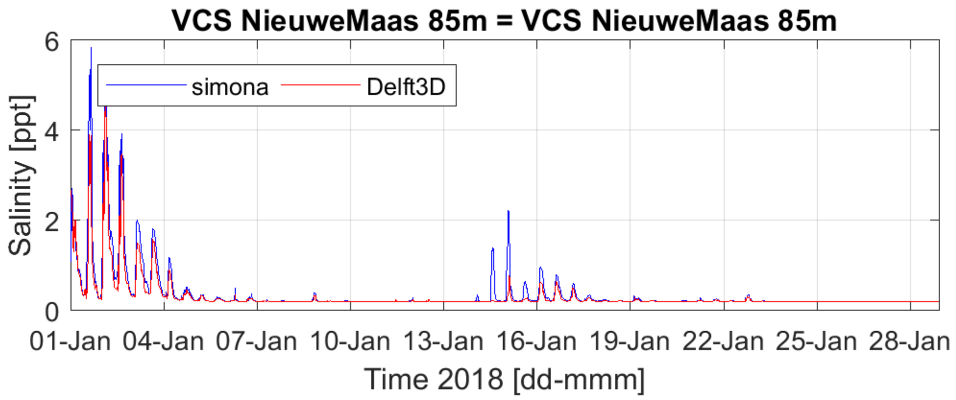

Hartelkering = Hartelkering
simona
Delft3D
Salinity [ppt]
10
5
0
01-Jan 04-Jan 07-Jan 10-Jan 13-Jan 16-Jan 19-Jan 22-Jan 25-Jan 28-Jan
Time 2018 [dd-mmm]
460
450
440
430
420
20 40 60 80 100 120

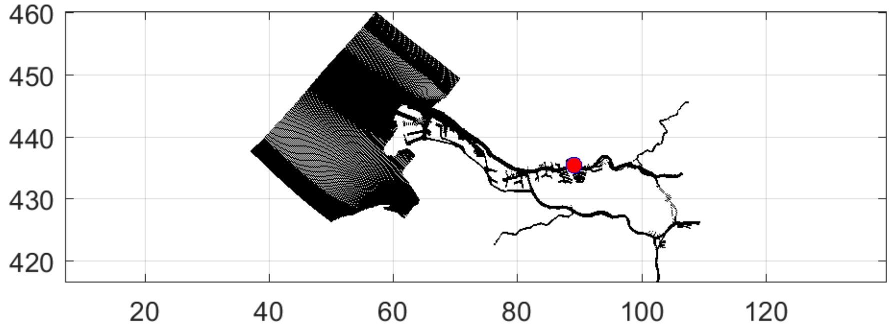

Parkhaven = Parkhaven
simona
Delft3D
Salinity [ppt]
0
1
2
3
01-Jan 04-Jan 07-Jan 10-Jan 13-Jan 16-Jan 19-Jan 22-Jan 25-Jan 28-Jan
Time 2018 [dd-mmm]
460
450
440
430
420
20
40
60
80
100
120


Splitsingsdam = Splitsingsdam
simona
Delft3D
Salinity [ppt]
0
10
20
30
40
01-Jan 04-Jan 07-Jan 10-Jan 13-Jan 16-Jan 19-Jan 22-Jan 25-Jan 28-Jan
Time 2018 [dd-mmm]
460
450
440
430
420
20
40
60
80
100
120

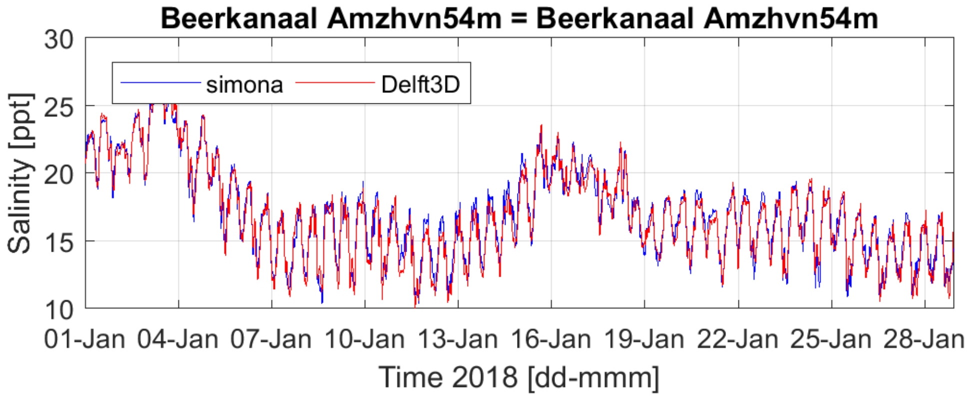

Suurhoffbrug 35m = Suurhoffbrug 35m
simona
Delft3D
Salinity [ppt]
30
20
10
0
01-Jan 04-Jan 07-Jan 10-Jan 13-Jan 16-Jan 19-Jan 22-Jan 25-Jan 28-Jan
Time 2018 [dd-mmm]

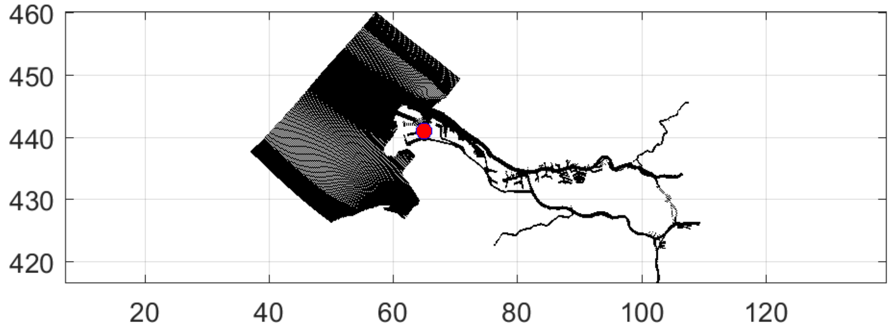

460
450
440
430
420
20
40
60
80
100
120

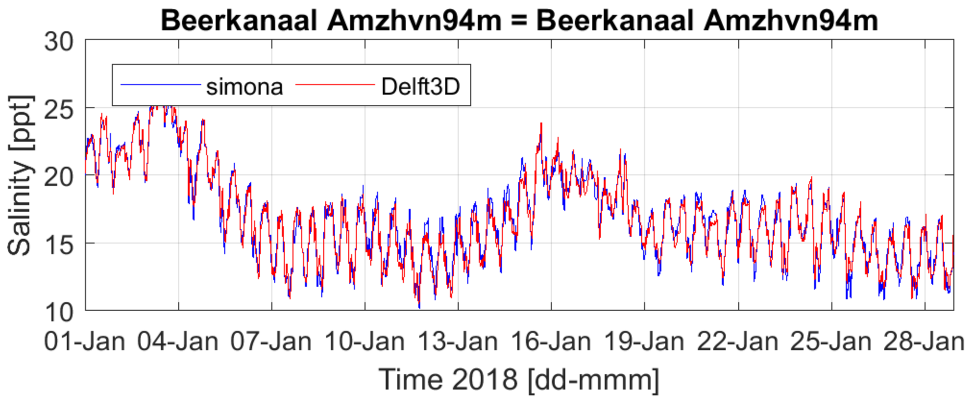

VCS NieuweMaas 85m = VCS NieuweMaas 85m
simona
Delft3D
Salinity [ppt]
6
4
2
0
01-Jan 04-Jan 07-Jan 10-Jan 13-Jan 16-Jan 19-Jan 22-Jan 25-Jan 28-Jan
Time 2018 [dd-mmm]

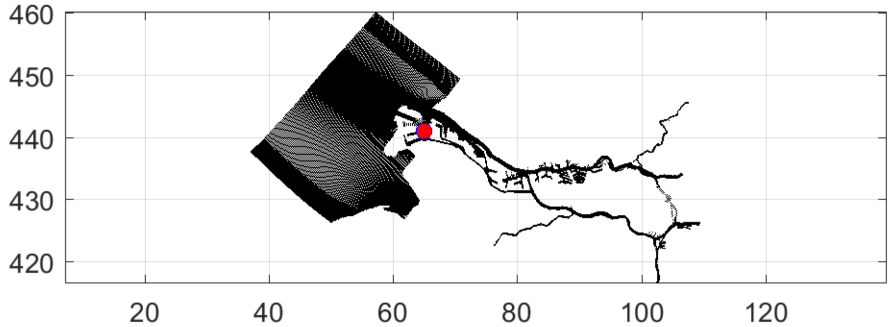

460
450
440
430
420
20
40
60
80
100
120

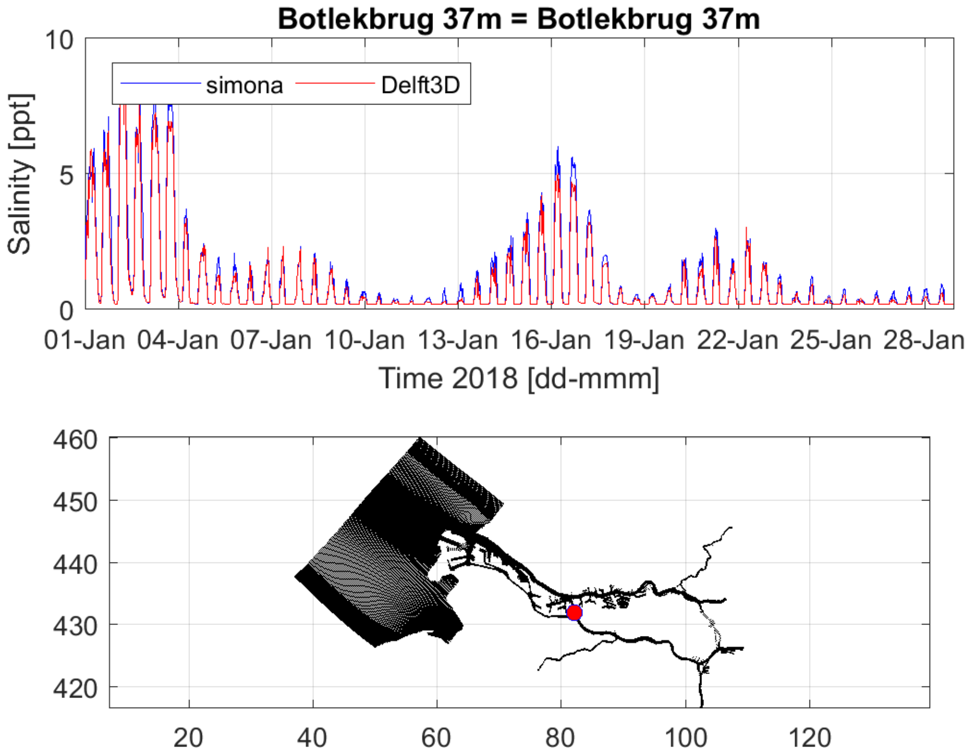
A.2.3 Comparison salinity concentrations (bottom)

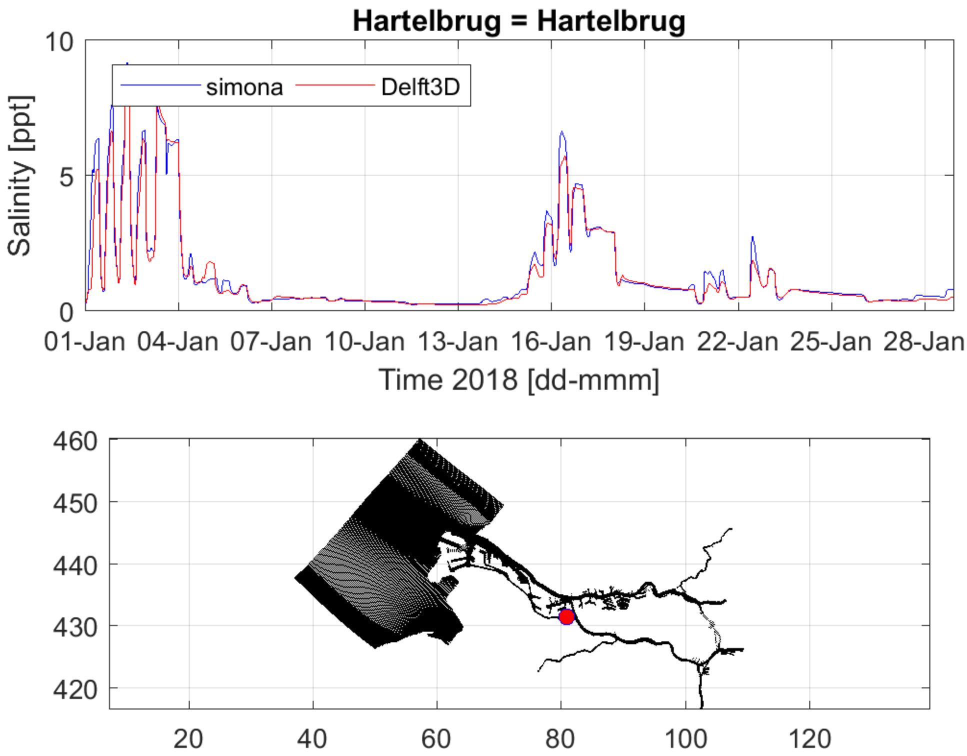


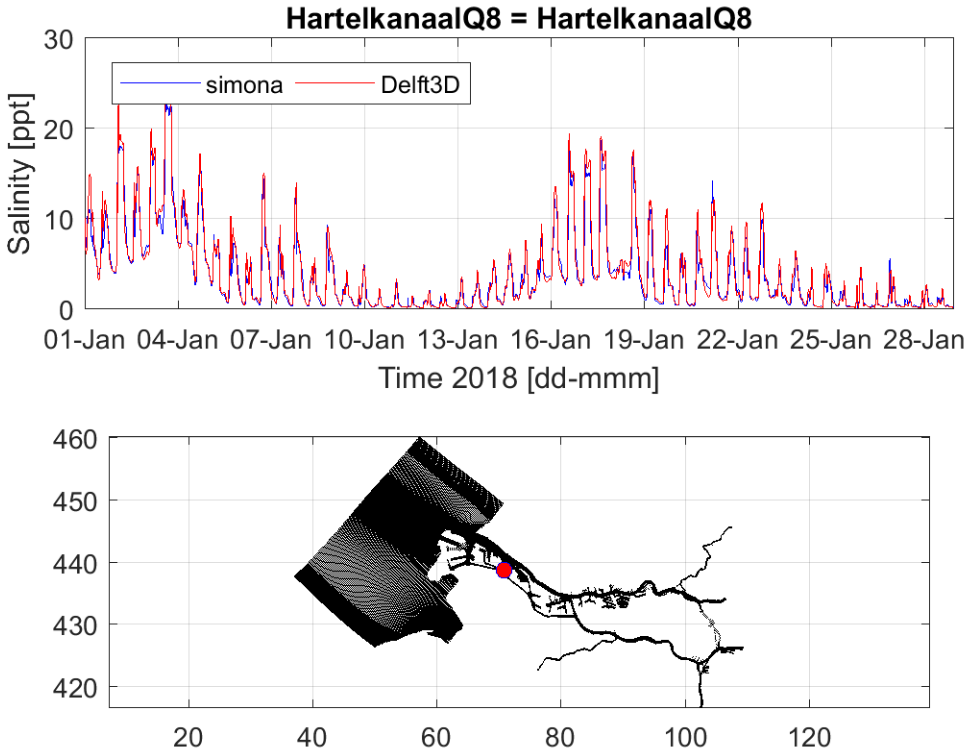


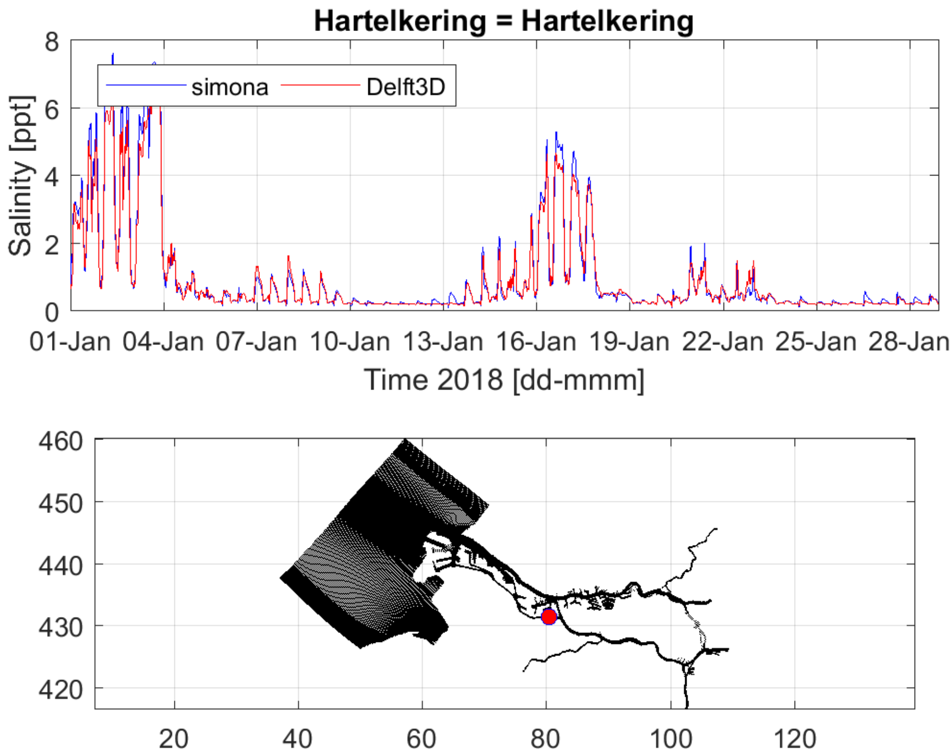


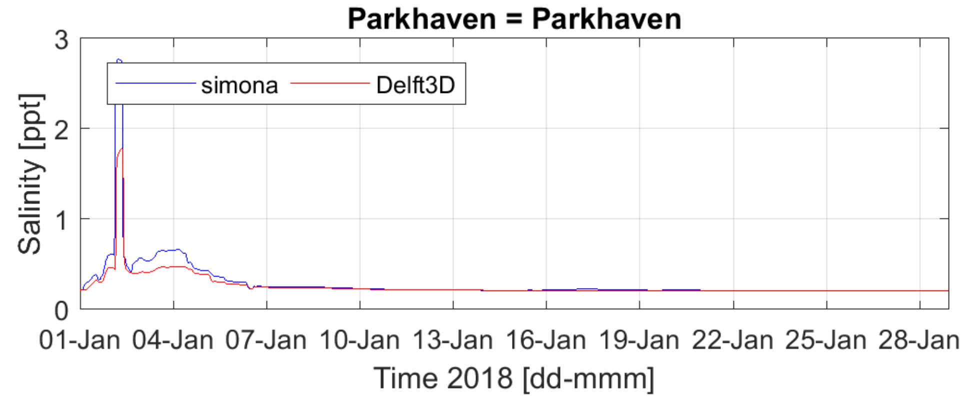


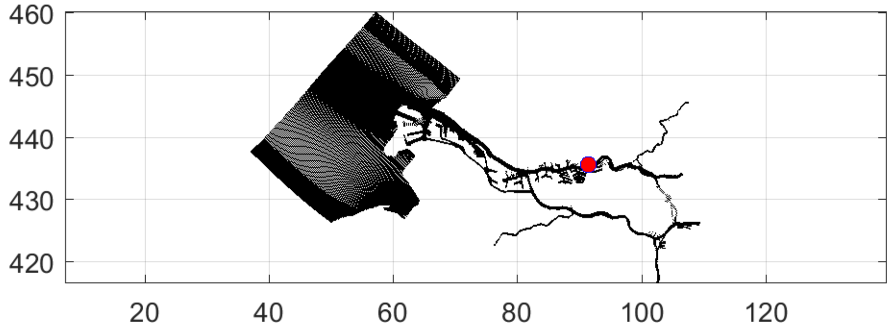

Botlekbrug 37m = Botlekbrug 37m
simona
Delft3D
Salinity [ppt]
Time 2018 [dd-mmm]
01-Jan 04-Jan 07-Jan 10-Jan 13-Jan 16-Jan 19-Jan 22-Jan 25-Jan 28-Jan

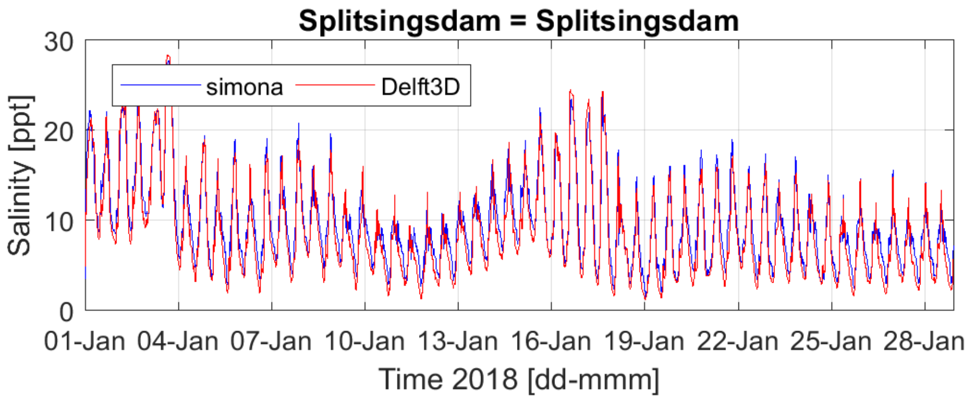

Hartelbrug = Hartelbrug
simona
Delft3D
Salinity [ppt]
Time 2018 [dd-mmm]
01-Jan 04-Jan 07-Jan 10-Jan 13-Jan 16-Jan 19-Jan 22-Jan 25-Jan 28-Jan

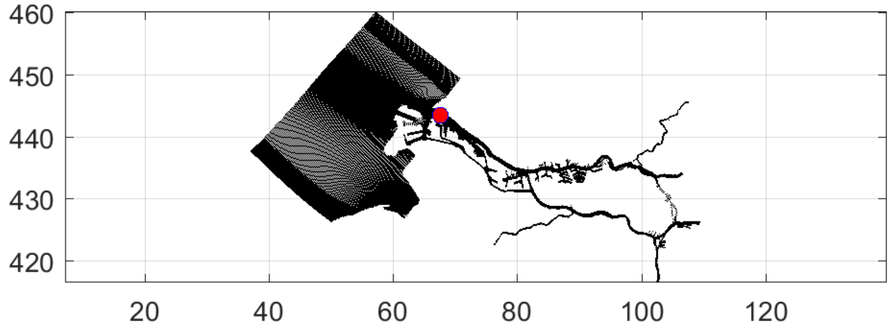

HartelkanaalQ8 = HartelkanaalQ8
simona
Delft3D
Salinity [ppt]
30
20
10
0
01-Jan 04-Jan 07-Jan 10-Jan 13-Jan 16-Jan 19-Jan 22-Jan 25-Jan 28-Jan
Time 2018 [dd-mmm]
460
450
440
430
420
20 40 60 80 100 120

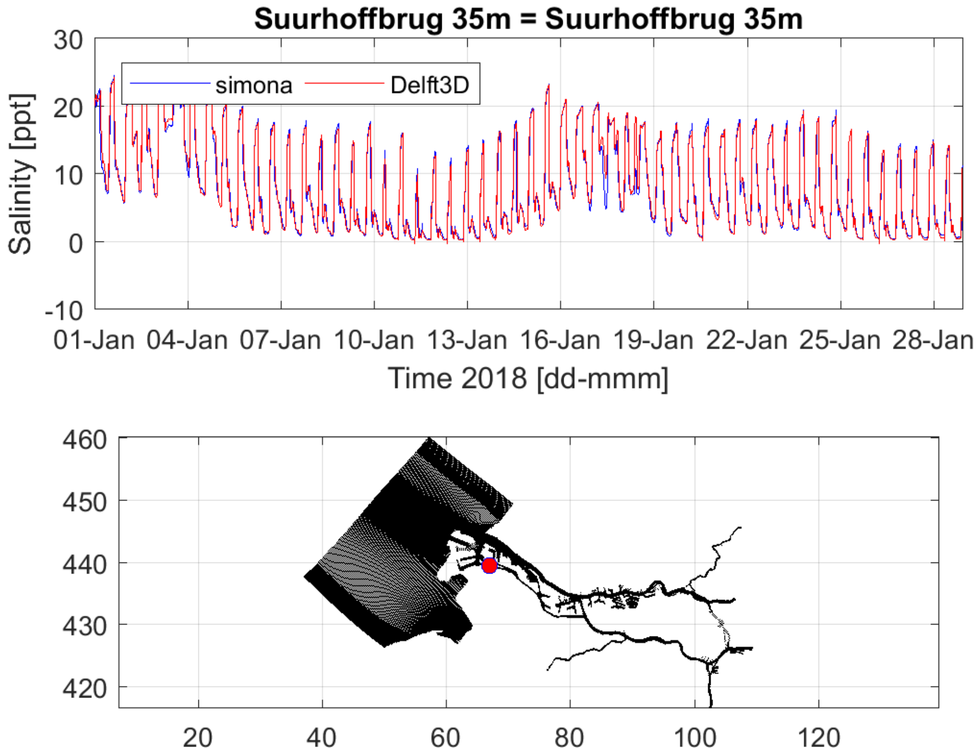

Hartelkering = Hartelkering
simona
Delft3D
Salinity [ppt]
8
6
4
2
0
01-Jan 04-Jan 07-Jan 10-Jan 13-Jan 16-Jan 19-Jan 22-Jan 25-Jan 28-Jan
Time 2018 [dd-mmm]
460
450
440
430
420
20 40 60 80 100 120

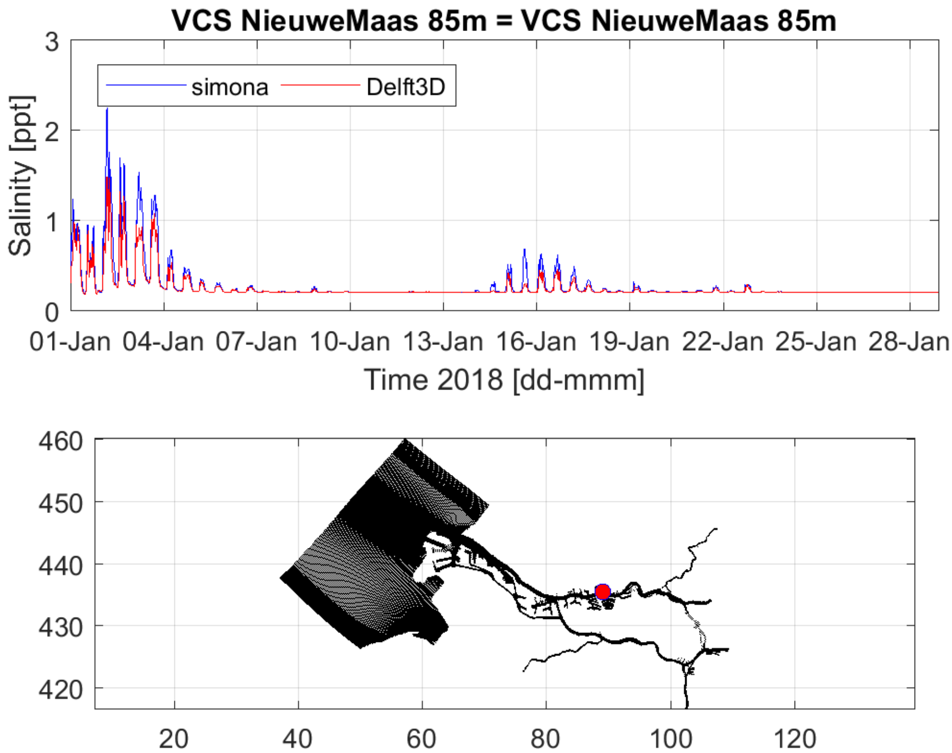

Parkhaven = Parkhaven
simona
Delft3D
Salinity [ppt]
0
1
2
3
01-Jan 04-Jan 07-Jan 10-Jan 13-Jan 16-Jan 19-Jan 22-Jan 25-Jan 28-Jan
Time 2018 [dd-mmm]


460
450
440
430
420
20
40
60
80
100
120


Splitsingsdam = Splitsingsdam
simona
Delft3D
Salinity [ppt]
0
10
20
30
01-Jan 04-Jan 07-Jan 10-Jan 13-Jan 16-Jan 19-Jan 22-Jan 25-Jan 28-Jan
Time 2018 [dd-mmm]


460
450
440
430
420
20
40
60
80
100
120


Suurhoffbrug 35m = Suurhoffbrug 35m
simona
Delft3D
Salinity [ppt]
30
20
10
0
-10
01-Jan 04-Jan 07-Jan 10-Jan 13-Jan 16-Jan 19-Jan 22-Jan 25-Jan 28-Jan
Time 2018 [dd-mmm]
460
450
440
430
420
20 40 60 80 100 120

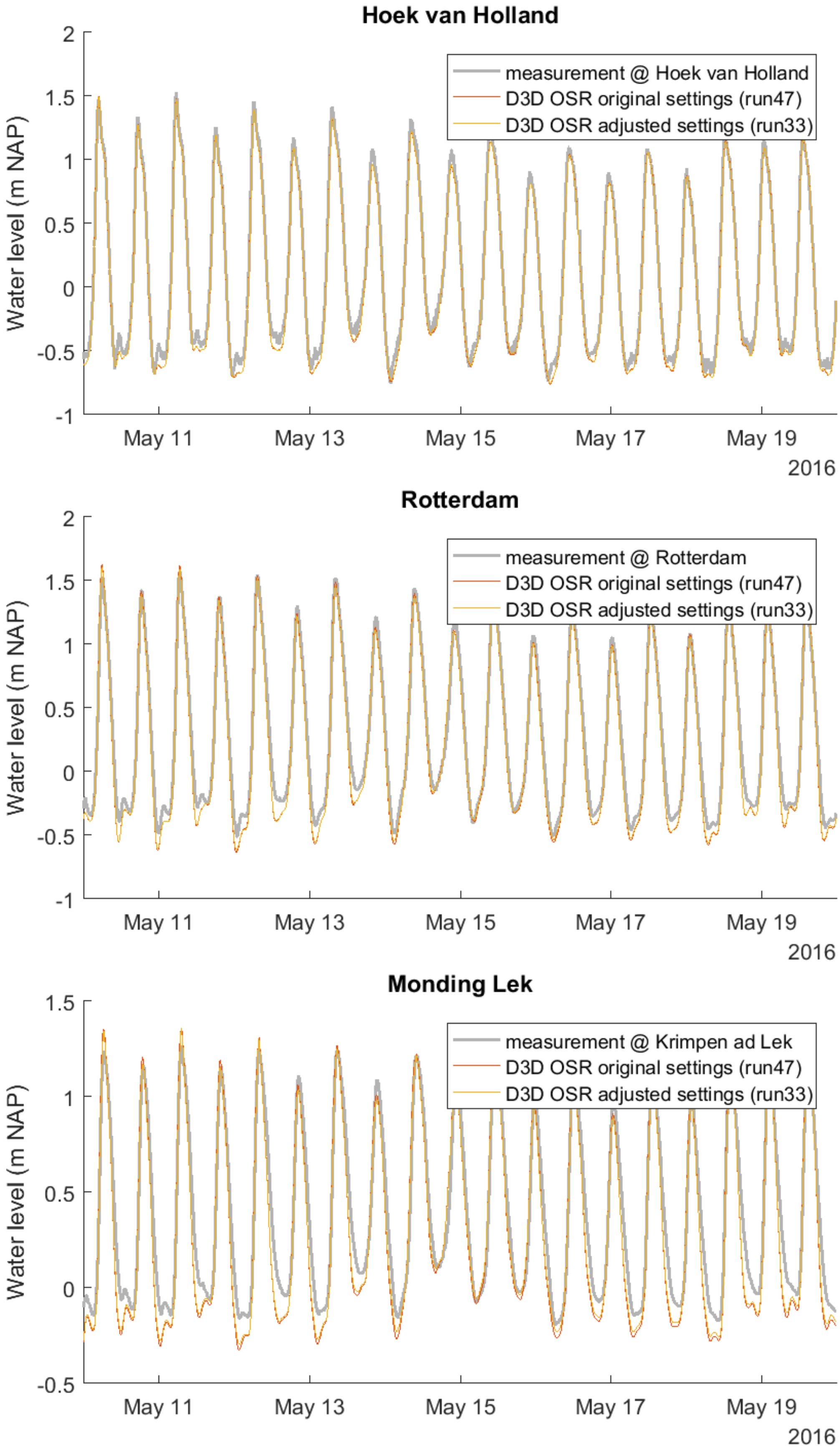

VCS NieuweMaas 85m = VCS NieuweMaas 85m
simona
Delft3D
Salinity [ppt]
3
2
1
0
01-Jan 04-Jan 07-Jan 10-Jan 13-Jan 16-Jan 19-Jan 22-Jan 25-Jan 28-Jan
Time 2018 [dd-mmm]
460
450
440
430
420
20 40 60 80 100 120

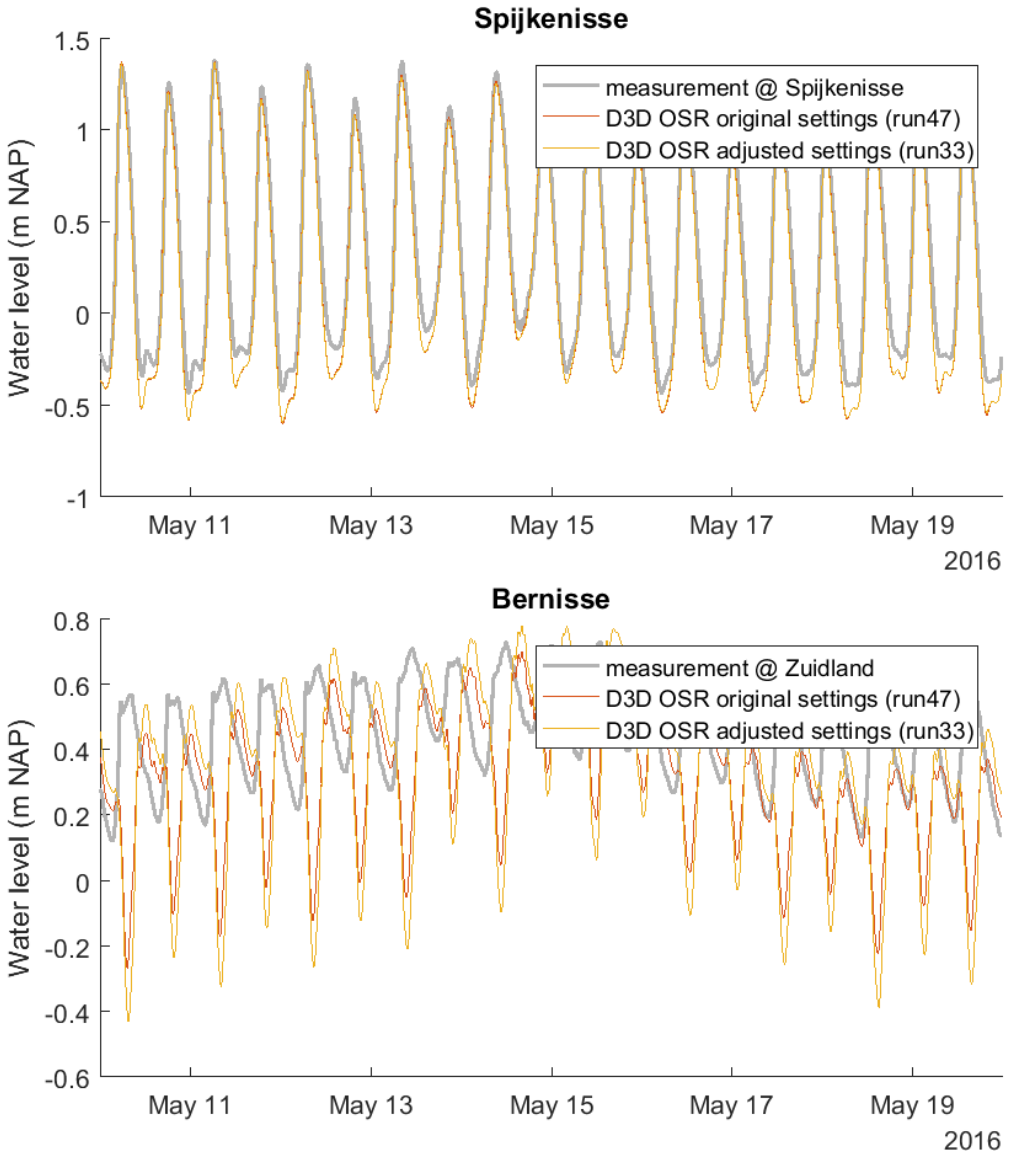
A.3 Validation with measurements

Below the hydrodynamic model is compared to measurements on water level and salinity. Two versions are validated, the model version with original settings for diffusivity, viscosity and depth interpolation and with adjusted settings, see overview in A.1.2 and explanation in section 2.2.5.

A.3.1 Water levels

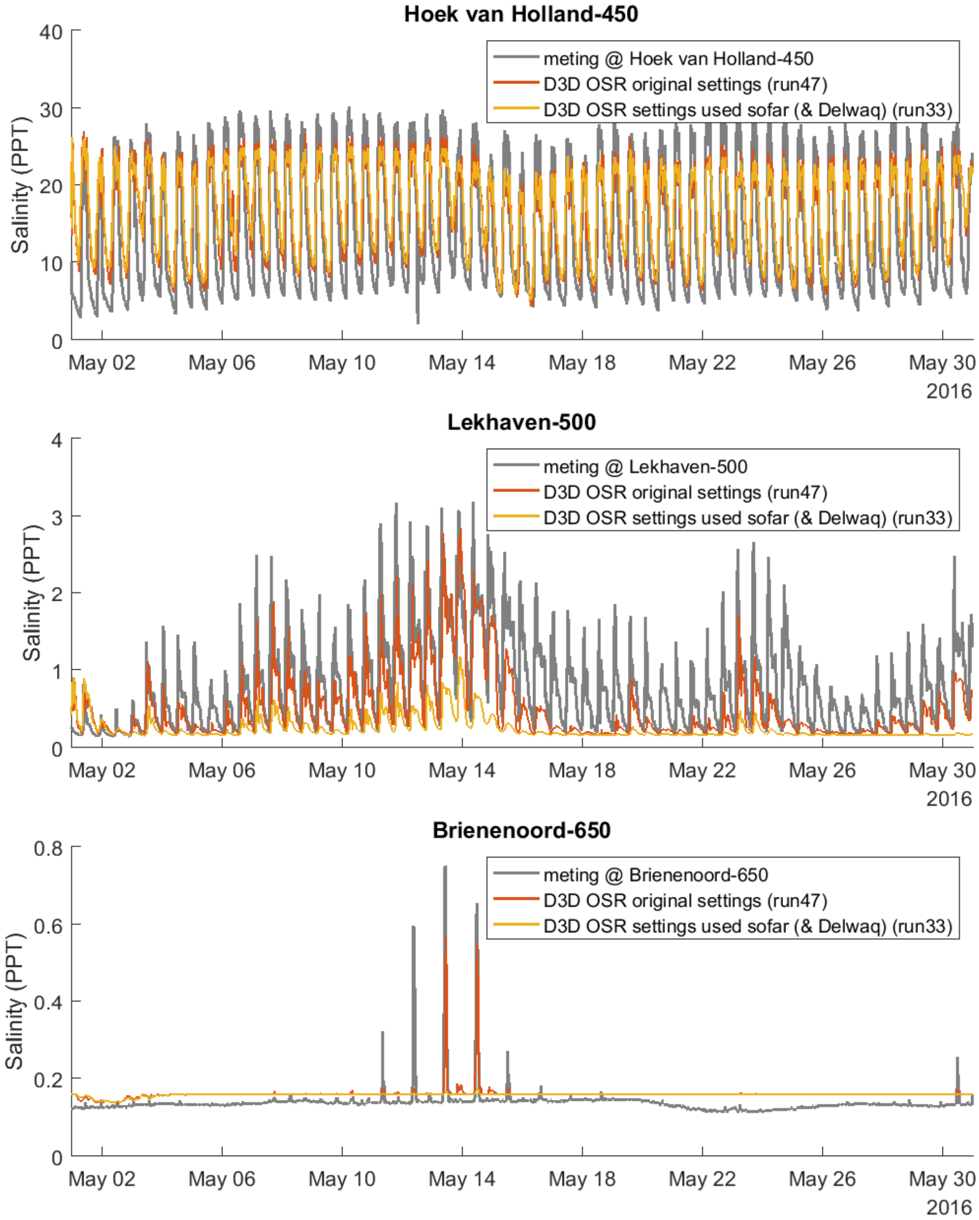
Figure A.1 Map with an overview of the RWS water level measurement stations (map taken from www.waterinfo.nl). In red the stations evaluated in this section are given.

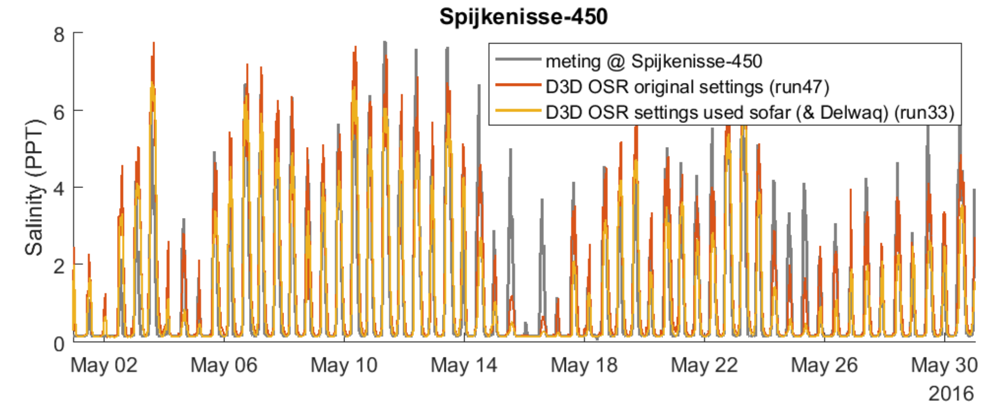

Hoek van Holland
measurement @ Hoek van Holland
D3D OSR original settings (run47)
D3D OSR adjusted settings (run33)
Water level (m NAP)
2
1.5
1
0.5
0
-0.5
-1
May 11
May 13
May 15
May 17
May 19
2016
Rotterdam
measurement @ Rotterdam
D3D OSR original settings (run47)
D3D OSR adjusted settings (run33)
Water level (m NAP)
2
1.5
1
0.5
0
-0.5
-1
May 11
May 13
May 15
May 17
May 19
2016
Monding Lek
measurement @ Krimpen ad Lek
D3D OSR original settings (run47)
D3D OSR adjusted settings (run33)
Water level (m NAP)
1.5
1
0.5
0
-0.5
May 11
May 13
May 15
May 17
May 19
2016

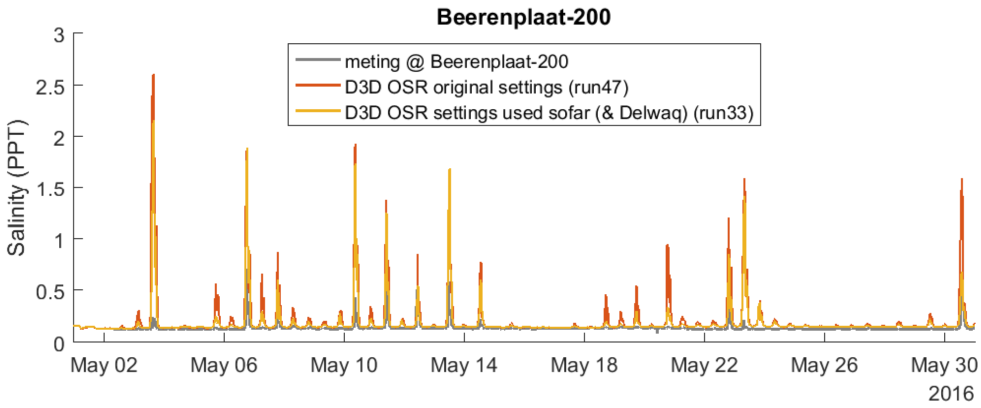


A.3.2 Chloride concentrations

Figure A.2 Map with an overview of the RWS measurement stations for salinity (map taken from www.waterinfo.nl). In red the stations evaluated in this section are given.


Hoek van Holland-450
Salinity (PPT)
meting @ Hoek van Holland-450
D3D OSR original settings (run47)
D3D OSR settings used sofar (& Delwaq) (run33)
May 02
May 06
May 10
May 14
May 18
May 22
May 26
May 30
2016
Lekhaven-500
meting @ Lekhaven-500
Brienenoord-650
meting @ Brienenoord-650


Spijkenisse-450
meting @ Spijkenisse-450
D3D OSR original settings (run47)
D3D OSR settings used sofar (& Delwaq) (run33)
Salinity (PPT)
0
2
4
6
8
May 02
May 06
May 10
May 14
May 18
May 22
May 26
May 30
2016


Beerenplaat-200
meting @ Beerenplaat-200
D3D OSR original settings (run47)
D3D OSR settings used sofar (& Delwaq) (run33)
Salinity (PPT)
0
0.5
1
1.5
2
2.5
3
May 02
May 06
May 10
May 14
May 18
May 22
May 26
May 30
2016

A.4 Salinity concentrations in the Haringvliet eb-tidal delta

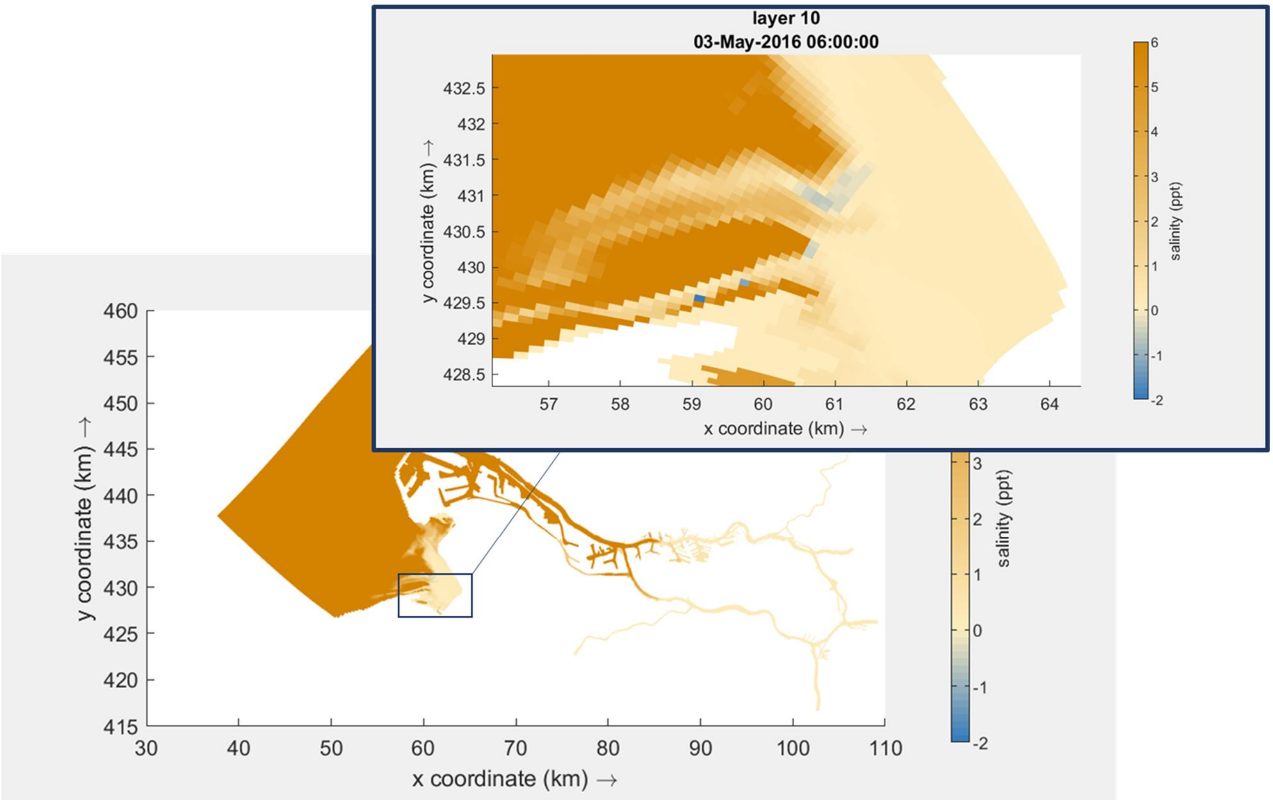


Figure A.3 Visualization of negative salinity concentrations occurring in the Haringvliet ebb-tidal delta.

B Details on the sediment model

B.1 Sediment settings long term model (Delft3D)

All settings for sediment are listed in the .mor and .sed files. For a complete overview of all settings used, below copies of those files are given.

B.1.1 Sediment settings test simulations

Settings that had different values for different simulations are displayed in green.

<u>Settings from the .mor file:</u>

[Morphology]			
EpsPar	= false		Vertical mixing distribution according to van Rijn (overrules k-epsilon model)
IopKCW	= 1		Flag for determining Rc and Rw
RDC	= 0.01	[m]	Current related roughness height (only used if IopKCW <> 1)
RDW	= 0.02	[m]	Wave related roughness height (only used if IopKCW <> 1)
MorFac	= 1.0000000e+000	[-]	Morphological scale factor
MorStt	= 7.2000000e+002	[min]	Spin-up interval from TStart till start of morphological changes
Thresh	= 5.0000001e-002	[m]	Threshold sediment thickness for transport and erosion reduction
MorUpd	= false		Update bathymetry during FLOW simulation
EqmBc	= true		Equilibrium sand concentration profile at inflow boundaries
DensIn	= true/false		Include effect of sediment concentration on fluid density
AksFac	= 1.0000000e+000	[-]	van Rijn's reference height = AKSFAC * KS
RWave	= 2.0000000e+000	[-]	Wave related roughness = RWAVE * estimated ripple height.
AlfaBs	= 1.0000000e+000	[-]	Streamwise bed gradient factor for bed load transport
AlfaBn	= 1.5000000e+000	[-]	Transverse bed gradient factor for bed load transport
Sus	= 1.0000000e+000	[-]	Multiplication factor for suspended sediment reference concentration
Bed	= 1.0000000e+000	[-]	Multiplication factor for bed-load transport vector magnitude
SusW	= 1.0000000e+000	[-]	Wave-related suspended sed. transport factor
BedW	= 1.0000000e+000	[-]	Wave-related bed-load sed. transport factor
SedThr	= 1.0000000e-001	[m]	Minimum water depth for sediment computations
ThetSD	= 0.0000000e+000	[-]	Factor for erosion of adjacent dry cells
HMaxTH	= 1.5000000e+000	[m]	Max depth for variable THETSD.
FWFac	= 1.0000000e+000	[-]	Vertical mixing distribution according to van Rijn
[Underlayer]			
IUnderLyr	= 1	[-]	Flag for underlayer concept 1 = one well mixed layer 2 = multiple layers
ExchLyr	= false	[T/F]	Switch for exchange layer
TTLForm	= 1	[-]	Transport layer thickness formulation
ThTrLyr	= 0.05	[m]	Thickness of the transport layer
MxNULyr	= 20	[-]	Number of underlayers (excluding final well mixed layer)
ThUnLyr	= 0.01	[m]	Thickness of each underlayer (dummy when IUnderLyr = 1)
[FluffLayer]			
Type	= 1	[1/2]	Flag for fluff layer concept 1 = all mud to fluff
BurFluff0	= 1e-4	[kg/m2/s]	Burial rate (dummy when Type = 2)
BurFluff1	= 1e-5	[kg/m2/s]	Burial rate (dummy when Type = 2)
DepFac	= 0	[-]	Alpha = Fraction of mud to underlayer (1-DepFac) to fluff layer

Settings from the .sed file:

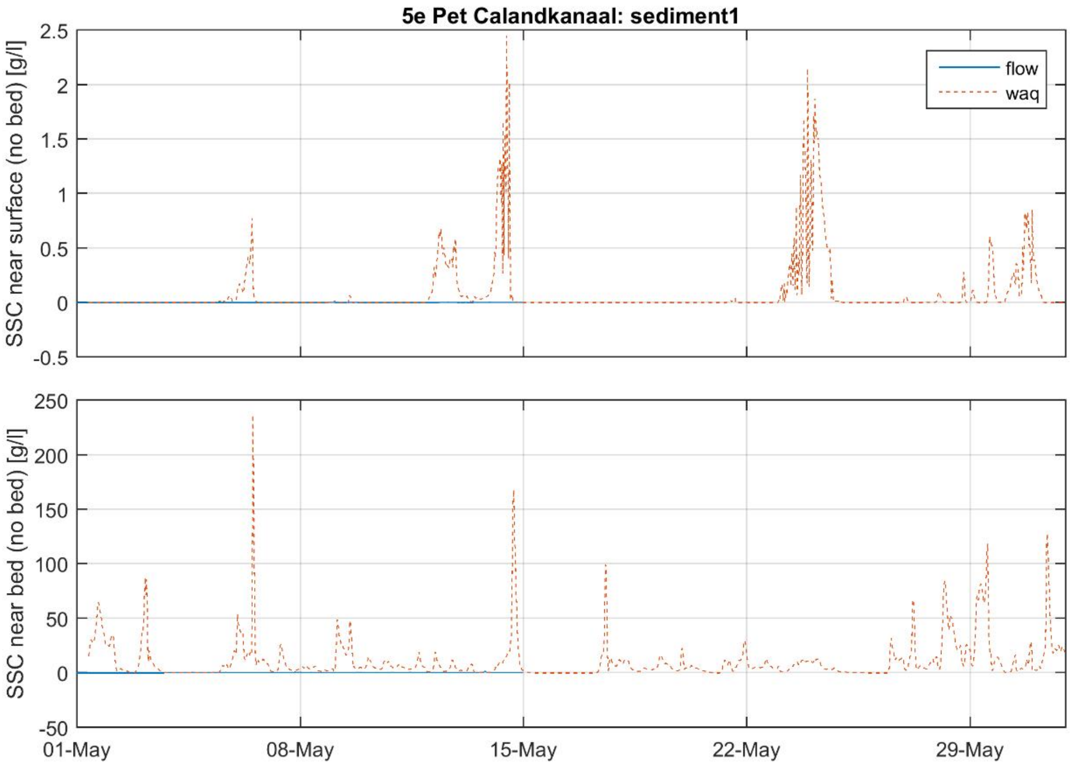
[SedimentOverall]
Cref = 1.0000000e+002 [kg/m3] CSoil Reference density for hindered settling calculations
IopSus = 0 If Iopsus = 1: susp. sediment size depends on local flow and wave conditions
[Sediment]
Name = #Sediment X# Name of sediment fraction
SedTyp = mud Must be "sand", "mud" or "bedload"
RhoSol = 2.6500000e+003 [kg/m3] Specific density
SalMax = 0.0000000e+000 [ppt] Salinity for saline settling velocity
WS0 = 2e-3, 1e-3, 0.5e-3, 0.1e-3, 1e-9 [m/s] Settling velocity fresh water
WSM = 2e-3, 1e-3, 0.5e-3, 0.1e-3, 1e-9 [m/s] Settling velocity saline water
TcrSed = 0.0000000e+000 [N/m2] Critical bed shear stress for sedimentation
TcrEro = 1.0000000e-003 [N/m2] Critical bed shear stress for erosion (uniform value or filename)
EroPar = 1.0000000e-001 [kg/m2/s] Erosion parameter
CDryB = 5.0000000e+002 [kg/m3] Dry bed density
IniSedThick = 0.0000000e+000 [m] Initial sediment layer thickness at bed (uniform value or filename)
FacDSS = 1.0000000e+000 [-] FacDss * SedDia = Initial suspended sediment diameter.
DepEff = 0 or 0.1000000e+000 [-] Beta or ed = Fraction of sediment from water column to bed
ParFluff0 = 1.0000000e-003 [kg/m2/s] Zero-th order erosion parameter
ParFluff1 = 1.0000000e-004 [1/s] First order erosion parameter, used when mass in fluff layer < ParFluff0/ParFluff1
TCrFluff = 2.0000000e-001 [N/m2] Critical bed shear stress for erosion of the fluff layer
IniFluffMass = 0.0000000e+000 [kg/m2] Initial sediment mass in fluff layer (uniform value or filename)

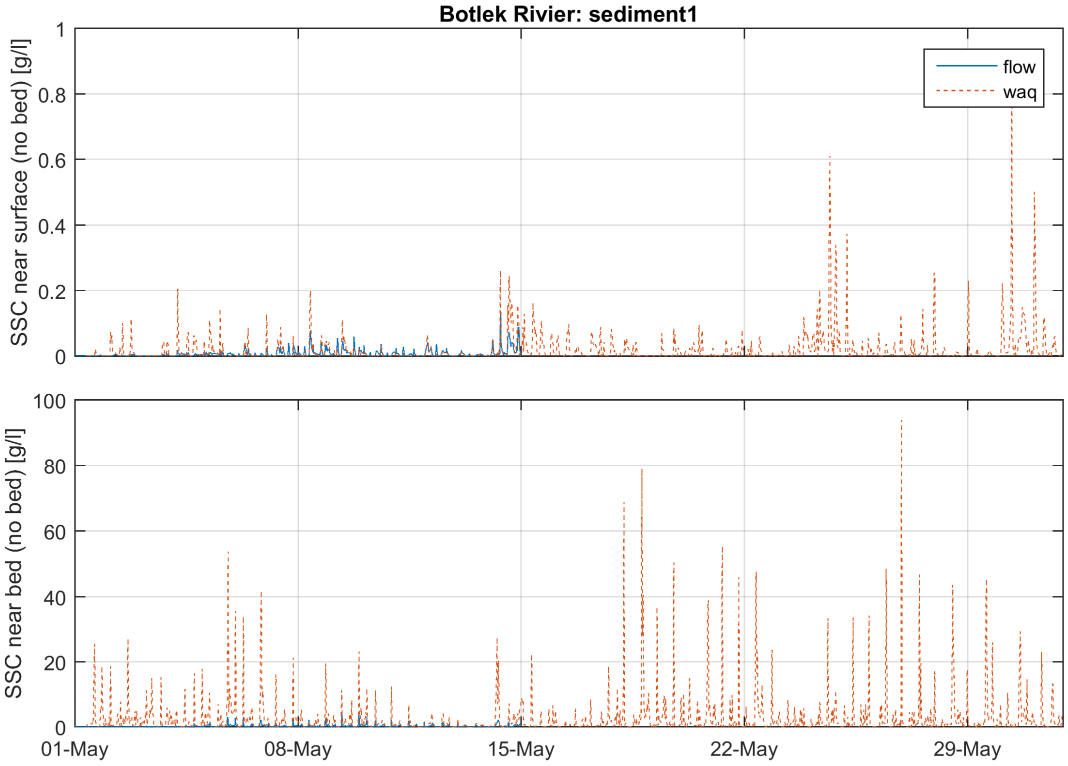
C Additional results

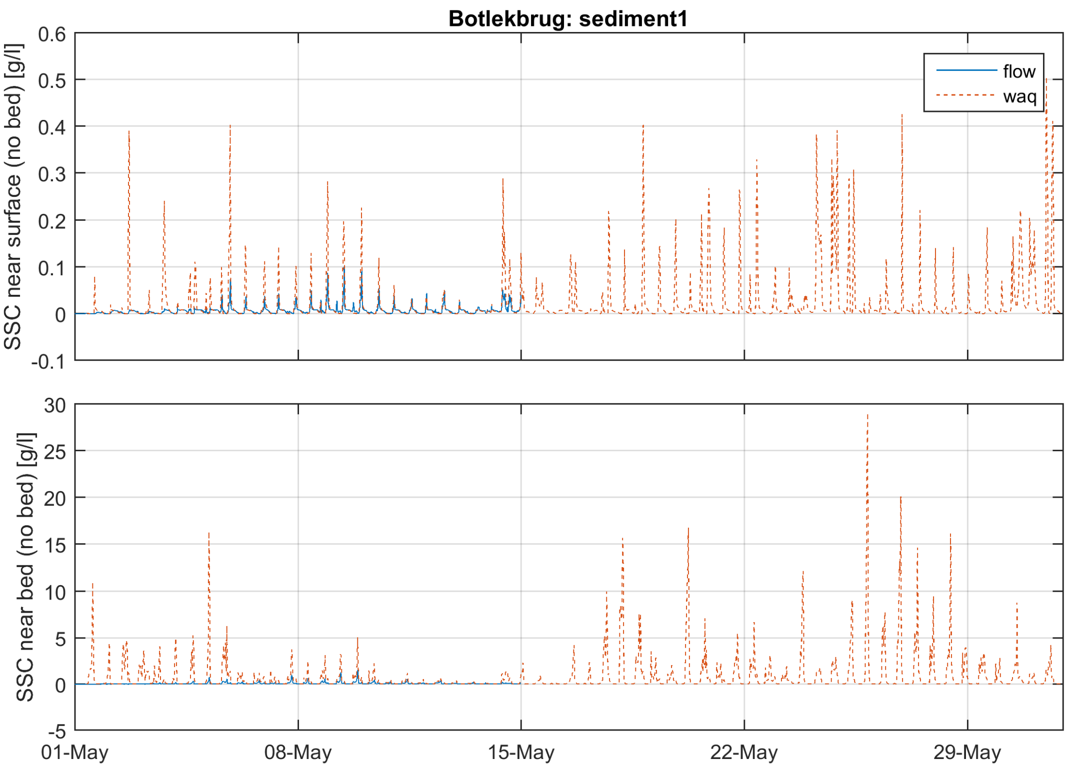
C.1 Comparison of suspended sediment for a simulation without water bed interaction

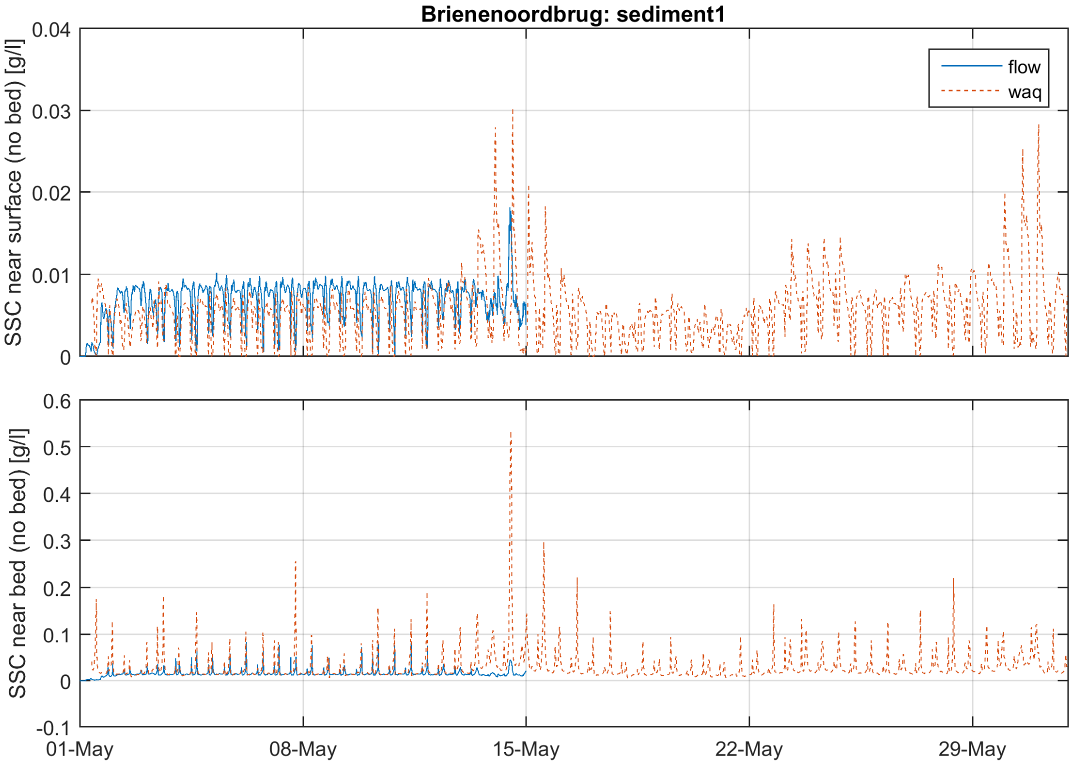
Below the suspended sediment concentrations of Delwaq (WAQ) and Delft3D (FLOW) are compared for the simulation without water bed interaction. The output is grouped per sediment fraction. For an overview of the locations, see Figure 3.1. Note that for Delft3D 2 weeks were computed, while for Delwaq a full month was computed.

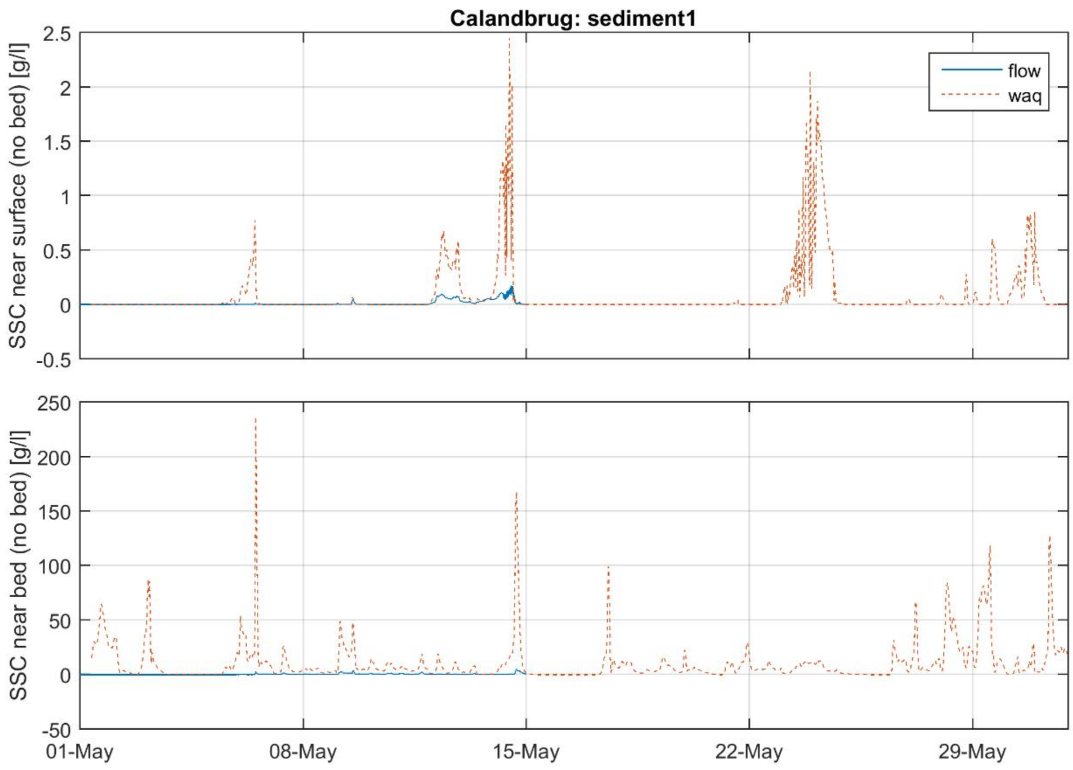
C.1.1 Sediment 1, fall velocity 2 mm/s

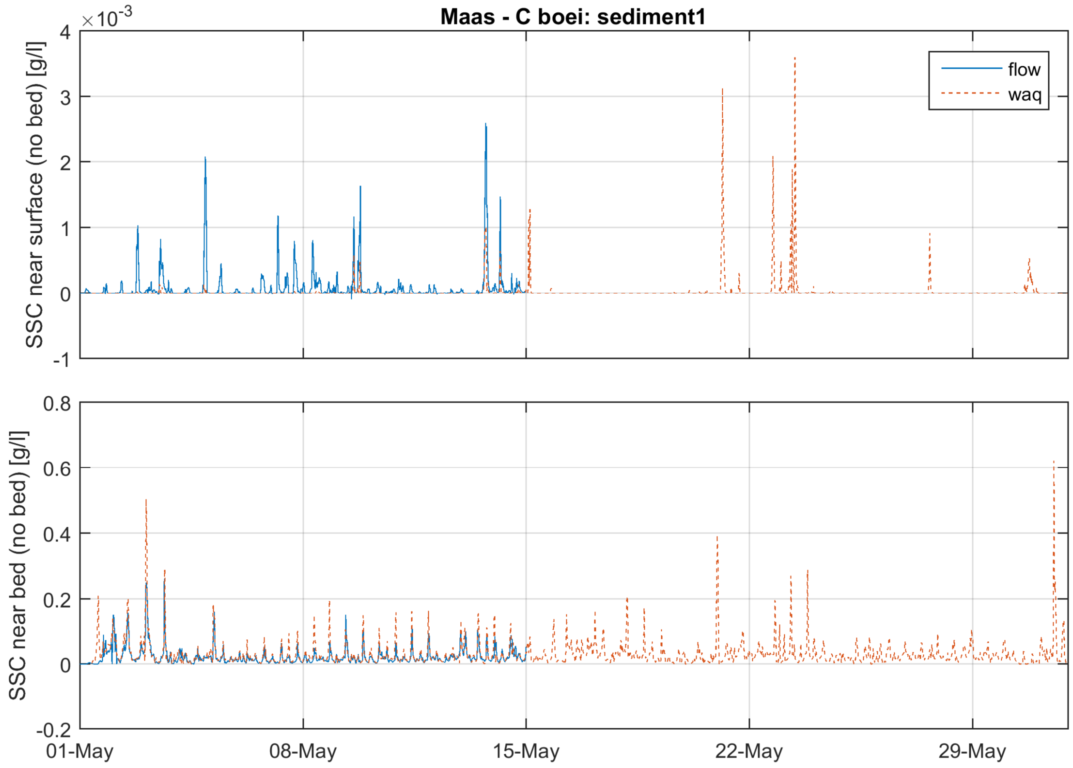


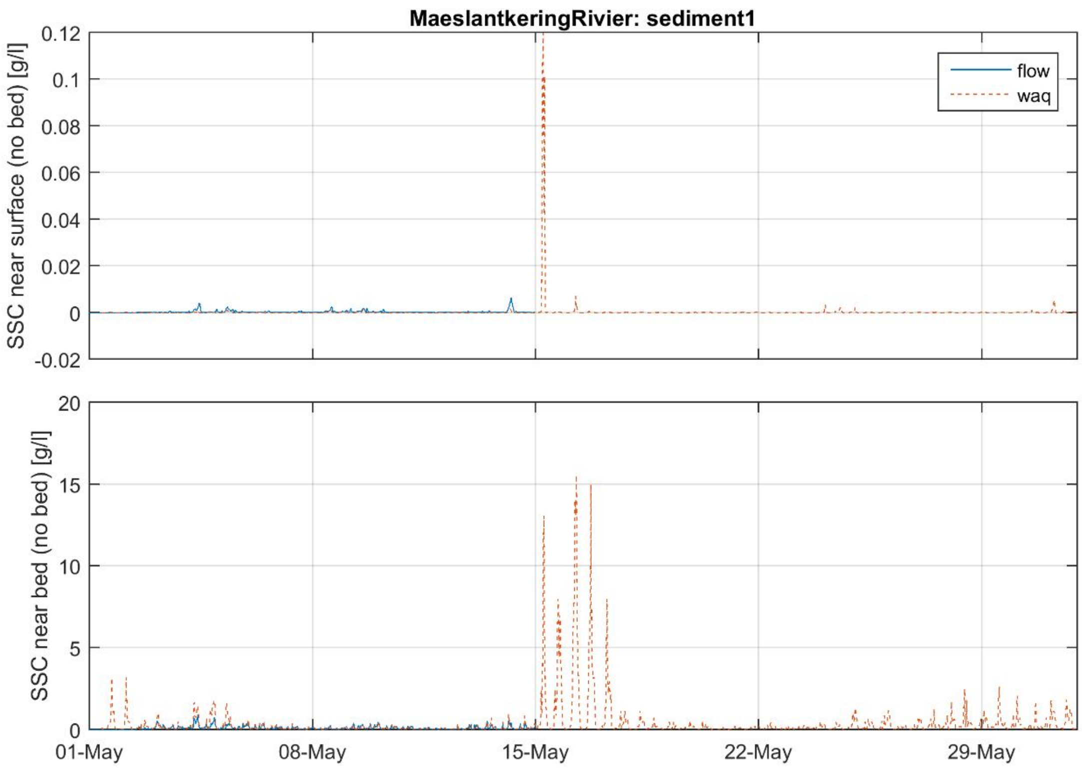

Botlek Rivier: sediment1
SSC near surface (no bed) [g/l]
flow
waq
SSC near bed (no bed) [g/l]
01-May
08-May
15-May
22-May
29-May

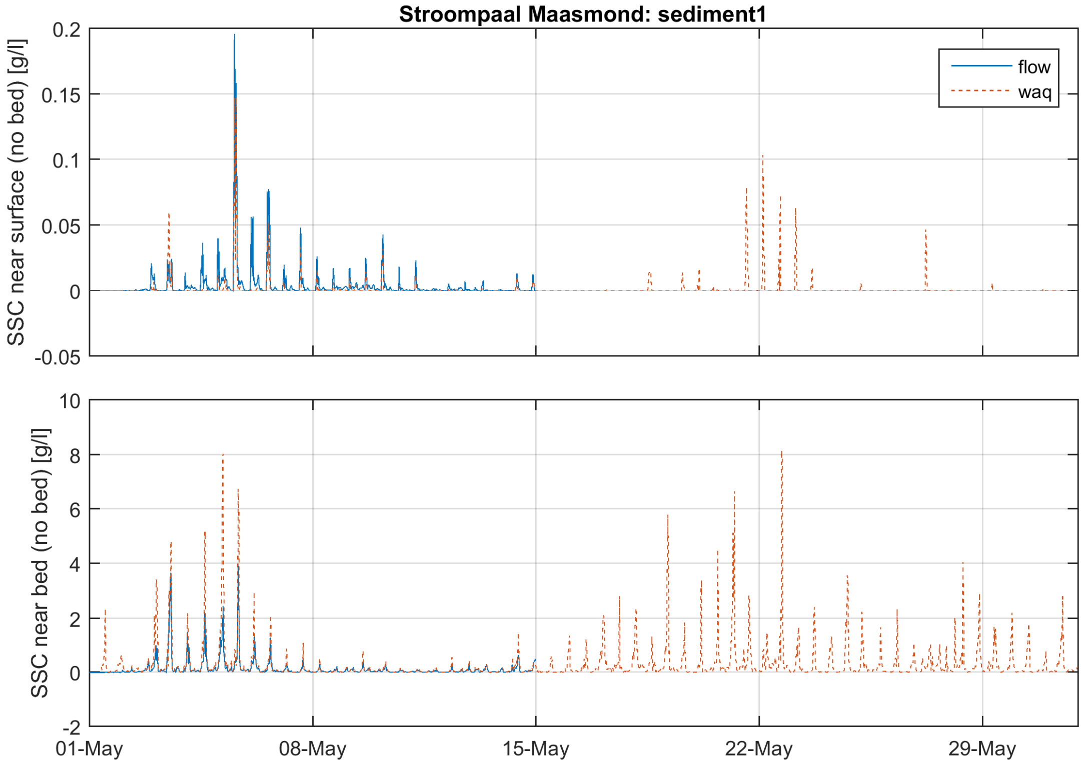

Botlekbrug: sediment1
SSC near surface (no bed) [g/l]
flow
waq
SSC near bed (no bed) [g/l]
01-May
08-May
15-May
22-May
29-May


Brienenoordbrug: sediment1
SSC near surface (no bed) [g/l]
SSC near bed (no bed) [g/l]
flow
waq
0.04
0.03
0.02
0.01
0
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
01-May
08-May
15-May
22-May
29-May

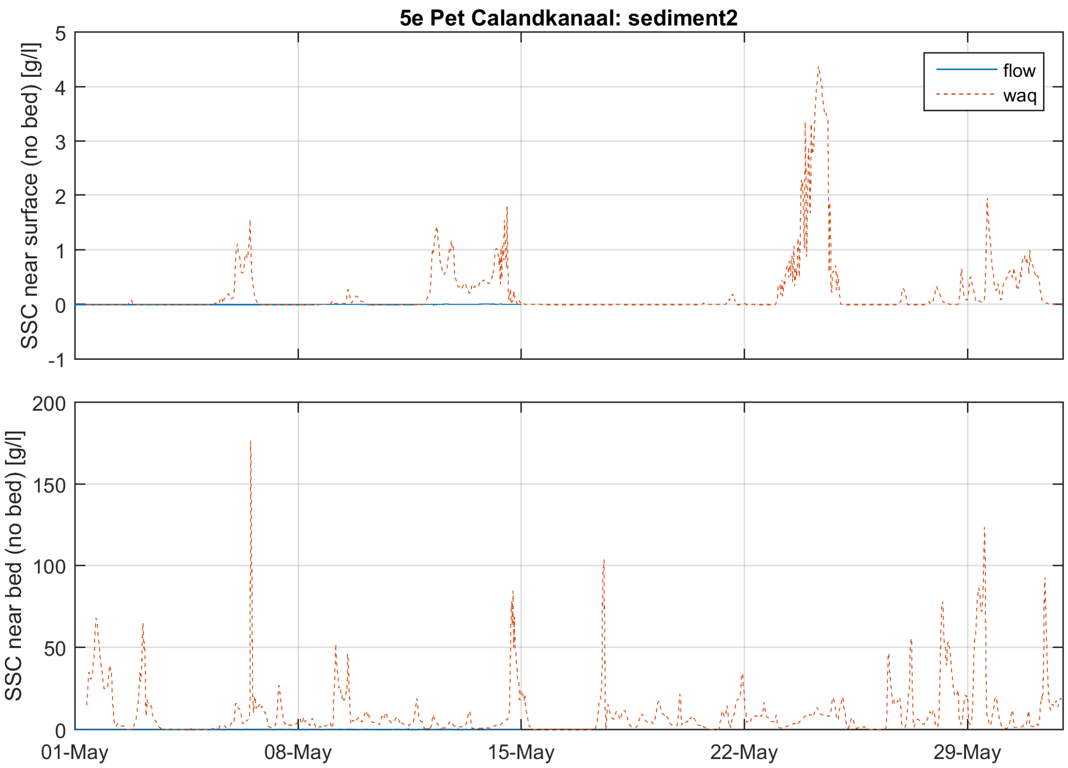

Calandbrug: sediment1
SSC near surface (no bed) [g/l]
SSC near bed (no bed) [g/l]
flow
waq
2.5
2
1.5
1
0.5
0
-0.5
250
200
150
100
50
0
-50
01-May
08-May
15-May
22-May
29-May

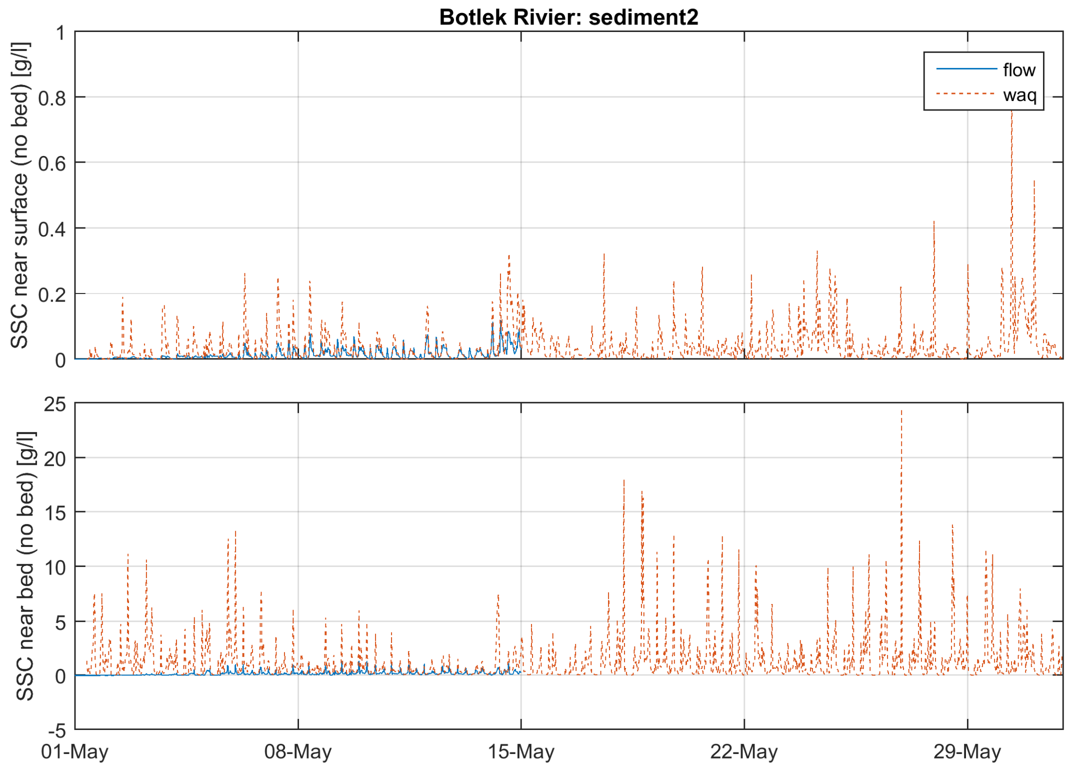

Maas - C boei: sediment1
×10^-3
SSC near surface (no bed) [g/l]
SSC near bed (no bed) [g/l]
flow
waq
01-May
08-May
15-May
22-May
29-May

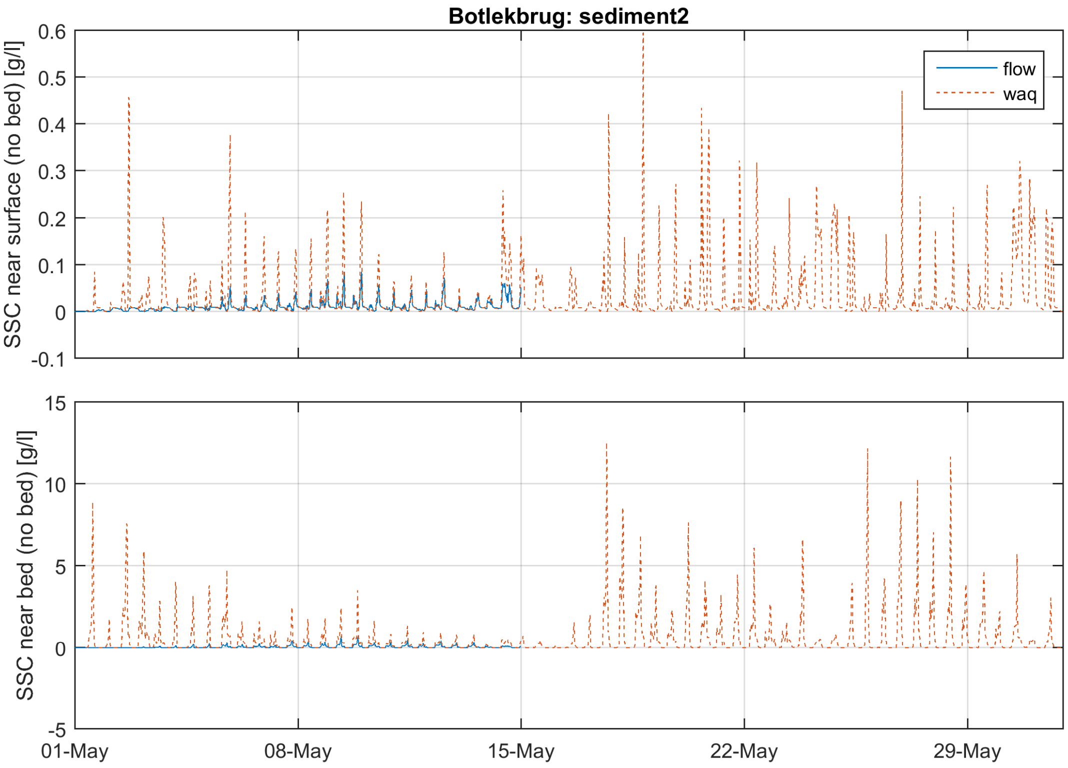

MaeslantkeringRivier: sediment1
SSC near surface (no bed) [g/l]
SSC near bed (no bed) [g/l]
flow
waq
01-May
08-May
15-May
22-May
29-May

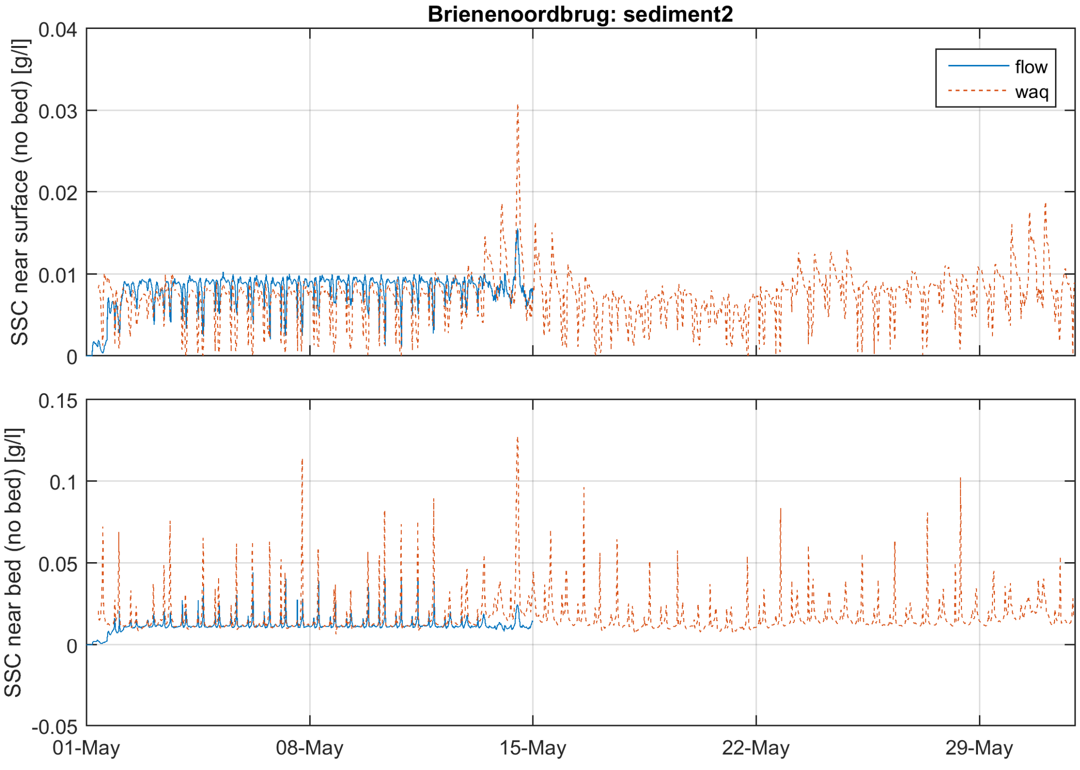

Stroompaal Maasmond: sediment1
SSC near surface (no bed) [g/l]
0.2
0.15
0.1
0.05
0
-0.05
flow
waq
SSC near bed (no bed) [g/l]
10
8
6
4
2
0
-2
01-May
08-May
15-May
22-May
29-May

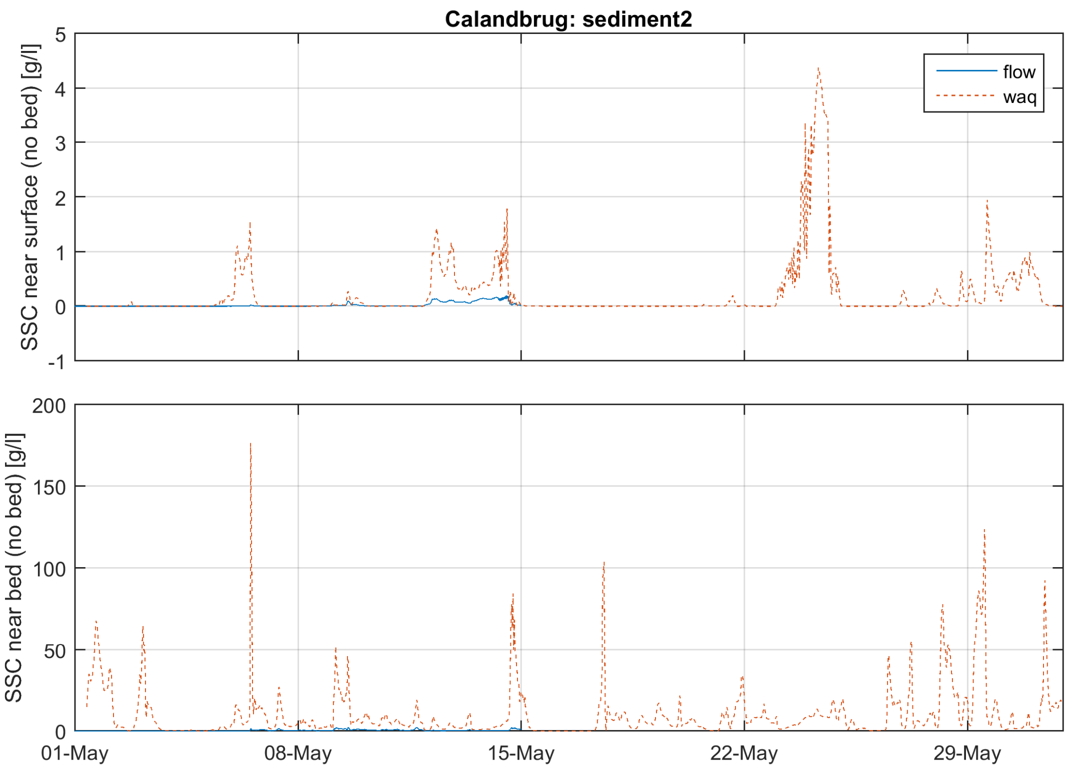
C.1.2 Sediment 2, fall velocity 1 mm/s

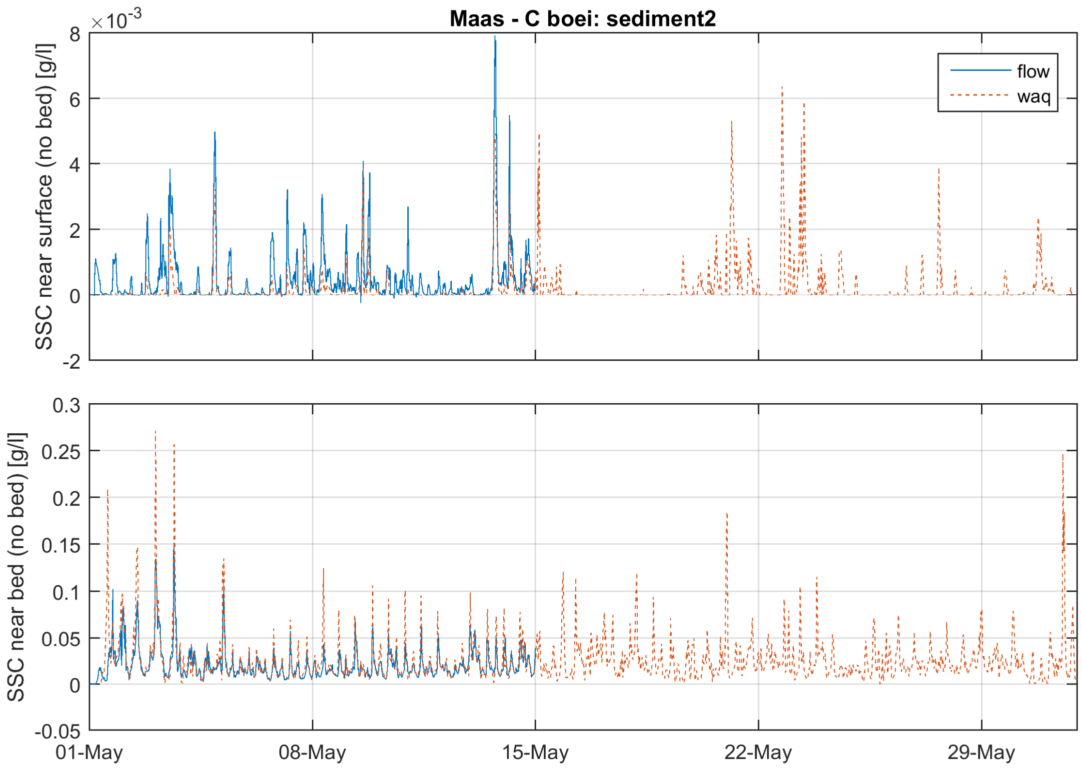


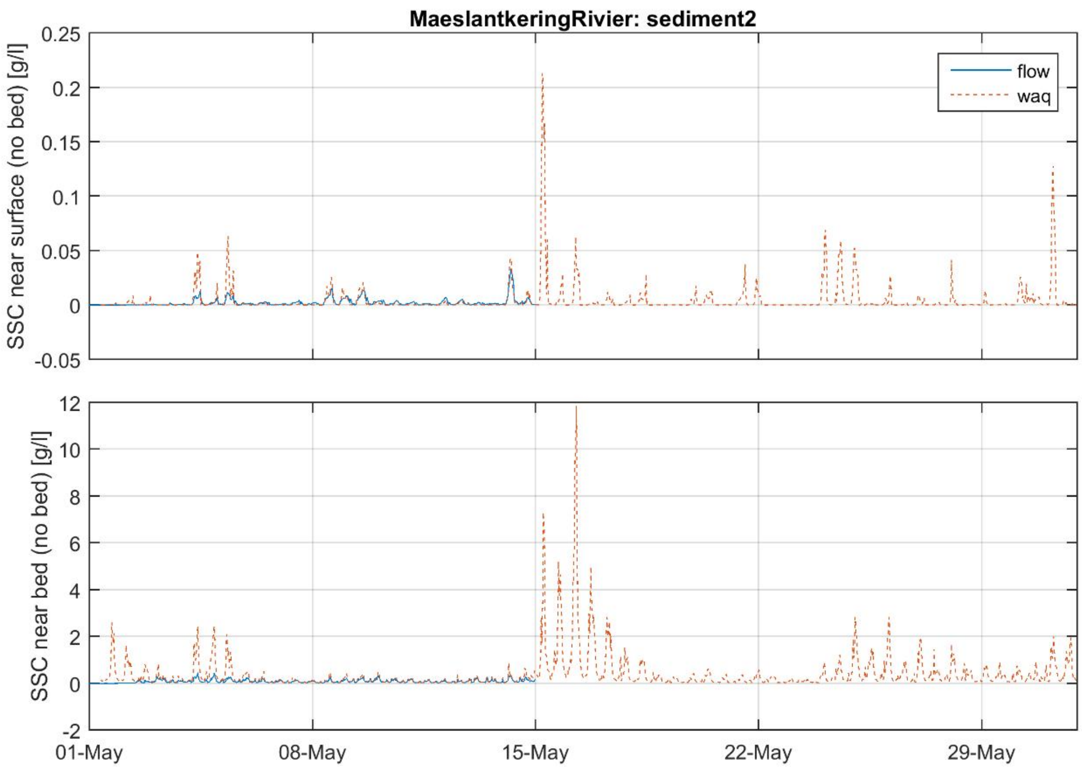


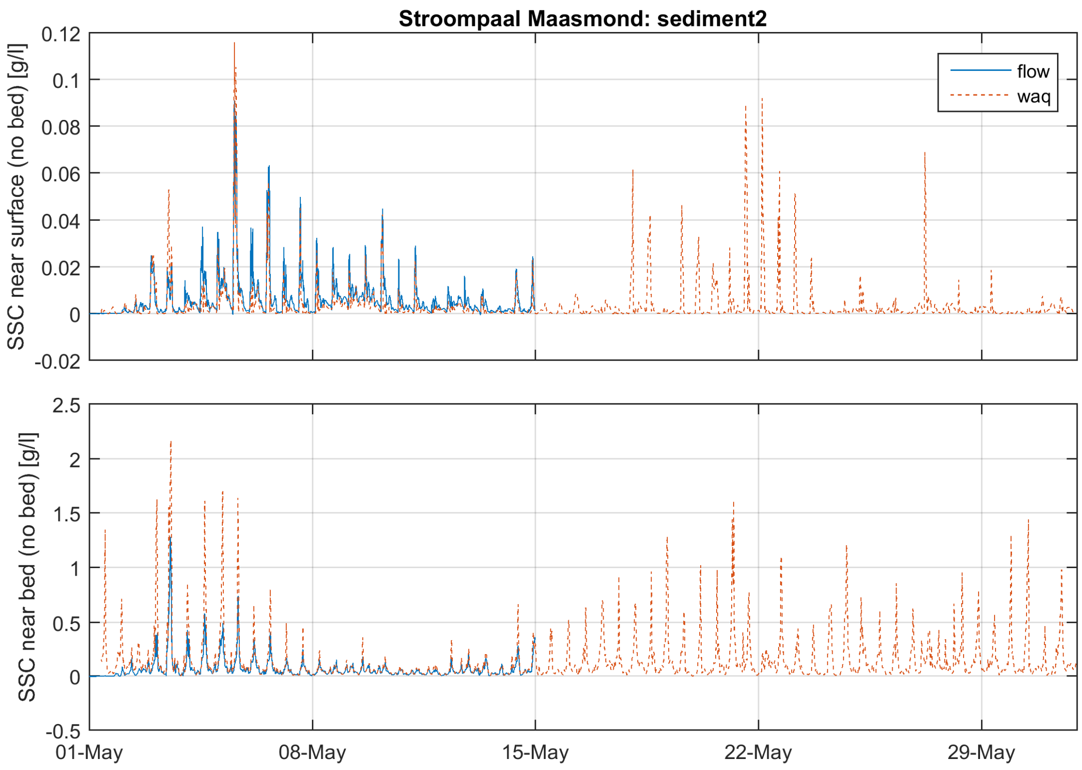

Botlekbrug: sediment2
SSC near surface (no bed) [g/l]
SSC near bed (no bed) [g/l]
flow
waq
01-May
08-May
15-May
22-May
29-May


Brienenoordbrug: sediment2
SSC near surface (no bed) [g/l]
SSC near bed (no bed) [g/l]
flow
waq
01-May
08-May
15-May
22-May
29-May

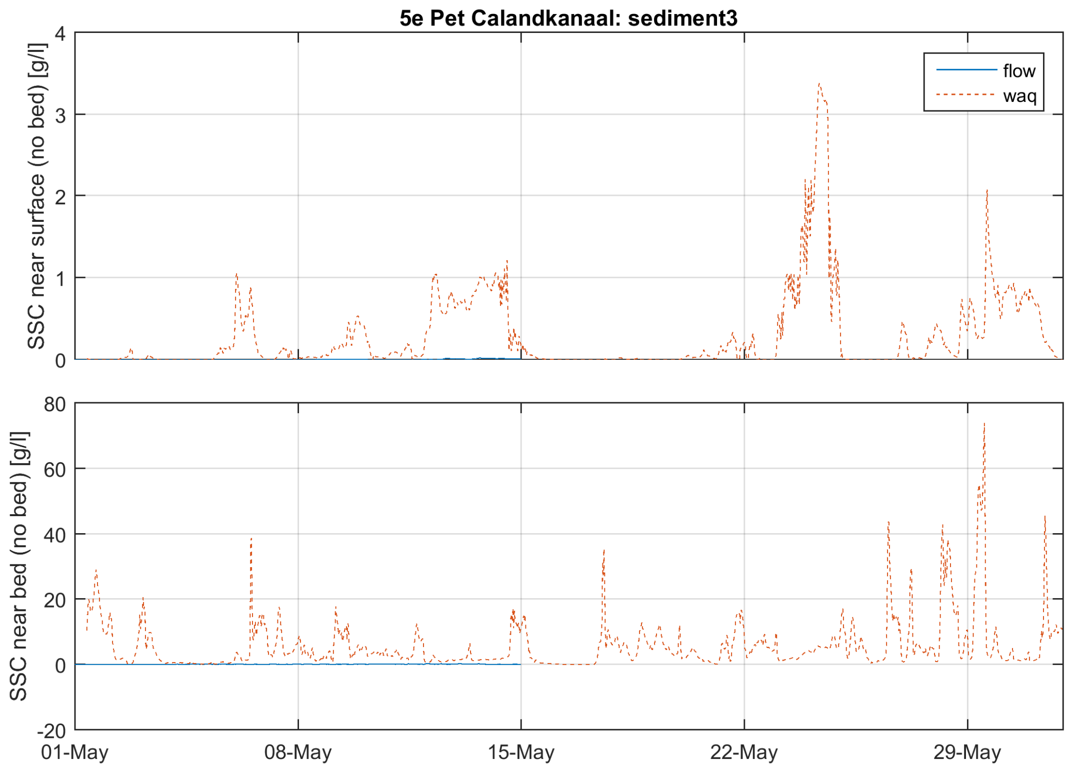

Calandbrug: sediment2
SSC near surface (no bed) [g/l]
SSC near bed (no bed) [g/l]
flow
waq
01-May
08-May
15-May
22-May
29-May

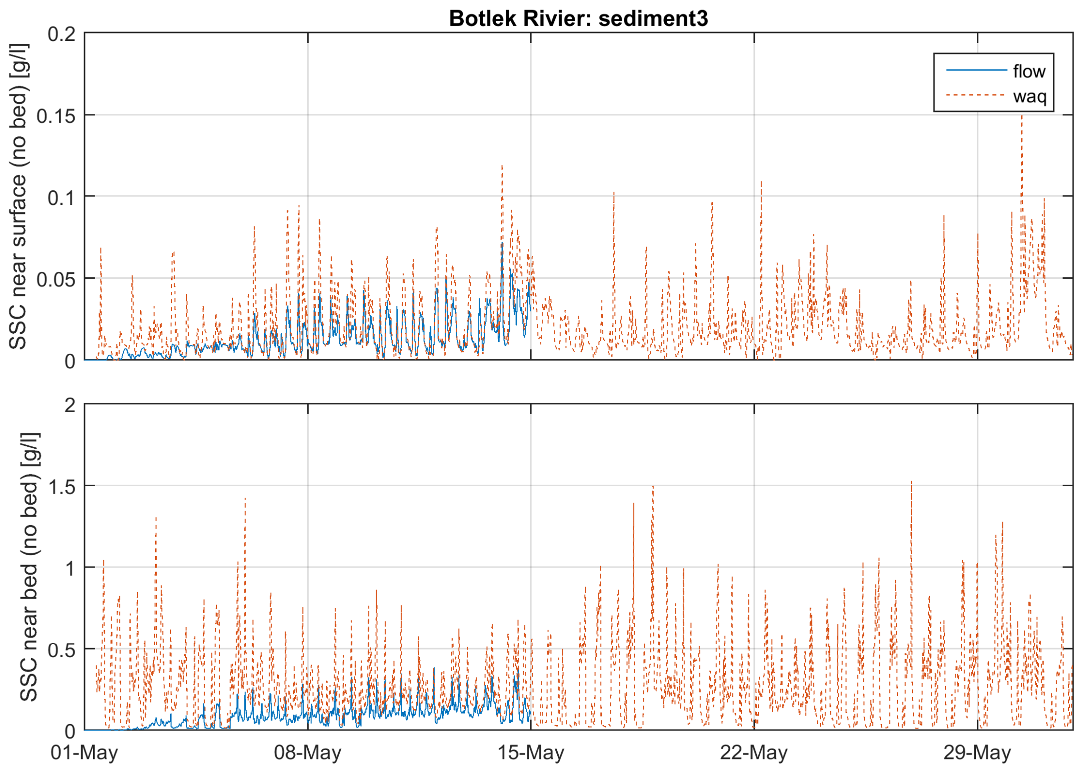

Maas - C boei: sediment2
$\times 10^{-3}$
SSC near surface (no bed) [g/l]
SSC near bed (no bed) [g/l]
flow
waq
01-May
08-May
15-May
22-May
29-May

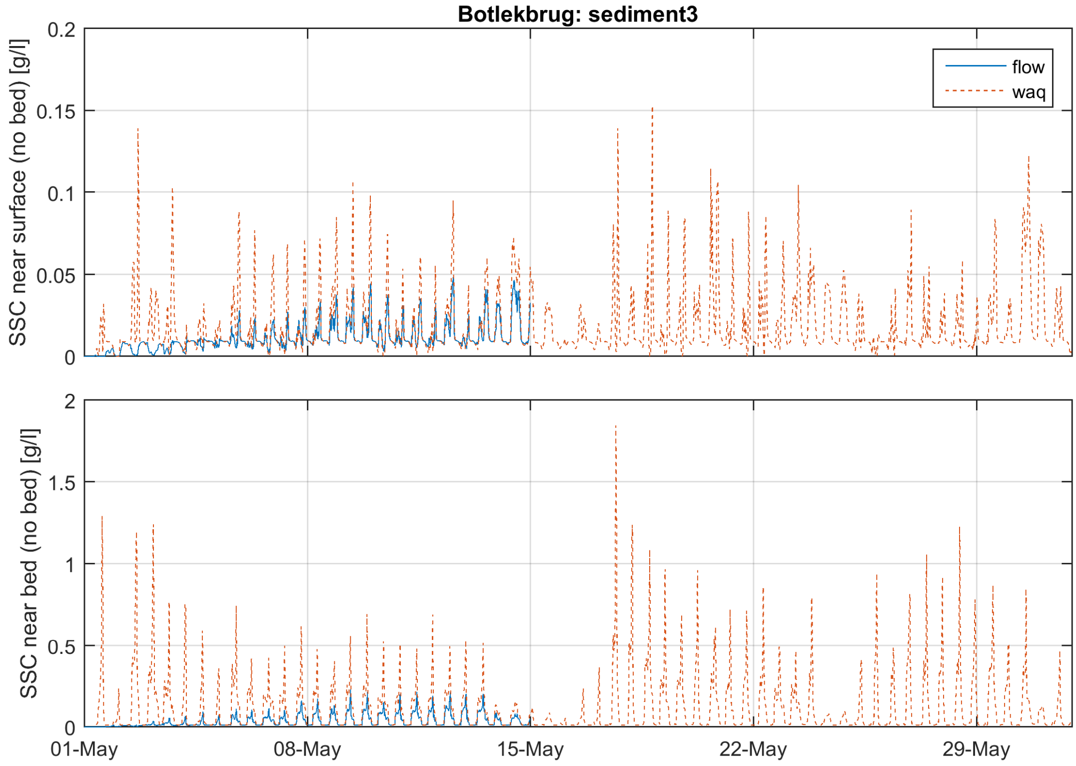

MaeslantkeringRivier: sediment2
SSC near surface (no bed) [g/l]
0.25
0.2
0.15
0.1
0.05
0
-0.05
flow
waq
SSC near bed (no bed) [g/l]
12
10
8
6
4
2
0
-2
01-May
08-May
15-May
22-May
29-May

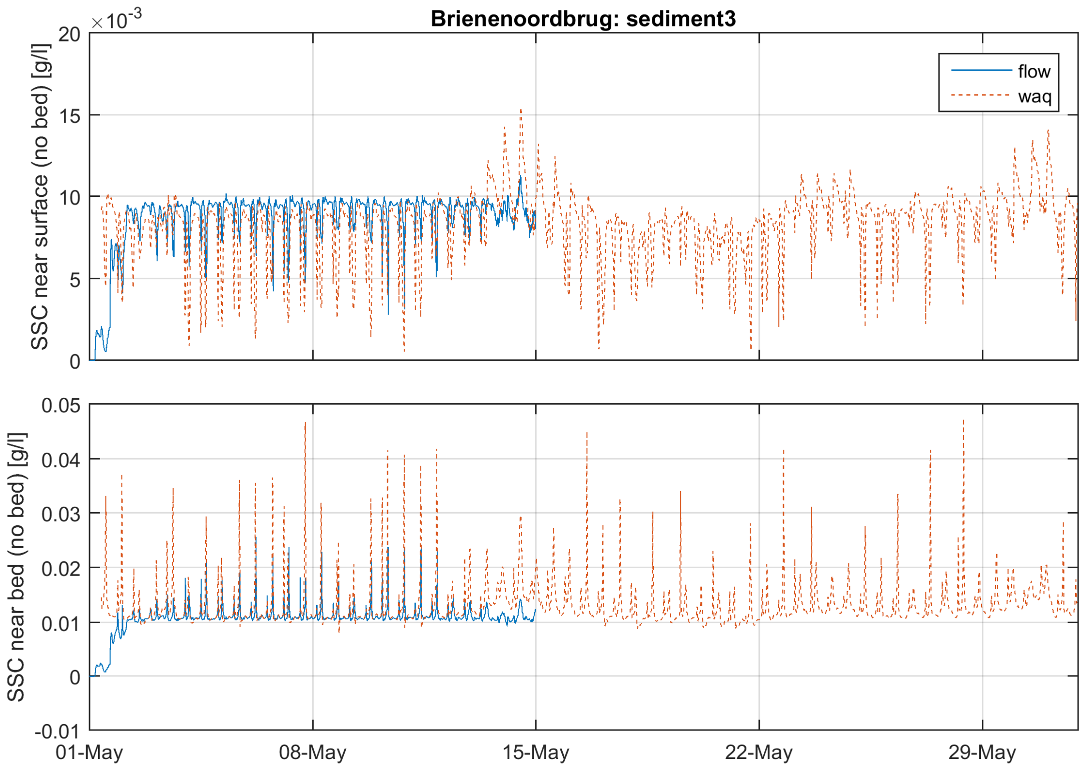

Stroompaal Maasmond: sediment2
SSC near surface (no bed) [g/l]
0.12
0.1
0.08
0.06
0.04
0.02
0
-0.02
flow
waq
SSC near bed (no bed) [g/l]
2.5
2
1.5
1
0.5
0
-0.5
01-May
08-May
15-May
22-May
29-May

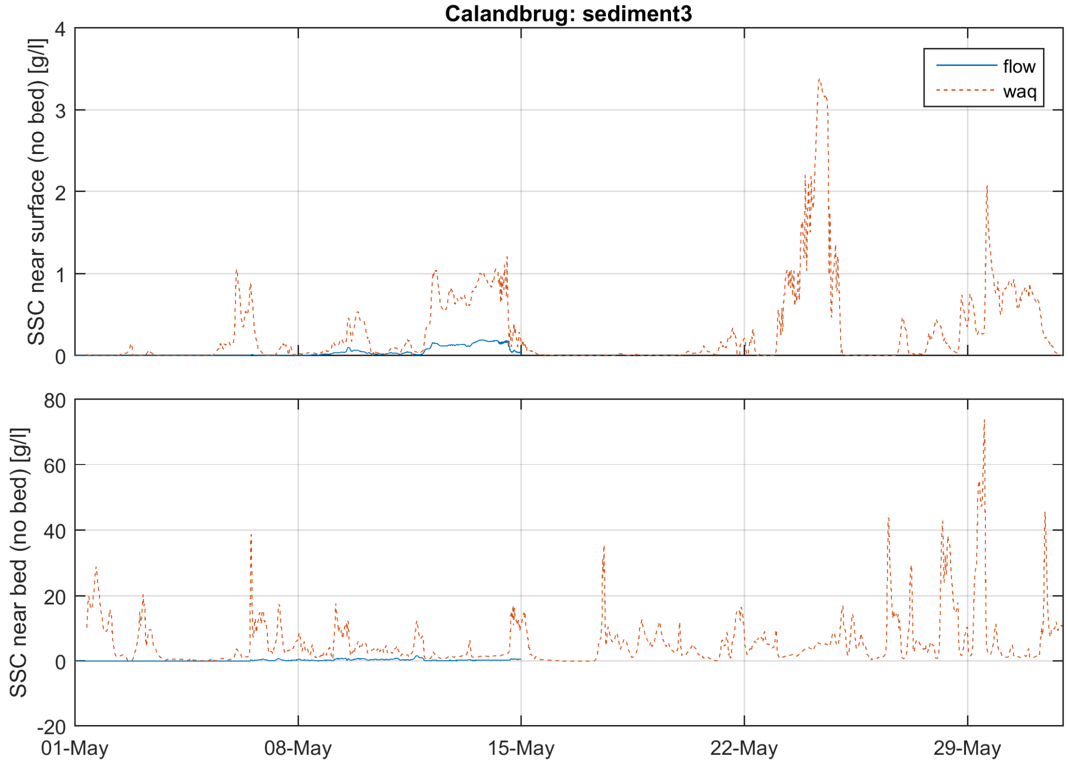
C.1.3 Sediment 3, fall velocity 0.5 mm/s

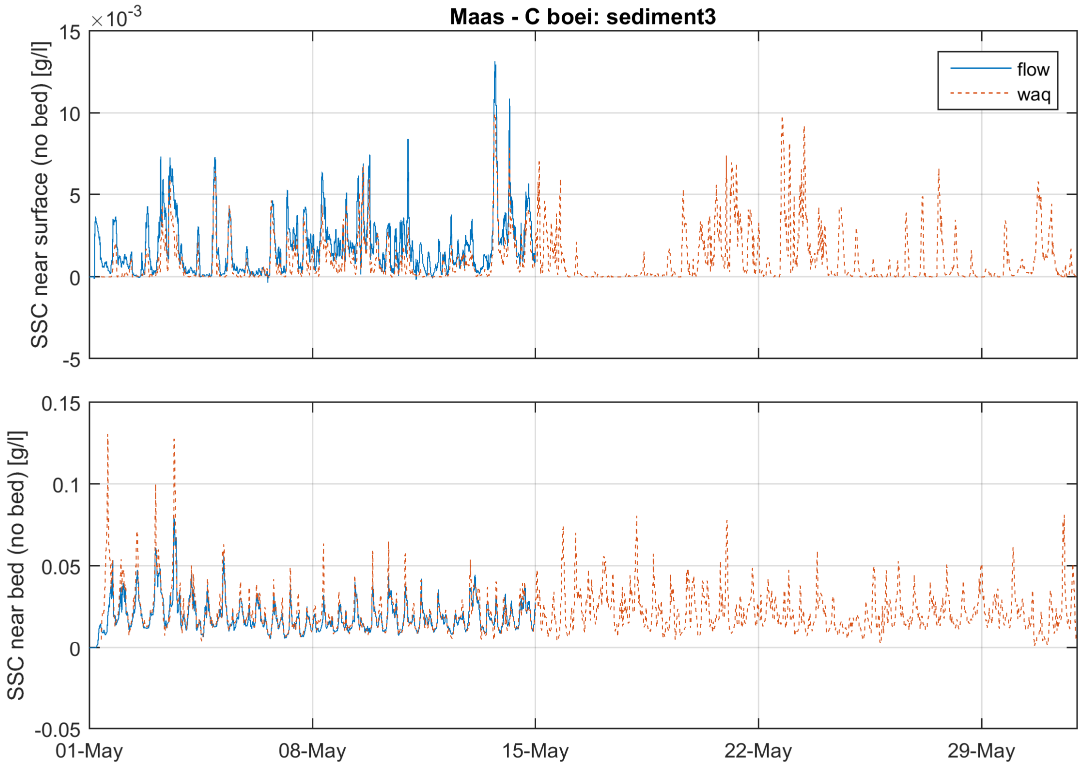


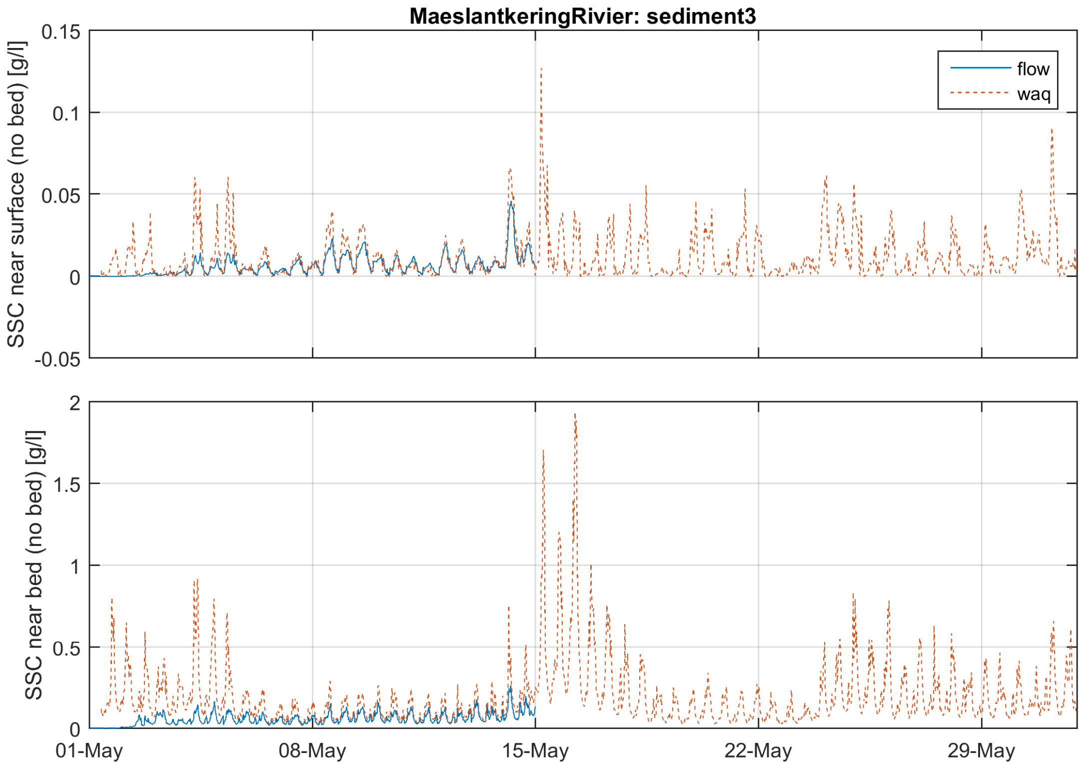


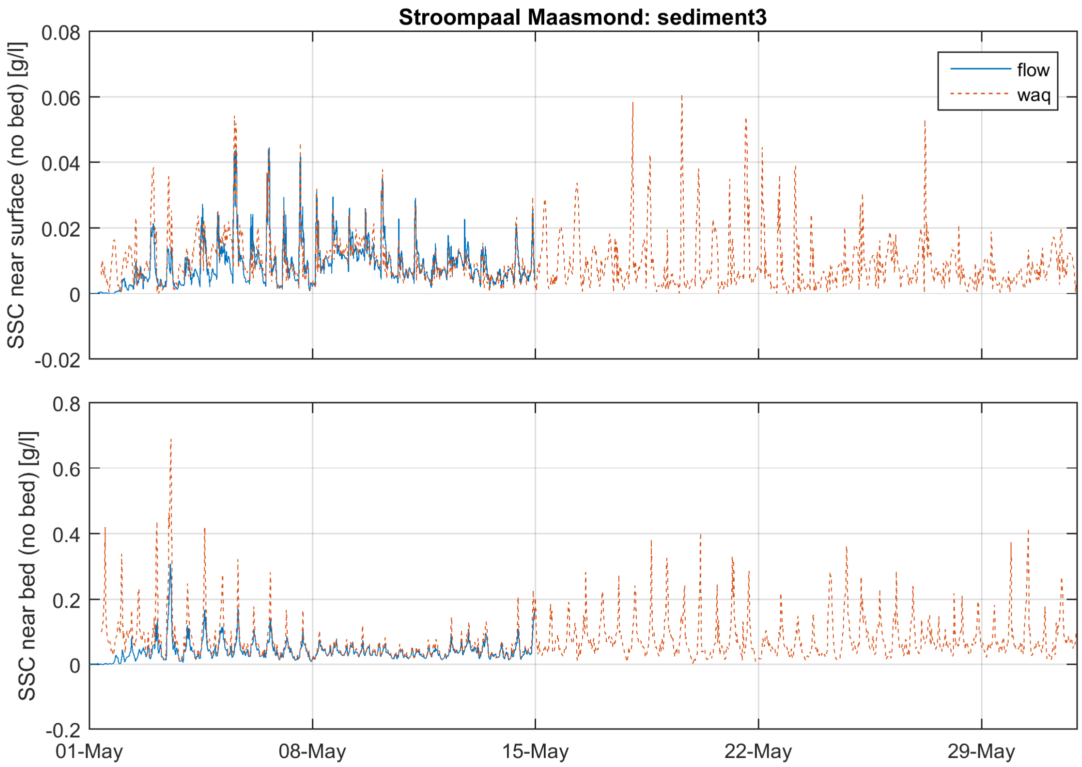

Botlekbrug: sediment3
SSC near surface (no bed) [g/l]
0.2
0.15
0.1
0.05
0
flow
waq
SSC near bed (no bed) [g/l]
2
1.5
1
0.5
0
01-May
08-May
15-May
22-May
29-May


Brienenoordbrug: sediment3
×10-3
SSC near surface (no bed) [g/l]
20
15
10
5
0
flow
waq
SSC near bed (no bed) [g/l]
0.05
0.04
0.03
0.02
0.01
0
-0.01
01-May
08-May
15-May
22-May
29-May


Calandbrug: sediment3
SSC near surface (no bed) [g/l]
SSC near bed (no bed) [g/l]
flow
waq
01-May
08-May
15-May
22-May
29-May


Maas - C boei: sediment3
×10-3
SSC near surface (no bed) [g/l]
SSC near bed (no bed) [g/l]
flow
waq
01-May
08-May
15-May
22-May
29-May


MaeslantkeringRivier: sediment3
SSC near surface (no bed) [g/l]
0.15
0.1
0.05
0
-0.05
flow
waq
SSC near bed (no bed) [g/l]
2
1.5
1
0.5
0
01-May
08-May
15-May
22-May
29-May


Stroompaal Maasmond: sediment3
SSC near surface (no bed) [g/l]
0.08
0.06
0.04
0.02
0
-0.02
flow
waq
SSC near bed (no bed) [g/l]
0.8
0.6
0.4
0.2
0
-0.2
01-May
08-May
15-May
22-May
29-May

D Delft3D-WAQ Buffer Formulations

D.1 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 D.1 illustrates the exchanges between both bottom layers and the water column for the buffer parameterization.

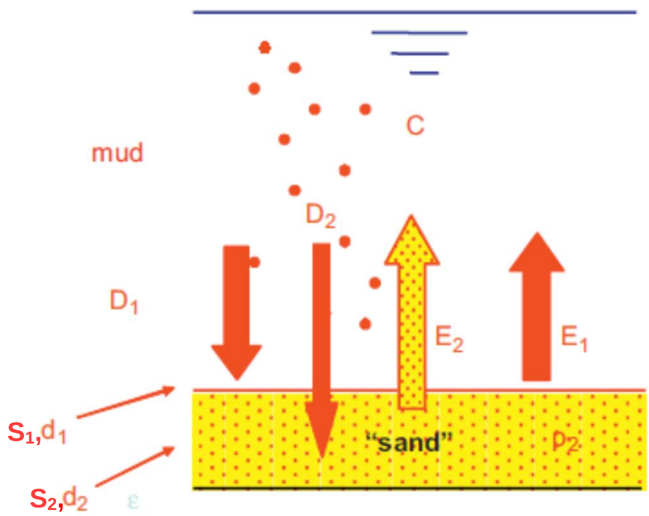


Figure D.1 Schematic representation of the buffer model. Layer S_1, thickness d_1: thin fluff layer. Layer S_2, thickness d_2: sandy sea bed infiltrated with fines. D_j deposition flux towards layer S_j, E_j erosion flux from layer S_j ($j \in [1,2]$) and C: SPM concentration. (Adopted from Van Kessel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

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

$$D_{1,IM_i} = (1-\alpha_{IM_i}) V_{Sed,IM_i} C_{IM_i} \qquad \text{(Eqn D.1)}$$

$$D_{2,IM_i} = \alpha_{IM_i} V_{Sed,IM_i} C_{IM_i} \qquad \text{(Eqn D.2)}$$

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 (Equation D.2) 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 (see Equation D.3 for details). The coarse and fine fractions have a different critical shear stress for resuspension (τ_{cr}). The zero-order formulations are based on Partheniades (1962), 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:

$$E_{1,IM_i} = \min\left(Z_{\mathrm{Res},IM_i}, V_{\mathrm{Res},IM_i} M_{i,1}\right)\left(\frac{\tau}{\tau_{\mathrm{cr},S_1 IM_i}} - 1\right) \qquad (Eqn\ D.3)$$

$$E_{2,IM_i} = F_{\mathrm{ResPUp}} M_{i,2}\left(\frac{\tau}{\tau_{\mathrm{Sh}}} - 1\right)^{1.5} \qquad (Eqn\ D.4)$$

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: $M_{i,2} = f_{IM_i S_2} d_2 (1\text{-Por}_{S_2})\rho_{sand}$, with thickness d_2 and

$f_{IM_i S_2}$ the fines fraction with respect to total bed,

Por_{S_2} the volumetric porosity of the bed,

ρ_{sand} the mass density of sand. Delwaq Sensitivity Tests

E Suspended sediment only with no water-bed exchange

Results for simulations with no water-bed exchange and only suspended sediments (all fractions) are shown in Figure E.1-Figure E.3 below representing a more offshore location, a location in the main channel and also further upstream. As to be expected sediment concentrations near the bed are higher at all stations.

Spatial maps (Figure E.4-Figure E.5) show very high concentrations remaining near the bed where it builds up during the simulation as a result of the lack of exchange with the bed. Where sediment concentrations are highest near the bed already gives an indication of where accumulation of mud would be high if sedimentation was activated in the model. This is an exaggerated effect of course as sediment remains in suspension and available for transport in this case. In reality, there would be a time lag between the settling and resuspension of sediments from the bed under different conditions.

Figure E.6-Figure E.8 show the same results per fraction. Sediment 1 (the heaviest fraction) with a settling velocity of 2 mm/s shows largest concentrations near the bed and the lowest concentration in the surface layer. Conversely Sediment 3 (the lightest fraction) with a setting velocity of 0.5 mm/s shows higher concentrations in the surface waters compared to Sediment 1 and lowest concentrations near the bed. This is because this fraction is more well mixed throughout the water column. Figure E.9-Figure E.14 show the spatial distribution of each fraction near the surface and near the bed.

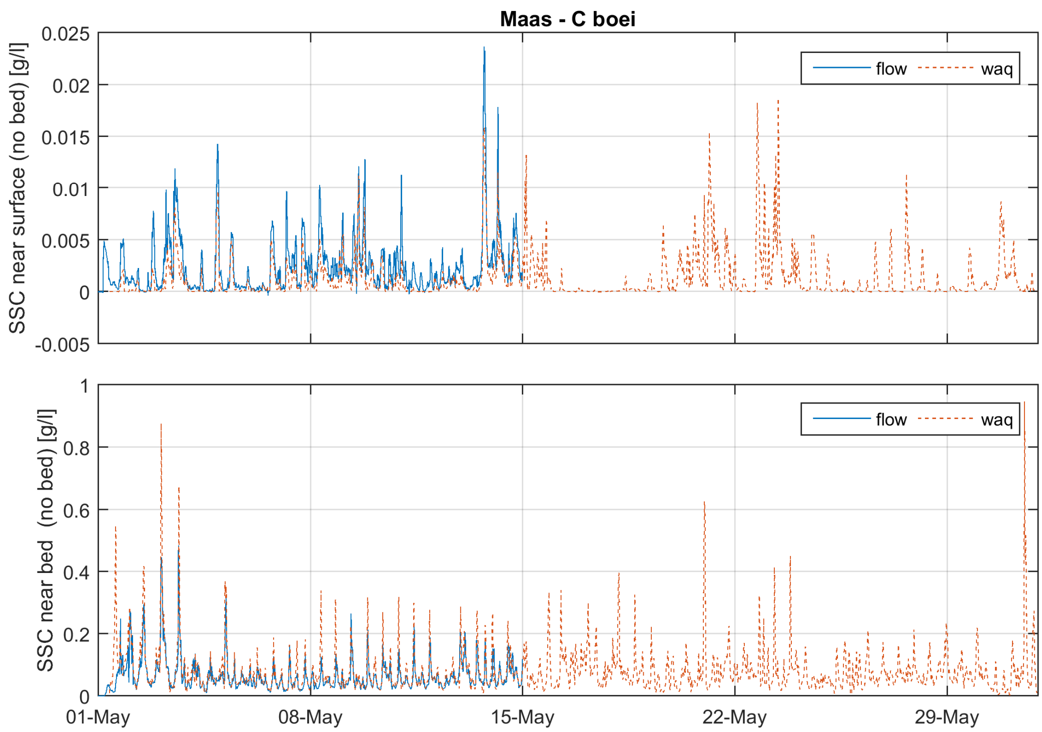


Figure E.1 Total suspended sediment concentrations at Maas C buoy just offshore in a simulation without water-bed exchange

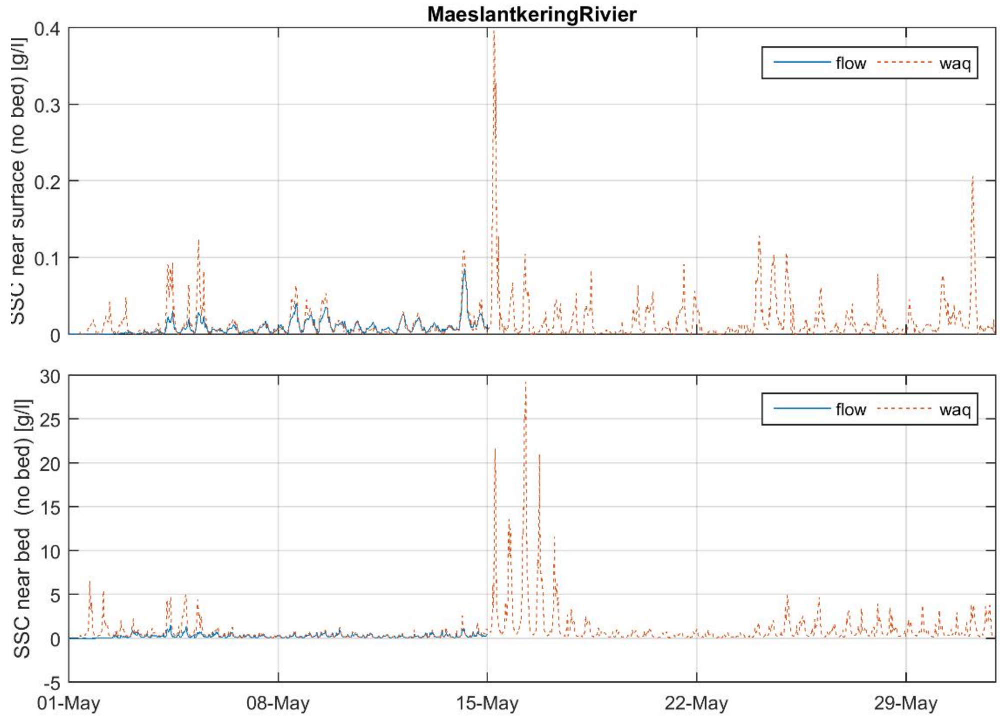


Figure E.2 Total suspended sediment concentrations at Maeslantkering Rivier in a simulation without water-bed exchange

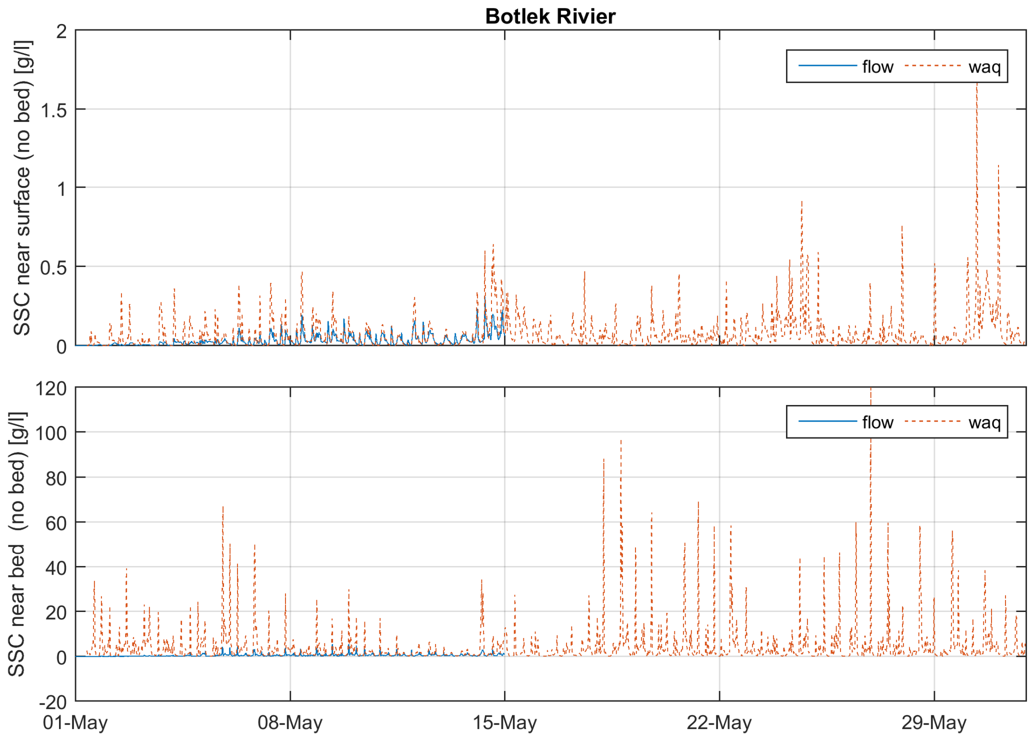


Figure E.3 Total suspended sediment concentrations at Botlek Rivier in a simulation without water-bed exchange

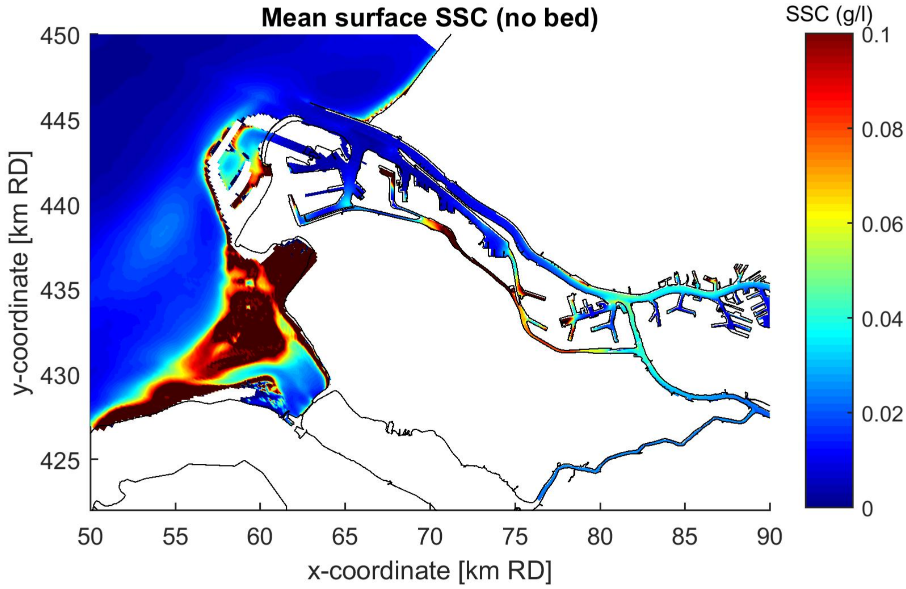


Figure E.4 Mean near surface total suspended solids distribution for May 2016 in the simulation with no water-bed exchange

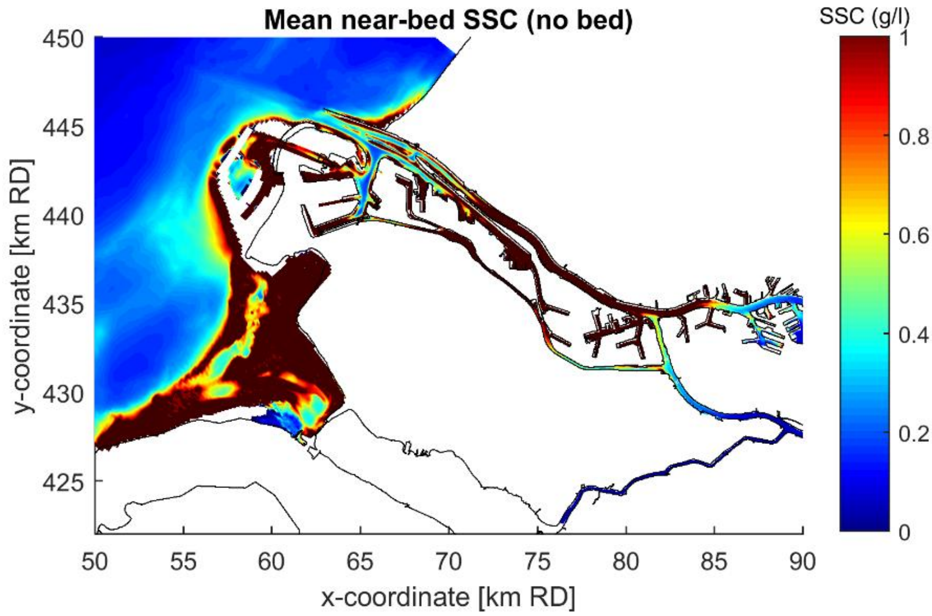


Figure E.5 Mean near bed total suspended solids distribution for May 2016 in the simulation with no water-bed exchange

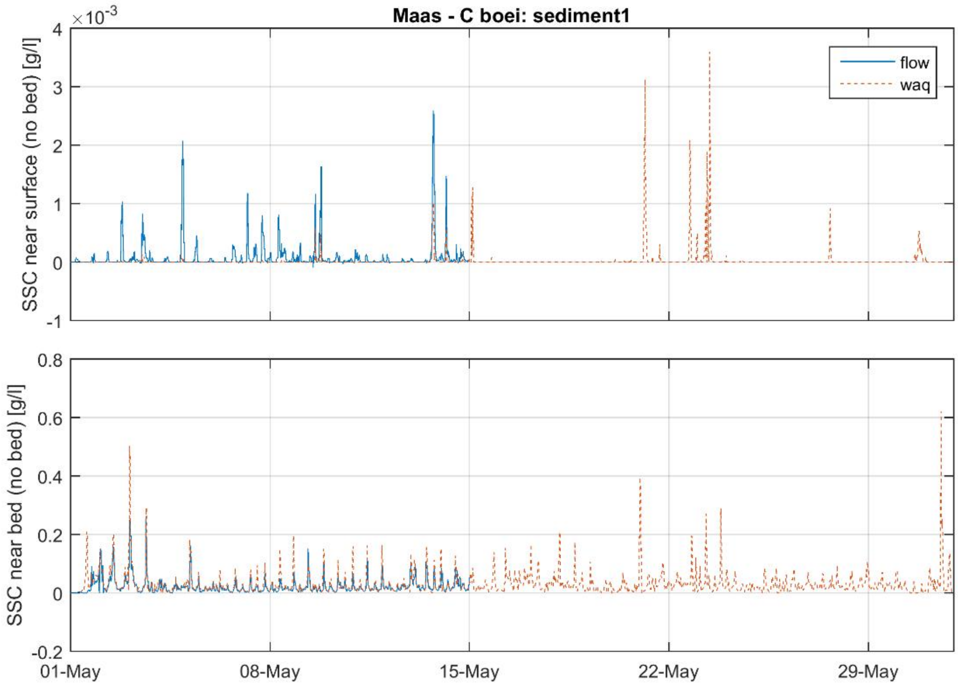


Figure E.6 Total suspended sediment concentrations for sediment 1 (heaviest fraction) at Maas C buoy

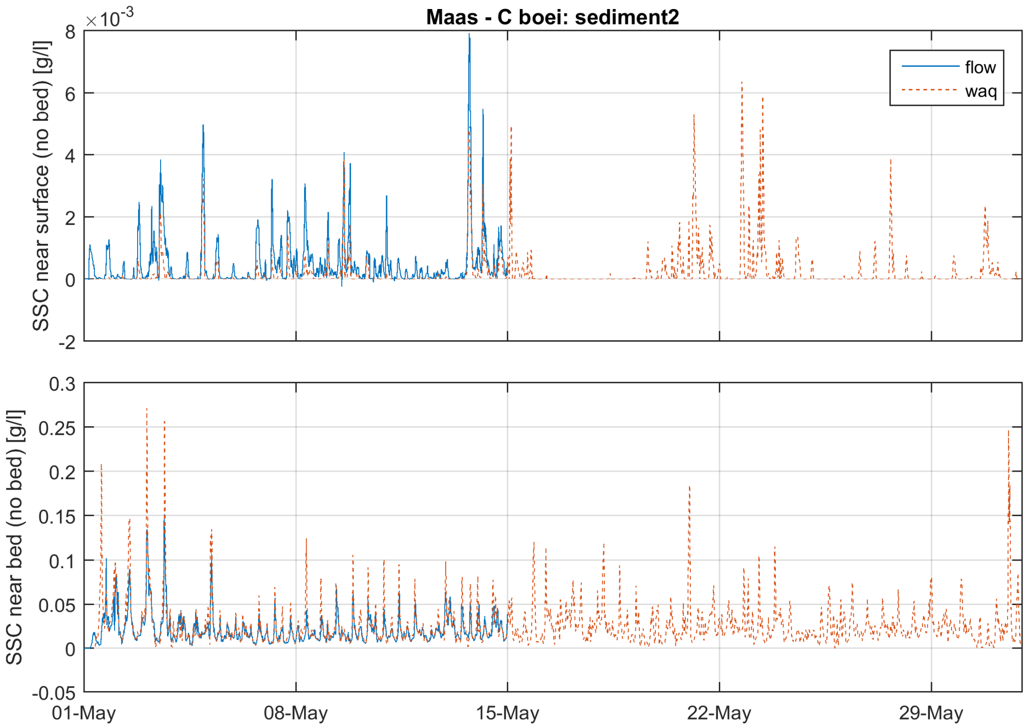


Figure E.7 Total suspended sediment concentrations for sediment 2 (middle fraction) at Maas C buoy

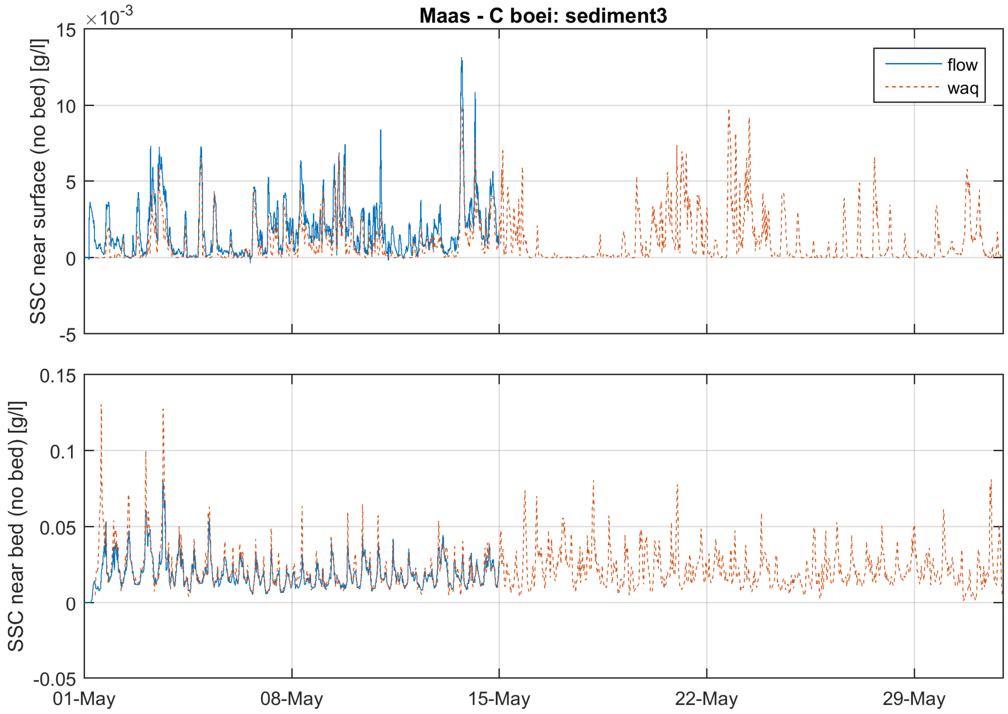


Figure E.8 Total suspended sediment concentrations for sediment 3 (lightest fraction) at Maas C buoy

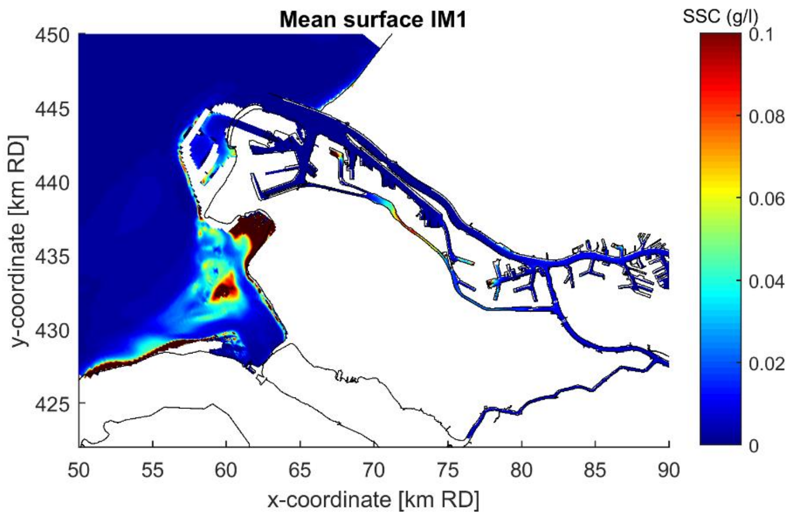


Figure E.9 Mean distribution of sediment 1 (heaviest fraction) near the surface

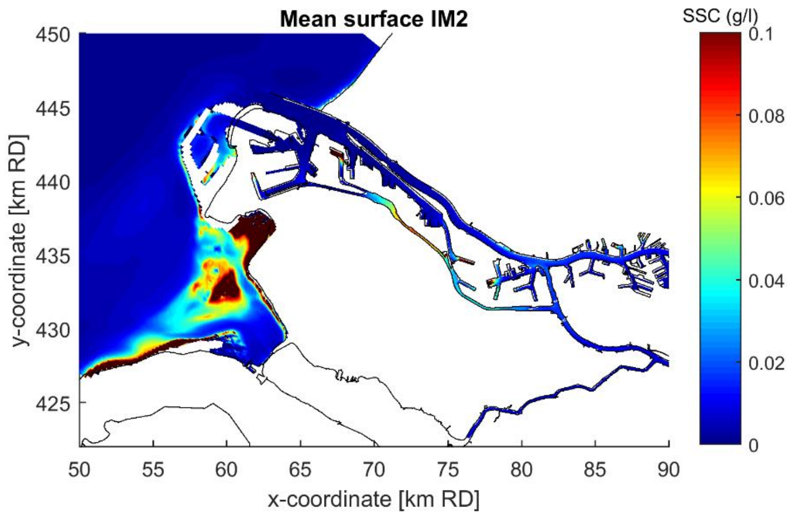


Figure E.10 Mean distribution of sediment 2 (middle fraction) near the surface

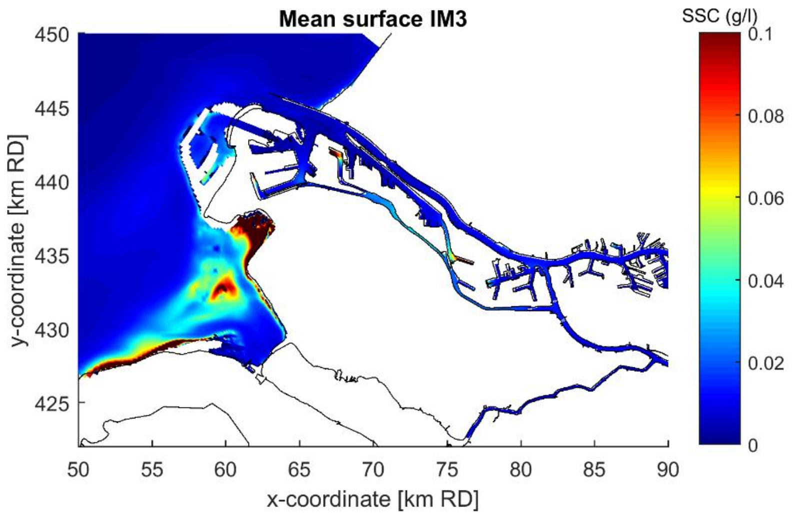


Figure E.11 Mean distribution of sediment 3 (lightest fraction) near the surface

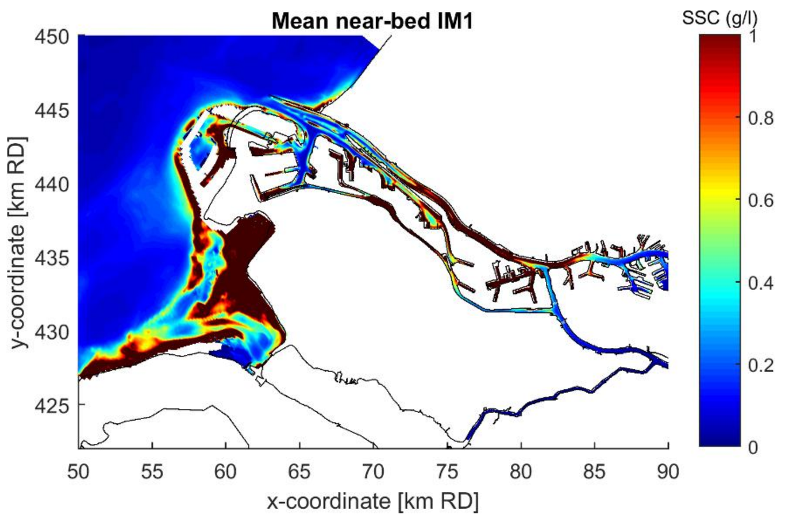


Figure E.12 Mean distribution of sediment 1 (heaviest fraction) near the bed

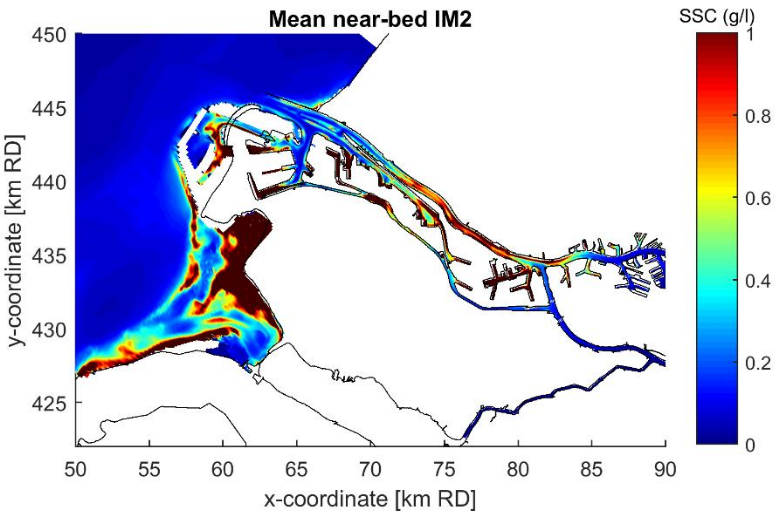


Figure E.13 Mean distribution of sediment 2 (middle fraction) near the bed

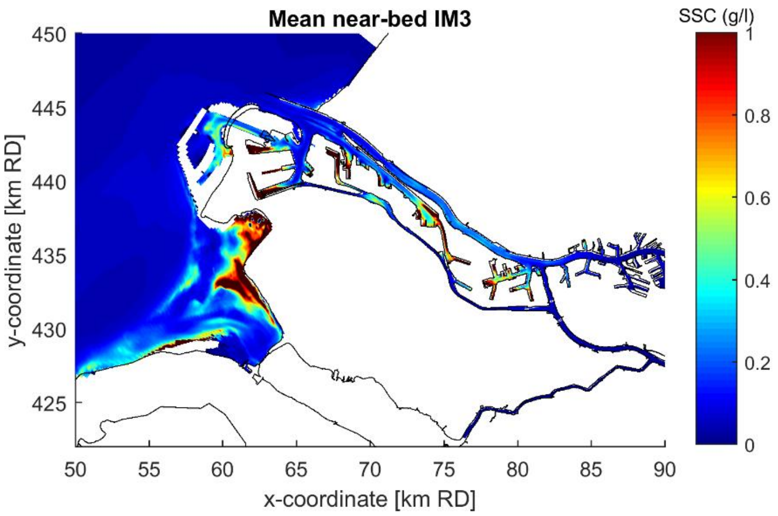


Figure E.14 Mean distribution of sediment 3 (lightest fraction) near the bed