Prepared for:

RIKZ

Development of a mud transport model for the Scheldt estuary

In the framework of LTV

Report

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Report

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Abstract:

In 2006, a work plan was conceived for the development of a mud transport model for the Scheldt estuary in the framework of LTV (Long Term Vision) (Winterwerp and De Kok, 2006). The purpose of this model is to support managers of the Scheldt estuary with the solution of a number of managerial issues. Also in 2006, the first two phases were initiated. The present report discusses the activities that have been carried out during the first half of 2007, *i.e.* further improvement of the hydrodynamic and mud transport model.

At a technical level, all model improvements scheduled for 2007 have been implemented. The most important developments are: longer hydrodynamic simulation period (up to one year), more accurate concentration boundary conditions, variable wave effects and biological effects.

The hydrodynamic simulation yields realistic values for water levels and salinities, although it is expected that the modelled velocities will be too high. Three actions are identified that can enhance the simulated hydrodynamics:

1. The high fresh water inflow event in the beginning of March can be modelled more accurately by adding more data points in the time series of fresh water inflow to increase the volume of fresh water contained in the peak.
2. The time series of fresh water inflow of the Bathse Spuikanaal has to be added in the model.
3. A different set of boundary conditions could yield better results for water levels.

Regarding the mud transport simulations, the following is concluded:

1. A minor shift of two dumping locations near Antwerp much improves the proper modelling of the ETM.
2. New concentration boundary conditions at sea result in more realistic SPM concentrations at sea.
3. The difference between simulations with 5 and 10 horizontal layers is only minor.
4. Variable waves temporarily enhance the concentration in the western part of the Western Scheldt during storms.
5. The biological impact on large-scale SPM concentrations in the Scheldt estuary appears to be minor.
6. The SPM levels appear to be rather sensitive to the volume of harbour siltation and dumping.

References:	contract RKZ – 1872

Ver	Author		Date	Remarks	Review		Approved by	
2.0	Thijs van Kessel	TvK	14/9/2007		Winterwerp	HW	Schilperoort	[illegible]

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Contents

1 Introduction

In 2006, a work plan was conceived for the development of a mud transport model for the Scheldt estuary in the framework of LTV (Long Term Vision) (Winterwerp and De Kok, 2006). The purpose of this model is to support managers of the Scheldt estuary with the solution of a number of managerial issues.

In the work plan five phases have been defined:
1. set-up of mud model
2. elaboration of managerial questions
3. year simulations
4. detail studies
5. sediment mixtures.

In 2006, the first two phases were initiated. The set-up of the hydrodynamic and mud transport model was reported in Van Kessel *et al*. (2006), whereas the managerial issues were elaborated in Bruens *et al*. (2006). The present report discusses the activities that have been carried out during the first half of 2007. These activities are based on the original work plan, but take also into account the findings from the set-up of the mud model and the discussions with Scheldt estuary managers during 2006.

In short, most activities for 2007 fall into the following two categories:
1. further improvement of the mud transport model
2. providing support for a few managerial issues

This report deals with the first activity only. The second activity will be carried out during the second half of 2007. Also, work on model improvements will not end after the completion of Phase 1 of 2007, for which the present report is the final document. In the following chapters, the work on the model improvements is further elaborated.

2 Data analysis

In Van Kessel *et al.* (2006) a data analysis is made regarding the suspended particulate matter (SPM) levels and sedimentation in the Scheldt estuary. Here only two aspects are elaborated:

1. selection of simulation year
2. SPM boundary concentrations

2.1 Year selection

The selection of a representative year is constrained by the following limitations:

- Boundary conditions for water level and salinity from the ZUNO model are readily available for the period 1996 – 2003;
- Validation data at DOW jetty (Terneuzen) with a high temporal resolution are available for the period 12/1998 – 2/2002.

These constraints limit the selection of years to 1999 – 2001. Of these years, the year 2000 appears to be most typical regarding average wind speed, number of storms and river discharge (191 m^3/s at Schaar van Ouden Doel). The average wind speed at HIRLAM grid point (86, 34) (at the North Sea approximately halfway between IJmuiden and Lowestoft) is 7.5 m/s with a direction of 263.4 deg. The number of storms is 11. For the year 2000 the western component of the wind is quite strong, resulting in an above-average residual current through Dover Strait (128,000 m^3/s or 0.128 Sv). The wind climate for the year 2000 is shown in Fig. 2.1.

Because of limitations on disk storage and simulation time, it was decided not to use a complete year initially, but the 3-month period February – April. At a later stage, the whole year will be simulated. Compared with the 14-day hydrodynamic used in the 2006 project, a three month period already means a major extension.

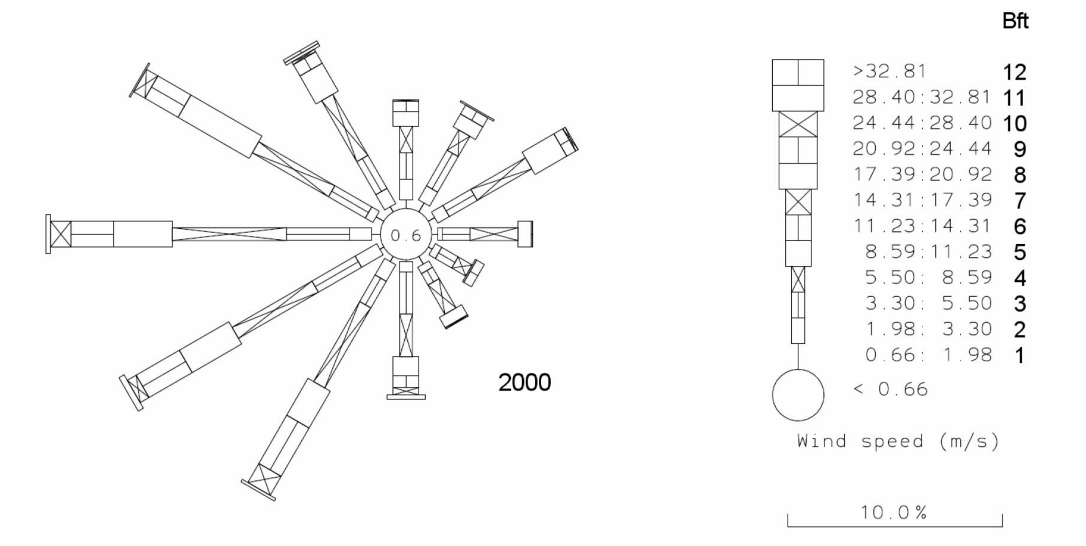

Fig. 2.1: Wind climate at HIRLAM gridpoint (86, 34) for the year 2000. Left: wind rose. Right: wind classes.

2.2 SPM boundary conditions

In the 2006 study, the southern boundary conditions were derived from the Appelzak transect, which is the southernmost transect from the silt atlas (Suijlen and Duin, 2001) based on the MWTL monitoring stations. However, the Appelzak transect is located quite far from the southern model boundary near the border between France and Belgium. Also, the Appelzak transect runs through the turbidity maximum north of Zeebrugge. As a result, the SPM levels applied at the southern boundary are probably too high. Therefore it was recommended to analyse remote sensing images on the SPM levels near the Belgian-French border in the next phase of the study.

Recently, Fettweis *et al.* (2007) analysed SeaWiFs images with regard to SPM levels in the Belgian part of the southern North Sea. Supported by a numerical model, they produced maps of the seasonal SPM surface and depth-averaged concentrations (see Fig. 2.2). The depth-averaged SPM boundary conditions applied in the present study were based on these SeaWiFs data. The approximate locations of the model boundaries are delineated in the upper left panel of Fig. 2.2. Figure 2.3 shows the applied cross-shore SPM concentration gradients, both at the southern and the northern model boundary.

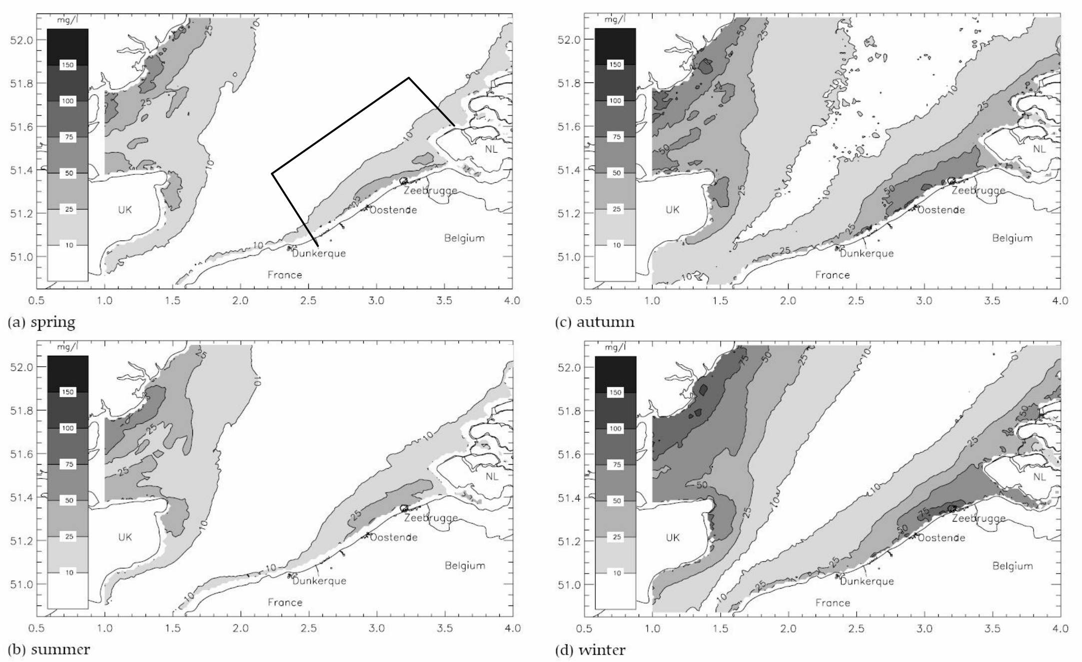

Fig. 2.2: Seasonal averages of SPM surface concentration in the southern North Sea derived from 362 SeaWiFs images (1997 – 2004). From Fettweis *et al.* (2007). The model boundaries are delineated in the upper left panel.

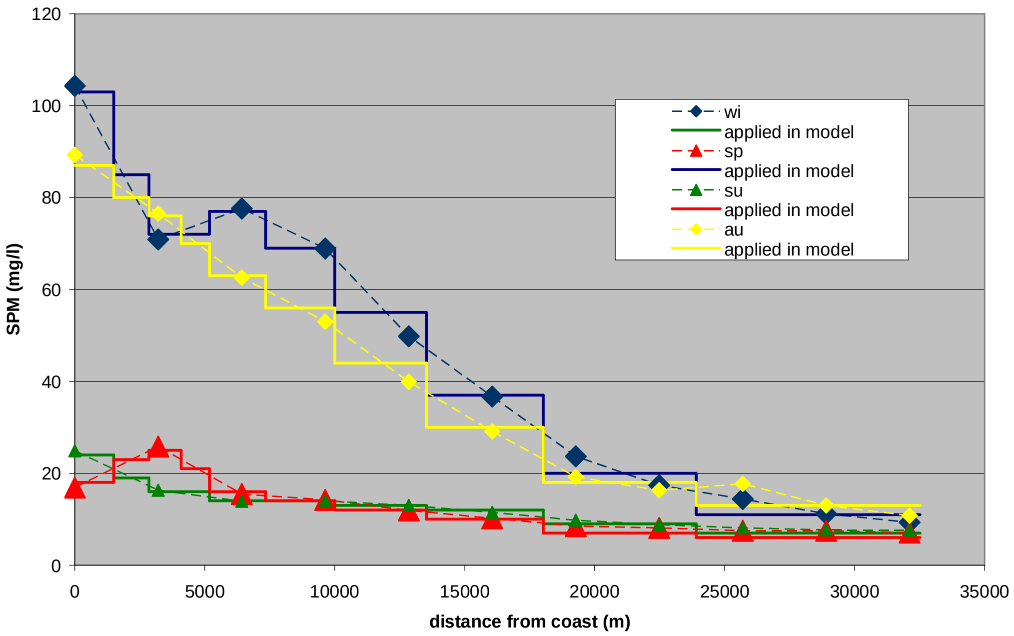

Fig. 2.3a: Applied concentration at northern boundary based on SeaWiFs images (wi = winter, sp = spring, su = summer and au = autumn observations converted to depth-averaged values).

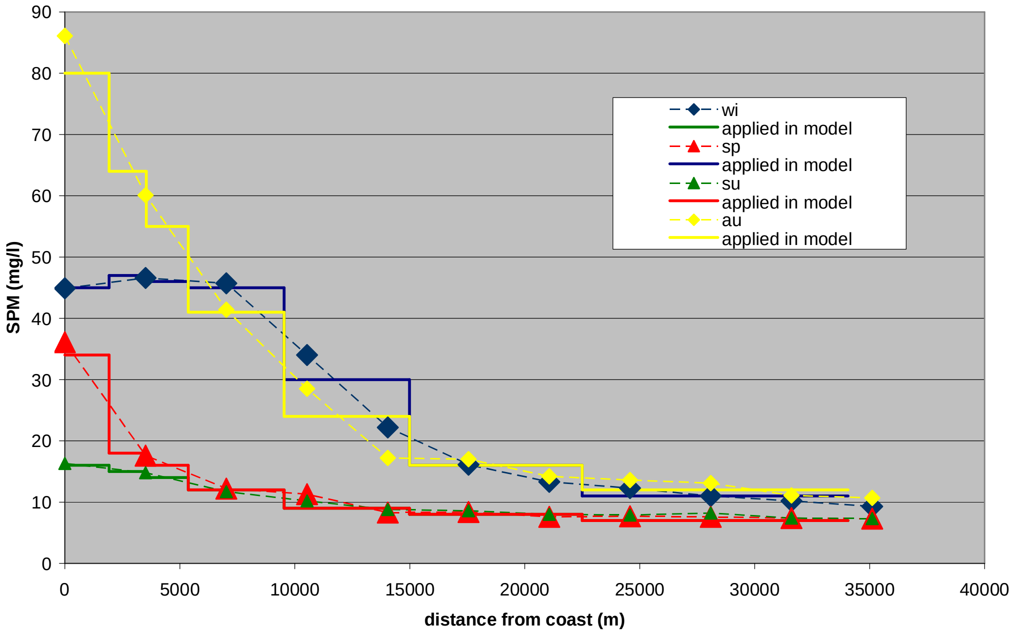

Fig. 2.3b: Applied concentration at southern boundary based on SeaWiFs images (wi = winter, sp = spring, su = summer and au = autumn observations converted to depth-averaged values).

3 Hydrodynamic model

3.1 Introduction

This chapter describes the hydrodynamic model that is used in the LTV-mud project. The description of boundary conditions, hard- and software is followed by a discussion of the results (water levels and salinities). Special attention is devoted to the differences with the hydrodynamic model that was used in the previous phase of the project, as described in Van Kessel *et al*. (2006). The figures that complement the description of the hydrodynamic model can be found in Appendix A.

3.2 Selection of simulation period

One of the improvements that was targeted for the LTV-mud project in 2007 was to move from a 14 day hydrodynamic simulation to a longer period (possibly one year). Another suggestion was to increase the vertical resolution of the hydrodynamic model from 5 layers to 10 layers. The main challenge would be to provide for enough storage capacity to store the model output, besides the computational time needed to simulate longer time periods. Table 3.1 gives an overview of estimates for both storage capacity and computational time needed for different model set-ups.

	Simulation period	
Computational time [days] **(storage capacity [GB])**	3 months	1 year
5 layer model	7 d. **(315 GB)**	28 d. **(1.260 GB)**
10 layer model	14 d. **(630 GB)**	56 d. **(2.520 GB)**

Table 3.1: Estimates of storage capacity and computational time for different model set-ups.

In order to avoid excessive storage needs and due to the limited time available to calculate the hydrodynamics, it was decided to select a 3 month simulation period. In the feasibility phase of the project, model results were compared for a 5- and a 10-layer model. The vertical parabolic profile of diffusivity proved to be comparable in both cases, as indicated in Figure A-3 for locations “Antwerpen loodsgebouw” and “Vlakte van de Raan”. Increasing the vertical resolution of the model from 5 to 10 vertical layers will therefore only have a small effect on the calculated suspended sediment transports, which was confirmed in a test calculation of mud transport with both vertical resolutions (see Chapter 4.3).

The months January to March 2000 were selected for the 3-month simulation. Both the monthly averaged values for wind speed and fresh water inflow are far from the extremes of the period 1995 – 2005 (Figures A-1 and A-2, respectively). In contrast, the months May, June, July and October 2000 show very high values for fresh water inflow while strong winds occurred in November 2000.

The monthly average fresh water inflow is higher in February (230 m^3/s) than it is in January and March (170 m^3/s). On a monthly timescale, one can indeed observe an increasing trend in the salinity in January and March and a slight decreasing trend in February (Figures A-9 through A-11). This effect is particularly visible in the mixing zone of saline and fresh water (stations Baalhoek and Overloop van Hansweert). The daily fresh water inflow for the different tributaries is summarised in Figure A-8. Especially the peak discharge event of 460 m^3/s on 04/03/2000 is noticeable as a drop in the observed salinities.

The monthly mean wind speed varies between 6 and 7 m/s (Figure A-1). Noticeable peaks in wind speed (10 minute mean > 17 m/s) occur at the end of January, and in the beginning of March, together with the peak of fresh water inflow. The main wind direction varies between NW and SW direction (225 to 315 ° from North).

3.3 Hydrodynamic model

The set-up of the model (grid, bathymetry, etc) is covered extensively in Van Kessel *et al.* (2006) and will not be repeated in this report. The hydrodynamic model runs from 1/1/2000 22h30 (HW) until 3/4/2000 22h30. A hydrodynamics simulation of 93 days is carried out.

3.3.1 Initial values

Initial values of water levels and velocities are read-in from a 4 day run of hydrodynamics. This avoids the wiggles in the first time-steps, that were observed in the 2006 version of the hydrodynamic model. The initial values of salinity are based on the available measurements (represented in Figure A-7). The following values are implemented:

Location	Salinity [ppt]
Sea	32.5
Vlakte van de Raan	32.5
Hoofdplaat	25
Overloop van Hansweert	17.5
Baalhoek	7.5
Oosterweel	0.4
Gent	0.3

Table 3.2: Initial salinity values.

In between these locations, salinity is linearly interpolated between the (*m*, *n*) points of the computational grid. Time series of salinity of Vlakte van de Raan, Hoofdplaat, Overloop Hansweert and Baalhoek were retrieved from HMCZ (www.hmcz.nl) on 25/07/2007. The timeseries at Oosterweel were provided by Flanders Hydraulics Research.

3.3.2 Downstream boundary conditions

The downstream boundary of the LTV model is partly located in the sea. In the 2006 version of the LTV model, 96 harmonic constituents of water level were prescribed at different points along the boundary. In the 2007 version of the model, the downstream boundary conditions for water level and velocity are read-in from a run of the ZUNO model. In order to have an optimal fit of the LTV model to the ZUNO model, a different (somewhat smaller) enclosure was chosen than the 2006 HD model, as is illustrated in Figure A-4. The downstream boundary condition is defined as a set of time-series with a 30 minute interval. All values (water levels, velocities and salinities) are prescribed uniformly over the depth.

At both the north- and sea downstream boundary of the model (different parts of the downstream boundary of the model are defined on figure A-4), water levels are prescribed. At the south downstream boundary, the along-shore component of velocity is prescribed. At every point of the downstream boundary a time series of salinity is prescribed. Typical salinity values for the northward, seaward and southward boundary are depicted in Figures A-5 and A-6. The salinity values at the northward boundary are significantly lower than the salinity values at the seaward and southward boundary. A possible explanation for this is the influence of the diffusive and advective mixing of the fresh water discharge of the river Rhine, which is modelled in ZUNO.

3.3.3 Fresh water inflow

At the upstream boundary of the tidal region, daily values of freshwater inflow are prescribed. The values were provided by Flanders Hydraulics Research. There is inflow in the model from the tributaries Kleine Nete, Grote Nete, Zenne, Dijle and Bovenschelde. At the time of writing of this phase report, the data of fresh water inflow from the Bathse Spuikanaal was not yet available. The fresh water inflow from the Bathse Spuikanaal will be included in the second phase of the project. The daily values (without Bathse Spuikanaal) are presented in Figure A-8 and briefly discussed in section 3.2.

3.3.4 Wind forcing

Wind measurements of Vlissingen were retrieved from the website of KNMI (www.knmi.nl) on 23/07/2007. Hourly values of wind speed at 10 m height, together with the wind direction are applied uniformly over the computational grid. The wind drag coefficient is set to 0.0026 (default). The hourly values of wind speed and direction are represented in Figures A-12 to A-14, and are briefly discussed in section 3.2.

3.3.5 Hardware

The hydrodynamic model was run on the Linux cluster of Flanders Hydraulics Research. The run is performed on 10 dual core nodes, thus using 20 processors. Each node is a HP proliant G3 node with a 2.33 GHz dual core Xeon 5140 processor and 2GB RAM. In this set-up, hydrodynamics are calculated with a speed-up of 13.5 (which means that the calculation runs 13.5 times faster than reality). However, if the heavy model output of 1 map of hydrodynamics every 30 minutes is switched off, the hydrodynamics are calculated with a speed-up of 28.8. A part of this difference can be explained by the extra communication needed to write the results to SDS-file. A part of the difference in speed-up however remains unaccounted for, and can possibly be optimised.

3.3.6 Software

The model is run in the SIMONA software suite of Rijkswaterstaat, release 0612. The WAQPRE module is used for pre-processing, and WAQPRO for processing. Postprocessing is done using the getdata routine to generate netCDF files of different variables (time series and spatial distributions). These files are then read-in and further processed in Matlab. netCDF is an open source standard of a binary data container for scientific datasets. netCDF-files are read in in Matlab using the mexcdf software package (freeware, retrieved from http://mexcdf.sourceforge.net/ on 25/04/2007).

3.4 Validation of results

3.4.1 Water level

Simulated water levels are compared to measurements at the locations Vlakte van de Raan, Vlissingen, Overloop Hansweert, Bath, Liefkenshoek and Antwerpen. Measurements of water level were retrieved from HMCZ (www.hmcz.nl) on 23/07/2007. Both measurements and simulations are represented in two-weak graphs for the period 26/02/2000 to 09/03/2000 (Figure A-24 to A-26) and for 25/03/2000 to 06/04/2000 (Figure A-27 to A-29).

The phasing of water level during the tide and the spring-neap cycle are predicted correctly. Deviations up to 0.5m can occur however, both for low water levels and high water levels. Generally, the tidal range is up to 1 m too high when compared to measurements. This means that simulated velocity and bottom friction (both during ebb and flood) will be too high.

Closer inspection of the results shows that the error in water levels at Vlakte van de Raan is similar to the error in water levels at Antwerpen. A possible explanation is that the boundary conditions of water levels have an amplitude that is too large. This error in boundary conditions then propagates through the model. The source of the error in water levels is known, and in the second phase of the project, a new set of downstream boundary conditions will be applied.

3.4.2 Salinity

Model results of salinity are compared to measurements in figures A-16 to A-23. Salinity measurements are available at stations Vlakte van de Raan, Hoofdplaat, Overloop van Hansweert, Baalhoek and Oosterweel. The measurements of all the stations are summarised in Figures A-9 to A-11. The measurements show that the amplitude of salinity variations reach a maximum in the mixing zone of fresh and salt water (stations Overloop Hansweert and Baalhoek). Typical amplitudes of salinity variation during one tidal cycle are 3 ppt at Vlakte van de Raan, 5 ppt at Hoofdplaat, 6 to 8 ppt at Overloop Hansweert and Baalhoek, and 2 to 3 ppt at Oosterweel.

The course of the simulated salinities at Vlakte van de Raan shows variations that need further investigation in the second phase of the project. Some peaks in simulated salinities occur at times of strong gusts of wind, so maybe a smoother time series of wind forcing might dampen the strong variations.

At Hoofdplaat the amplitudes of salinities show a similar course than the measurements. The amplitude is higher in the first decades of January, and becomes smaller in the last days of January and the first days of February, due to a peak in river discharge at the end of January. Simulated salinities at Hoofdplaat have a maximum that is 1 to 2 ppt higher than the measurements. The peak discharge in the beginning of March has a stronger effect in nature than in the model. This can have two possible causes. The peak in the fresh water discharge data set is based on one data point only (460 m^3/s on 04/03/2000). This yields a very narrow peak in the fresh water discharge that possibly does not cover the correct volume of fresh water that is flushed in the estuary during the event. Better results may be obtained by adding more points in the curve of fresh water discharge in order to smoothen the peak and to increase the volume of fresh water that it contains. Secondly, the data of the Bathse Spuikanaal are not yet included in the version of the model that is reported in this intermediate report. The fresh water discharge of this canal can reach peak values of more than 100 m^3/s, which has an important effect on the salinity in the Western Scheldt.

The salinities at Hansweert and Baalhoek show a good accordance in January. The rising trend is predicted correctly. In February, the measured values at low water slack are 1 to 2 ppt lower than the simulation. At Baalhoek, the maxima are also 2 ppt too high while this is not the case in Hansweert. In March the measurements again are lower than the simulation, possibly due to the same two reasons as stated above. At Oosterweel the simulation yields maxima that are 1 to 2 ppt too high. The major differences occur during March, which supports the hypothesis that not enough fresh water is contained in the simulated peak flow at the 4th of March.

3.5 Conclusions

The simulation of hydrodynamics has resulted in an SDS file containing every 30 min. water levels, velocities, and vertical mixing coefficients (among other parameters). The simulated period extends from 01/01/2000 22u30 to 03/04/2000 22u30, which spans a period of 93 days. The tidal range in the model is too high, so it is expected that the modelled velocities will also be too high. This also has an important effect on the predicted levels of bottom boundary stress. Three issues are identified that can improve the hydrodynamic simulation:

1. First of all, a different set of downstream boundary conditions will be implemented.
2. The time series of fresh water inflow of the Bathse Spuikanaal will be added in the model.
3. The high fresh water inflow event in the beginning of March can be modelled more accurately by adding locally more data points in the time series of fresh water inflow in order to increase the volume of fresh water contained in the peak.

Also, a more profound analysis of the hydrodynamics will be carried out. Tidal asymmetry will be assessed using harmonic analysis, and maps of residual currents will be drawn. These additional issues will be discussed in the report of the second phase of 2007.

4 Mud transport model

In this chapter, a number of improvements to the mud transport model are discussed, following the recommendations from the previous phase of the LTV project. A major limitation of the 2006 model was the unsatisfactory reproduction of the turbidity maximum near Antwerp. The following simulations are discussed:

4. a minor shift of the dumping locations of dredged material near Antwerp;
5. new concentration BC based on SeaWiFs images;
6. comparison between simulations with 5 and 10 horizontal layers (regarding both hydrodynamics and mud transport);
7. incorporation of variable wave forcing;
8. matching of sediment dumping and siltation fluxes;
9. effect of stabilizing and destabilizing effects of biological activity;
10. potential effect of shipping traffic;
11. validation on 3-month hydrodynamics.

Recapitulating from the 2006 study, the parameter settings used are shown in Table 4.1. For a description of the model formulations is referred to Van Kessel *et al.* (2006). All mud transport simulations are made for a period of one year. As the period for which hydrodynamic results are available is much shorter (either 2 weeks or 3 months), this shorter period is applied consecutively to fill up a complete year. Depending on the spin-up time for the mud transport model, it may be required to simulate a second year to reach a dynamic steady-state condition. As the applied boundary conditions and wave-induced bed shear stress exhibit seasonal dynamics, also the mud model may show seasonal behaviour.

parameter	**value**	**units**	**value**	**units**
	fraction 1: marine		*fraction 2: fluvial*	
w_s	1.0	mm/s	1.0	mm/s
α	0.1	–	0.05	–
τ_{crit1}	0.2	Pa	0.2	Pa
M_1	2.3×10^{-5}	s^{-1}	2.3×10^{-5}	s^{-1}
d	0.05	m	0.05	m
τ_{crit2}	0.5	Pa	0.5	Pa
M_2	$3.5\ 10^{-7}$	$kg/m^2/s$	$3.5\ 10^{-7}$	$kg/m^2/s$

Table 4.1: Final parameter settings used in 3D model. Note that the settings for the marine and fluvial fraction are equal apart from α.

4.1 Shift of dumping locations

First the effect of a shift of the dumping locations Punt van Merelse and Plaat van Boomke a few 100 m towards the navigation channel (see Fig. 4.1) was studied, as it appeared that the grid cells at the original locations remained inactive during the 14-day hydrodynamic simulation. As a result, all sediment dumped accumulated permanently in these cells and did not become available for transport. Accretion in the access channels and harbours was therefore not compensated by dumping, causing sediment depletion and low SPM levels near Antwerp. At the new locations, however, sediment can be resuspended and further dispersed. This results in higher SPM concentrations near Antwerp that are in better agreement with observations. This is illustrated in Fig. 4.2, showing the computed concentration levels near Doel and Zuidergat for the original and new dumping locations. The observed 10 and 90 percentile, summer and winter mean SPM concentrations are indicated herein with coloured horizontal lines. The horizontal and vertical SPM concentration distributions are shown in Appendix B.1.

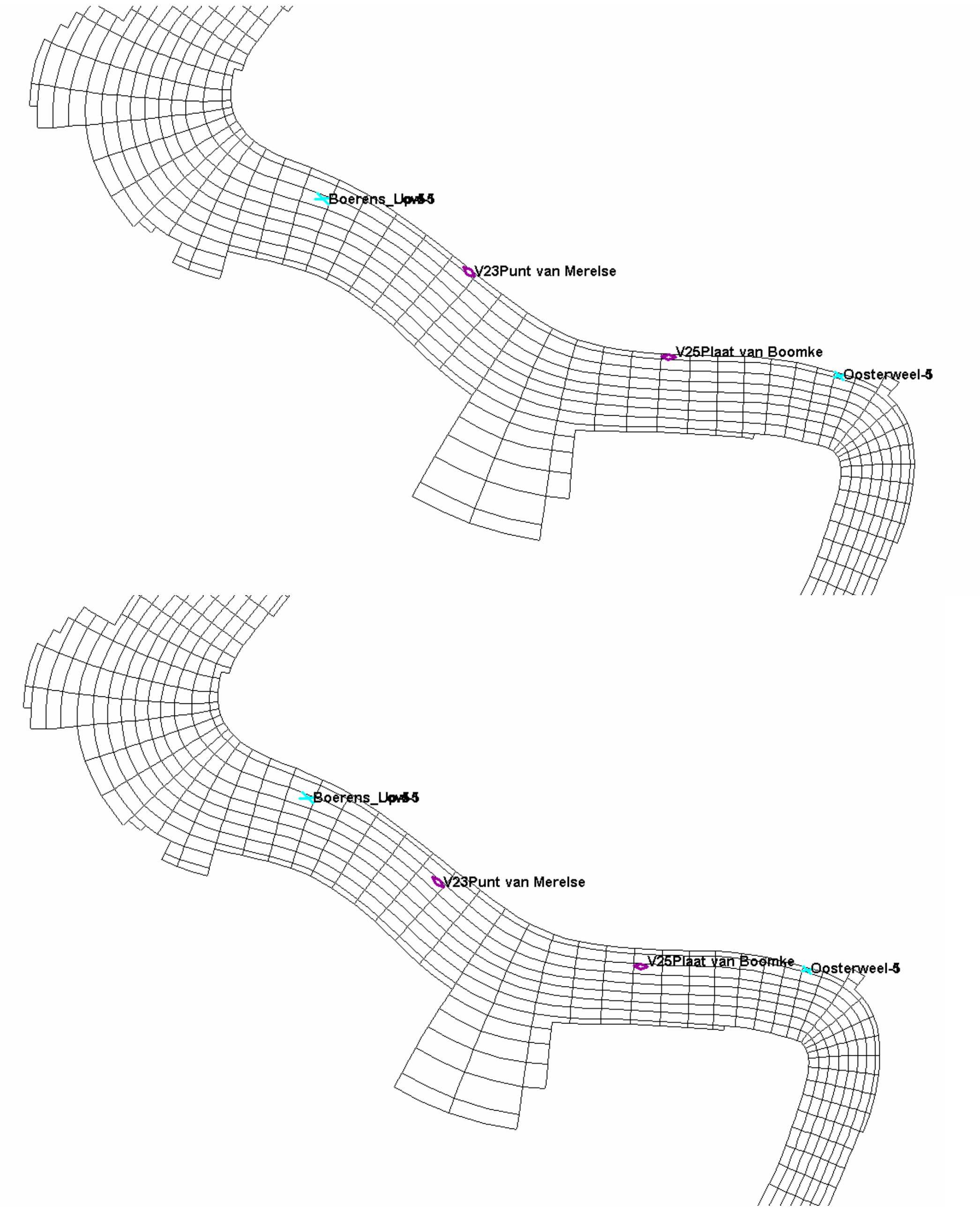

Fig. 4.1: Shift of dumping locations. Top: original locations Punt van Merelse and Plaat van Boomke; Down: new locations. (N.B. light-blue markers designate observation points).

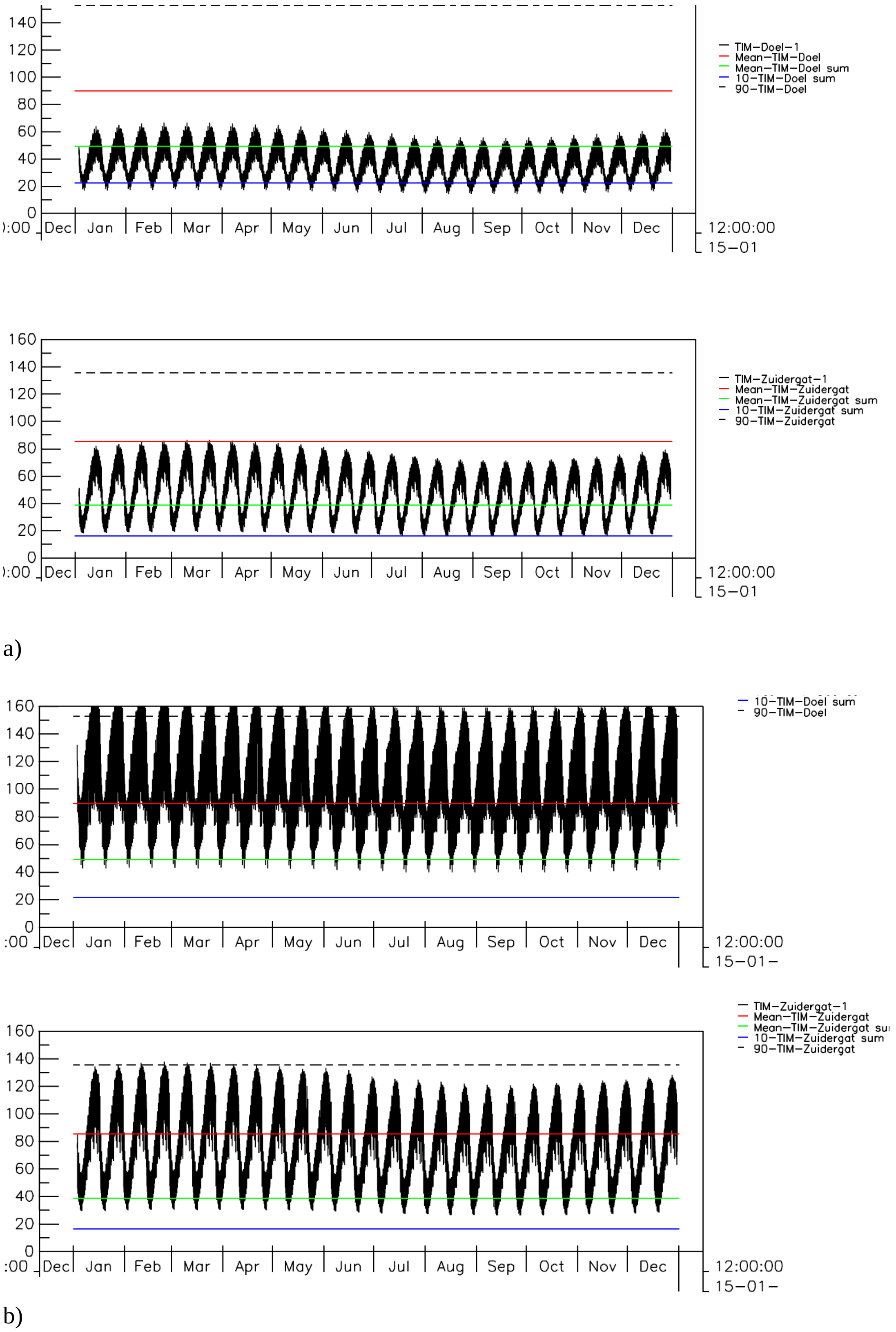

Figure 4.2: Computed SPM surface concentration near Doel and Zuidergat. a) original dumping locations; b) new dumping locations. Observed mean levels are indicated with horizontal lines. In blue: 10-percentile level; in green: mean summer level; in red: mean winter level; dashed black: 90-percentile level.

4.2 New concentration boundary conditions

Figure 4.4 shows horizontal distribution of the 14-day average SPM surface concentration for the original and new concentration boundary conditions (see Chapter 2.2). The new BC result in a significant decrease of the SPM levels at the North Sea, which are in a better agreement with observations. This is illustrated in Appendix B-2, in which the modelled and observed SPM concentrations at Wielingen are shown. The concentration maximum near the port of Zeebrugge is maintained with the new BC, which agrees with the SeaWiFs observations (Fig. 2.1).

With the new BC, the alongshore residual sediment flux ranges between 32 MT/y and 66 MT/y for summer and winter condition, respectively. Although this flux is substantially less than that for the original BC (up to 174 MT/y), it is still fairly high compared with estimates of the residual SPM flux through Dover Strait (between 22 in June and 58 MT/y in January according to McManus and Prandle, 1997) and along the Belgian coast (approximately 25 g/ms according to Fettweis *et al*., 2007, which is equivalent with 28 MT/y for a 35 km long transect normal to the coastline, see Fig. 4.3). It is remarked that the analysis by McManus and Prandle (1997) was based on 15 monthly survey cruises between August 1988 and October 1989.

As a 14-day hydrodynamic period is too short to draw well-founded conclusions on residual fluxes in view of the large variability of the residual currents, it is judged that the model performance is sufficient regarding the residual SPM flux. When a longer hydrodynamic simulation (based on a 3 month period or a complete year) becomes available, the residual SPM flux will be re-investigated to make a more conclusive judgement.

xxx result on 3-month hydrodynamic period:

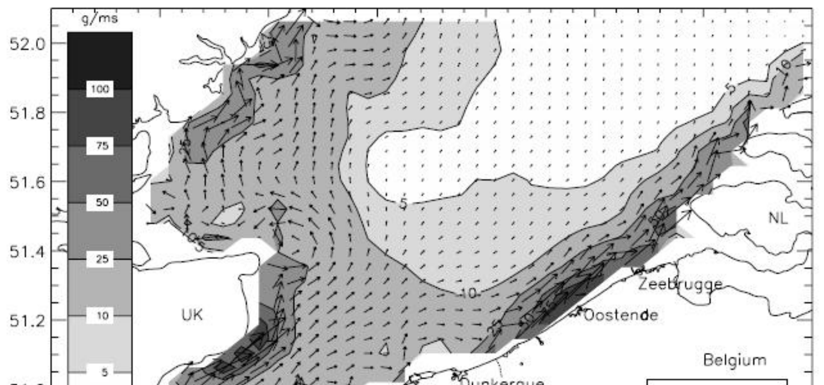

Figure 4.3: Yearly averaged SPM transport per unit width (g/ms) in the southern North Sea. The SPM concentration from the satellite images has been corrected vertically to obtain depth-averaged values (after Fettweis *et al.*, 2007).

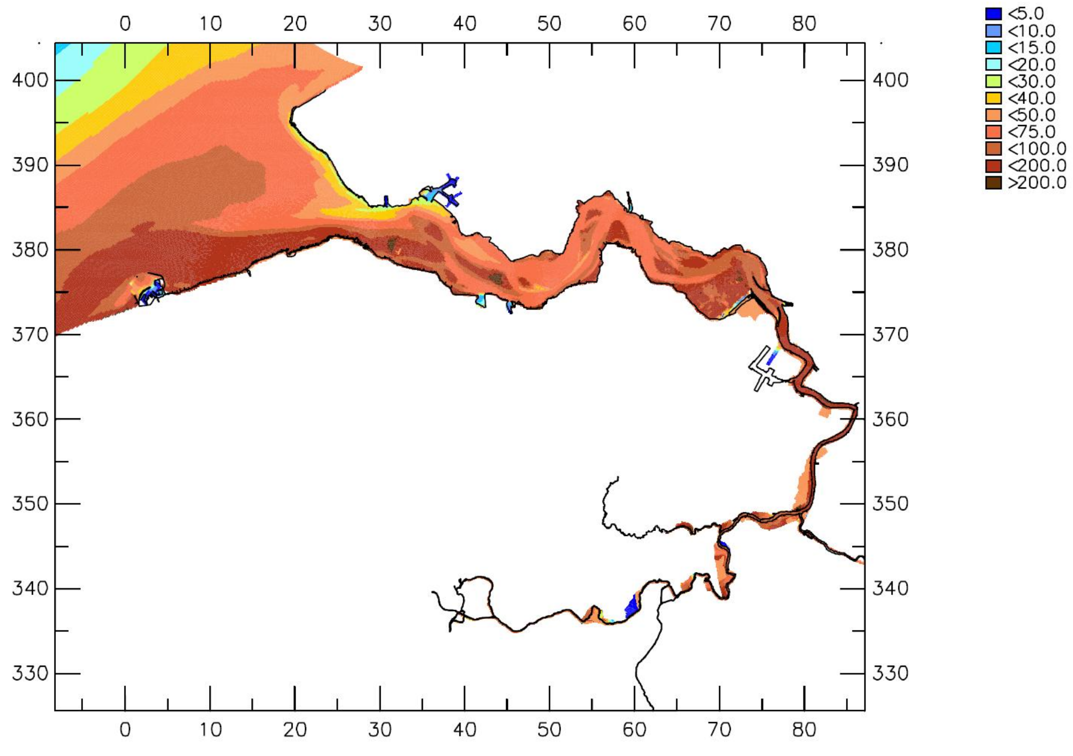

Fig. 4.4a: 14-day winter averaged SPM surface concentration (mg/l), original BC (ws19).

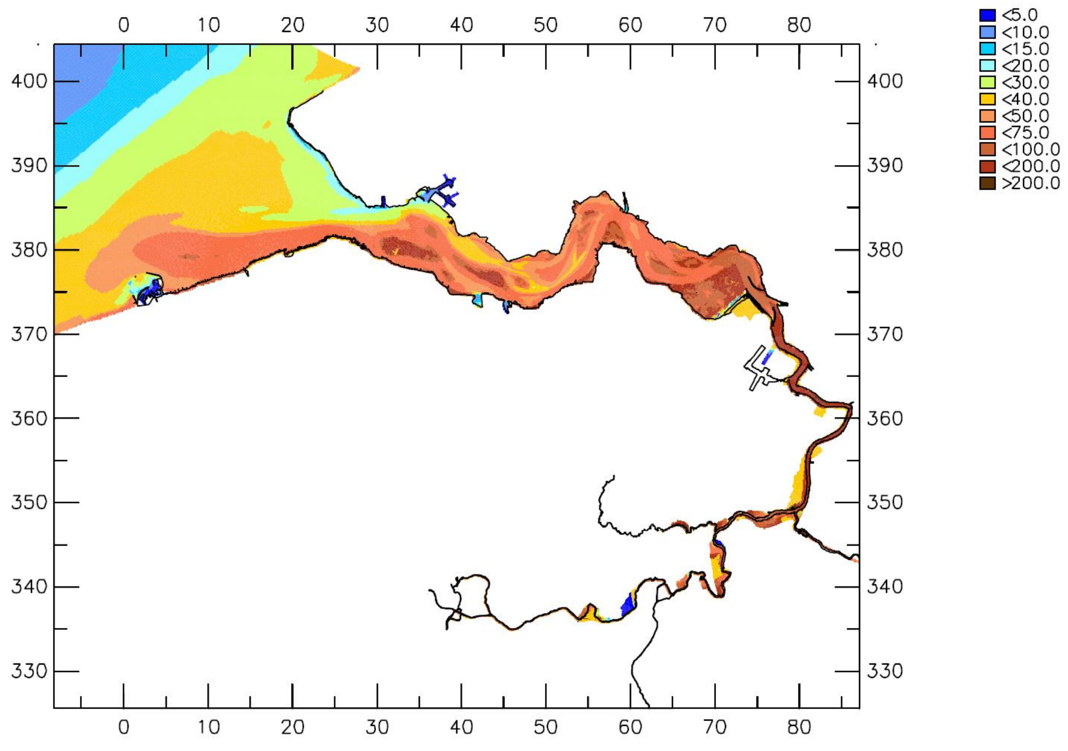

Fig. 4.4b: 14-day winter averaged SPM surface concentration (mg/l), new SeaWiFs BC (ws20)

4.3 Comparison between 5 and 10 layers

A proper simulation of the estuarine circulation requires sufficient vertical detail. The number of 5 layers used in the base simulation is considered to be a bare minimum. To investigate the sensitivity of the simulation results on the vertical resolution, also a 14-day hydrodynamic period was also computed with 10 horizontal layers. Results on the vertical current and eddy viscosity profiles for 5 and 10 layers were already discussed in Chapter 3.2 (see also Fig. A-3). It was concluded that the 5-layer profiles did not deviate significantly from the 10-layer profiles.

The same conclusion is drawn from the mud transport simulations. Figure 4.5 shows the 14-day winter averaged vertical SPM concentration transects along the Scheldt estuary in case of 5 and 10 horizontal layers. Although the near-bed concentrations do increase moderately, concentration levels in the remainder of the water column are similar. Also the spatial distribution of SPM remains largely unaffected (see Figs. B.3). It is therefore concluded that at this phase of the project, the limited benefit of 5 additional layers does not justify the required twofold increase in CPU time and disk storage capacity.

4.4 Wave effects

In 2006, wave effects were included by applying a constant, year-averaged wind speed of 7 m/s and assuming a constant fetch length of 25 km. Subsequently, the wave-induced bed shear stress was computed from the equilibrium wave height as a function of the local water depth throughout the model domain.

In this phase of the project, wave effects are included based on a SWAN wave model of the Scheldt estuary forced by observed wave conditions at the North Sea boundary (observations from location Scheur West, see Fig. 4.6) and observed wind speed and direction measured at Vlissingen. The wave fields are computed at a two-hourly interval for the year 2000, resulting in approximately 4400 wave fields. The computations were made with a variable water depth supplied by the hydrodynamic model, which is especially important for the shallow areas. With a Matlab-script, the wave fields computed by SWAN are converted into map fields for the wave-induced bed shear stress that are imported into the DELWAQ mud transport model.

The results presented in this concept report do not yet cover the complete year 2000, but only the first two months of this year. However, this is sufficient to evaluate the method.

The results of the simulation with variable wave forcing are shown in Appendix B-4. For comparison, also the results of the simulation with constant wave forcing are shown herein. Note that both simulations are still based on a hydrodynamic simulation period of 14 days. The most pronounced changes do occur at the North Sea and in the western part of the Western Scheldt, where the typical wave energy is significant compared to the tidal energy. Towards Antwerp, the tidal energy is by far dominant. Nevertheless, high-concentration peaks generated by wave-induced resuspension in the western part of the estuary may be advected up-estuary by tidal pumping and result in temporarily higher SPM concentrations.

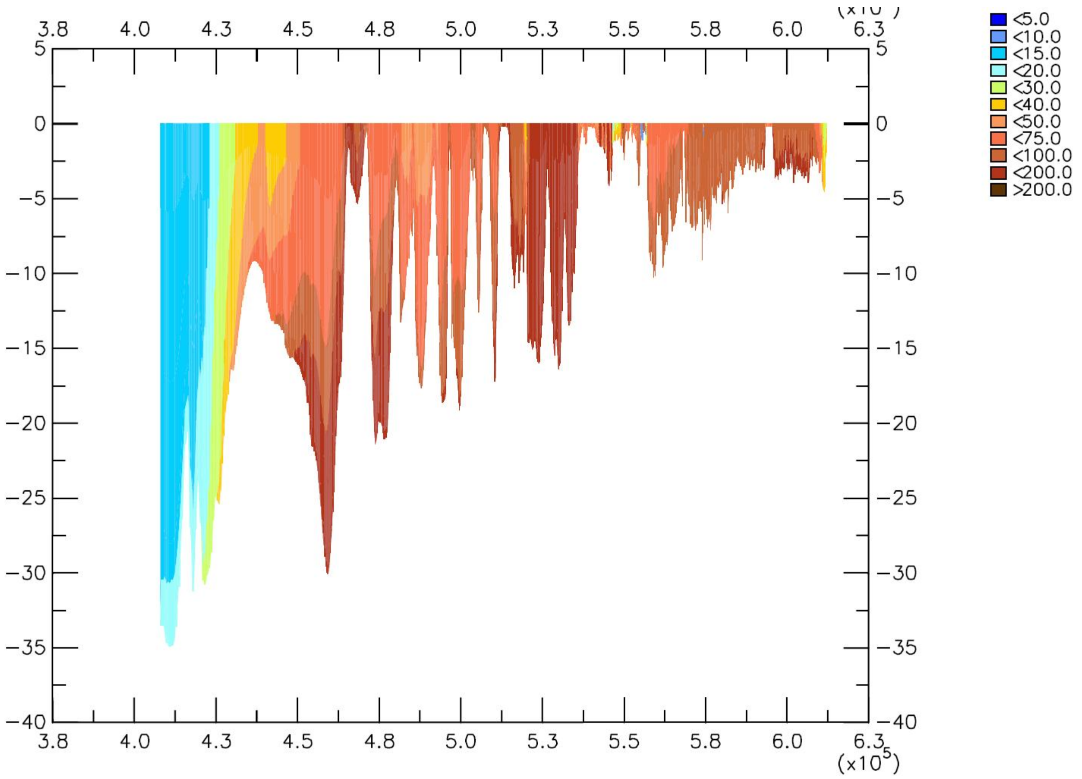

Fig. 4.5a: 14-day winter averaged vertical SPM concentration transect (mg/l), 5 horizontal layers (05L01).

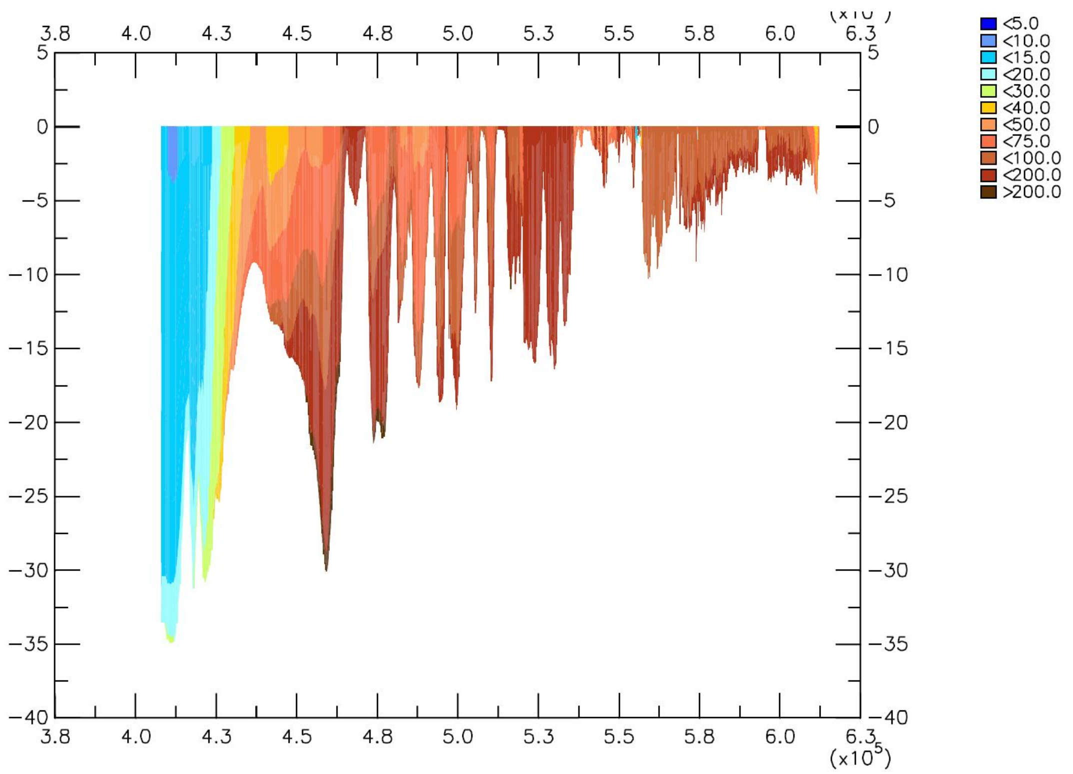

Fig. 4.5b: 14-day winter averaged vertical SPM concentration transect (mg/l), 10 horizontal layers (10L01).

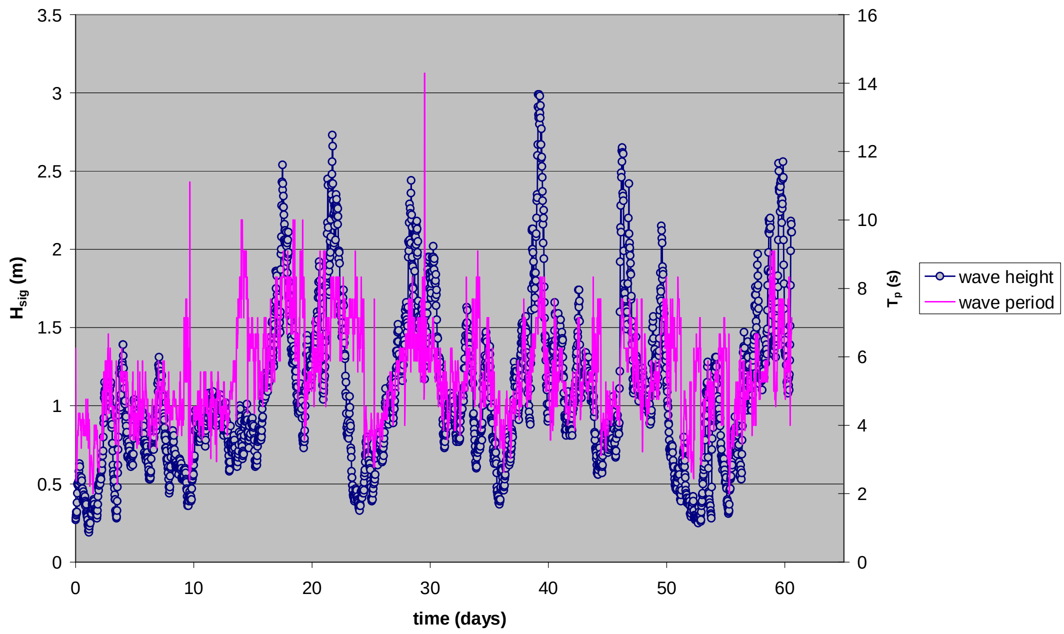

Fig. 4.6: Wave boundary conditions at North Sea (location Scheur West). Start date 01/01/2000.

Because of the variable waves, the average SPM concentration tend to increase in the western part of the model domain. This can be explained by the peaks in bed shear stress during storm, which do not occur for the simulation with a constant wave-induced bed shear stress.

It is concluded that the technique for applying variable wave forcing is available and gives sensible results. However, a more detailed validation needs to be carried out when the 3-month hydrodynamic simulation becomes available.

4.5 Influence of biology

Stabilisation and destabilisation of the seabed by biological activity may have an impact on the SPM levels in the Scheldt. Biological activity plays a role notably in the shallow parts of the estuary. In the deeper parts (below NAP –3 m), physical effects are dominant (Borsje *et al.*, 2007).

Diatoms have a stabilising influence on the sediment surface, whereas the clam *Macoma bathica* and the mud snail *Hydrobia ulvae* have a destabilising influence. The biomass of these organisms shows a seasonal variation, with low values in winter and high values in summer. In summer, the biological impact is therefore expected to be more pronounced than in winter.

As an initial step, the variation of the biomass of diatoms, *Macoma* and *Hydrobia* as a function of depth and season is assumed to be equal to the variation in the Wadden Sea reported by Borsje *et al*. (2007). At a later stage, values more representative for the Scheldt estuary may be applied. Also other stabilising or destabilising species may be considered. However, a comparison with data from De Jong and De Jonge (1995) on the chlorophyll-*a* distribution in the Western Scheldt does not reveal large discrepancies.

The relative effect of biology on the critical shear stress for erosion τ_c and the resuspension parameter M during summer is shown in Fig. 4.7. At a level above 0 m NAP, the stabilising effect of diatoms dominates, resulting in an increase in τ_c and a decrease in M. At levels between –3 and 0 m NAP the destabilising effect of *Macoma* and *Hydrobia* dominates, resulting in a decrease in τ_c and an increase in M. At levels below –3 m NAP, the biomass is set at zero and therefore no effect of biology is found.

Fig. 4.8 shows the 14-day average surface SPM concentration at Terneuzen with and without biology. The biological impact results in a concentration decrease in summer and a concentration increase in winter. Also, the concentration minimum occurs approximately one month earlier in the year, which is in better agreement with observations (*e.g.* see Fig. 3.10 in the previous report by Van Kessel *et al.*, 2006). However, for the settings presently applied the overall effect of biology on the SPM concentration is quite small: the in- and decrease is in the order of 1 mg/l only.

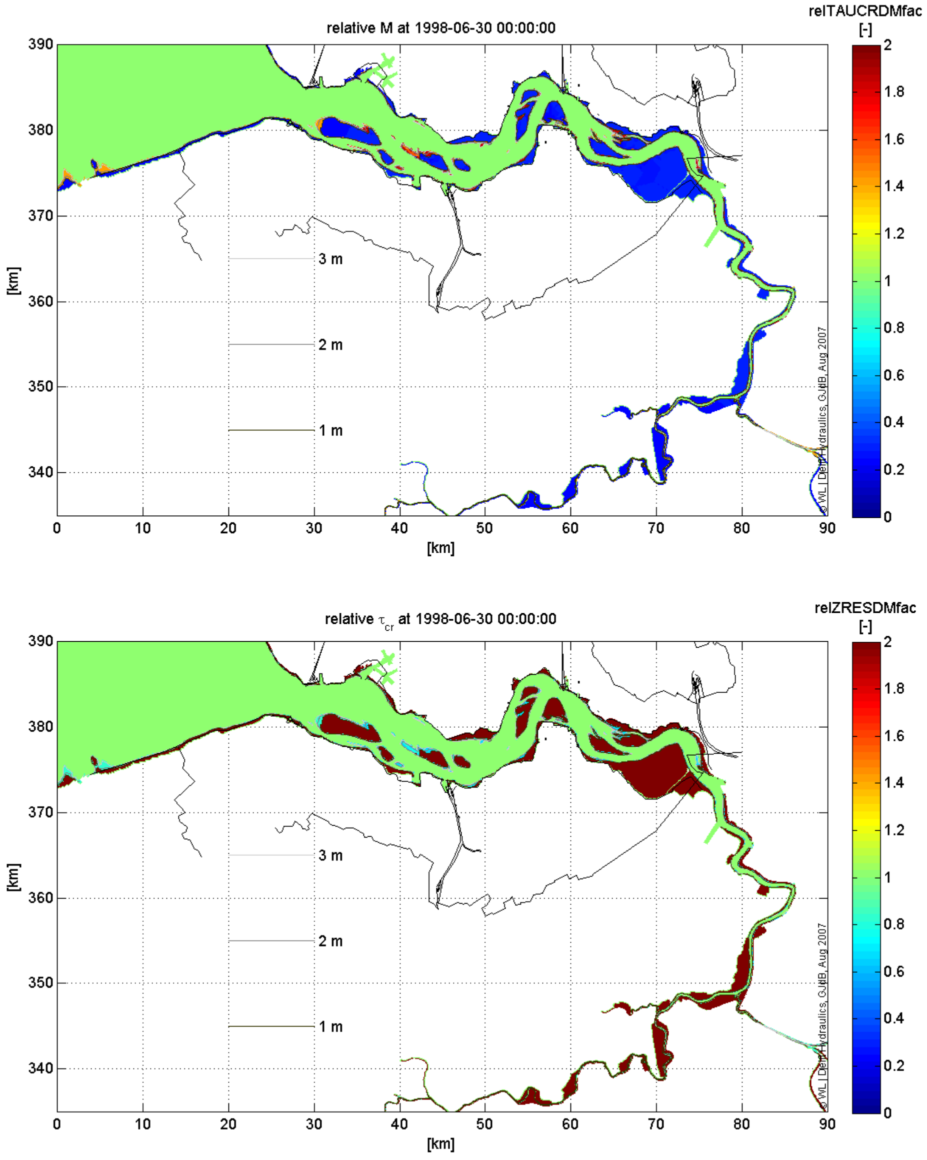

Fig. 4.7: Relative influence of biology on resuspension parameter M (upper panel) and critical shear stress for erosion τ_c (lower panel) on June 30. 1 = no biological effect.

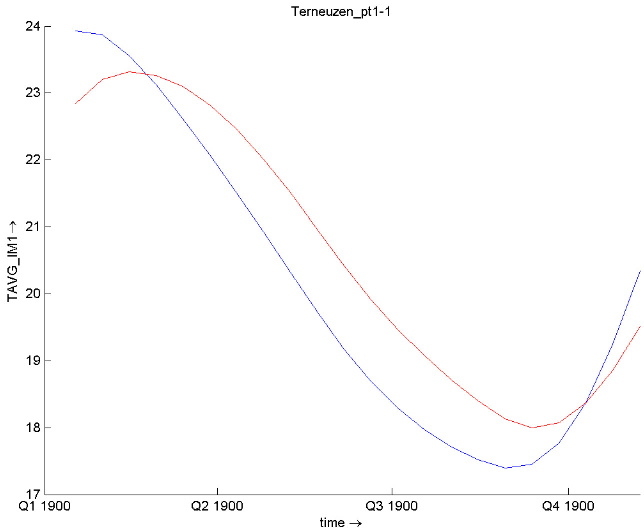

Fig. 4.8: Year variation of the 14-day averaged SPM surface concentration (mg/l) at Terneuzen; red line: without biology; blue line: with biology.

It should be realised that the surface area above –3 m NAP in the Scheldt area is relatively much smaller than in the Wadden Sea, thus reducing the potential impact of biological effects.

Appendix B-5 shows both the 14-day average SPM surface concentration and the mud content in the bed in summer. It is clear that although the computed overall effects of biology in the estuary are minor, the biological effects are significant on the intertidal flats: because of stabilisations, the mud content is locally increased in summer, whereas the SPM concentration is decreased.

It is concluded that:

1. The technical infrastructure required to include biological effects is available.
2. Assuming that the settings in the Wadden Sea are representative for the Scheldt estuary, the biological impact on the overall SPM levels appears to be minor. SPM levels appear to be much more influenced by physical processes such as waves.
3. However, local effects on bed composition and SPM levels appear to be significant.
4. The biological settings should be more tailored for the conditions in the Scheldt, *e.g.* by optimising biomass availability, considering other species and taking into account the effect of salinity gradients on the distribution of species.

4.6 Matching of siltation and dumping flux

The 2006 mud transport simulations were not yet balanced regarding the rate of harbour siltation and dumping of dredged material from harbours. Table 4.1 shows the rate of siltation and dumping for a simulation with 2006 settings, apart from the new SeaWiFs concentration BC (ws20). Harbour siltation amounted to 3 MT/y, whereas sediment dumping amounted to 7.7 MT/y.

Location	siltation (kT/y)		dumping (kT/y)	
	ws20	ws24	ws20	ws24
Zeebrugge + Western Scheldt	1714	1915	5636	2718
Sea Scheldt	1286	1316	2075	2075
TOTAL	3000	3131	7711	4793

Table 4.1 Siltation and dumping rates for original settings (ws20) and new settings (ws24).

To improve the balance between siltation and dumping, two actions have been taken:
1. Enhance sedimentation by increasing τ_c in the harbour basins.
2. Reduce the rate of dumping.

The first action has most effect at Zeebrugge, where in reality waves to not propagate into the harbour basins. However, the jetties have not yet been included in the wave model. Therefore too little siltation is computed at Zeebrugge. A local increase in τ_c will compensate for this unrealistic behaviour. The second action is justified in view of the uncertain (and highly variable) data on sediment duping, including the mud content of the dredged material.

Fig. 4.9 shows the 14-day average SPM surface concentration for the simulation with the original and new settings. It is obvious that the SPM levels decrease substantially. From a comparison with observed levels (see Appendix B-6, which also shows detailed mud budgets for both simulations), it is concluded that the modelled SPM concentrations become too low for the new settings, notwithstanding a better (though not yet sufficient) balance between dumping and harbour siltation. The two most likely explanations for this performance loss are:
1. The model is presently calibrated for the situation with an unbalance between harbour siltation and mud dumping; for the situation with an improved balance, other parameter settings may increase the SPM levels towards the observed range.
2. Too much of the released mud is stored on mudflats; too little may remain in suspension and return to the harbour basins.

As the SPM levels appear to be rather sensitive to the cycle of harbour siltation and dumping, this aspect should be an integral part of the model calibration. Further optimisation is still required.

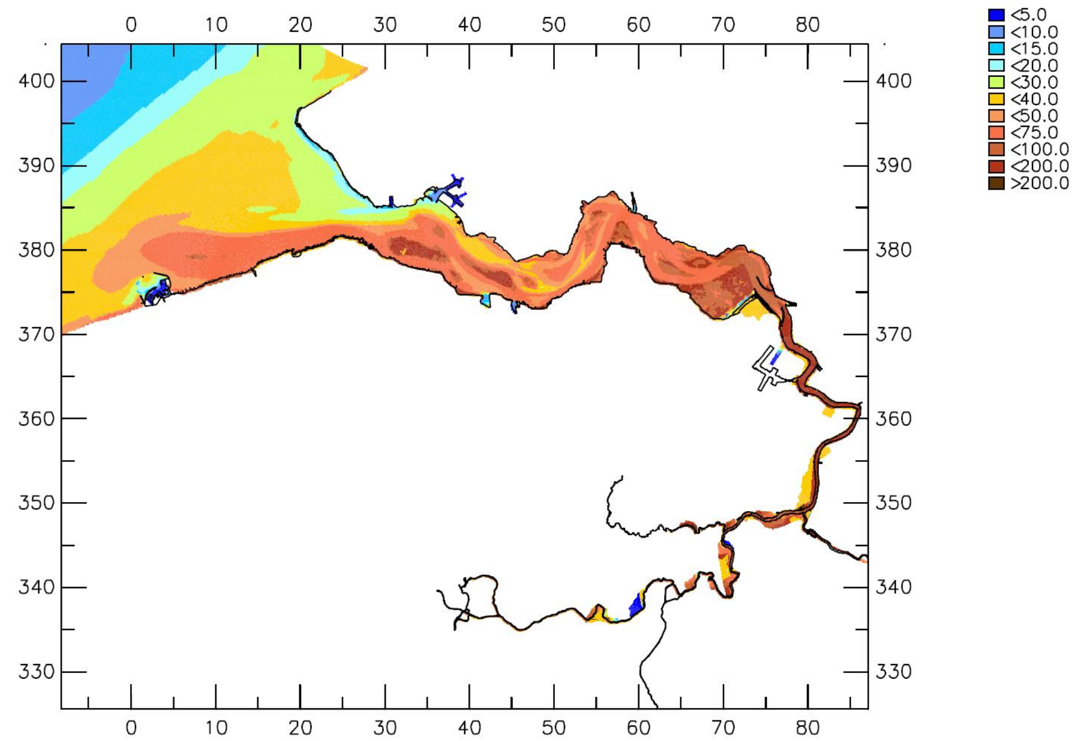

Fig. 4.9a: 14-day winter averaged SPM surface concentration (mg/l), original settings (ws20).

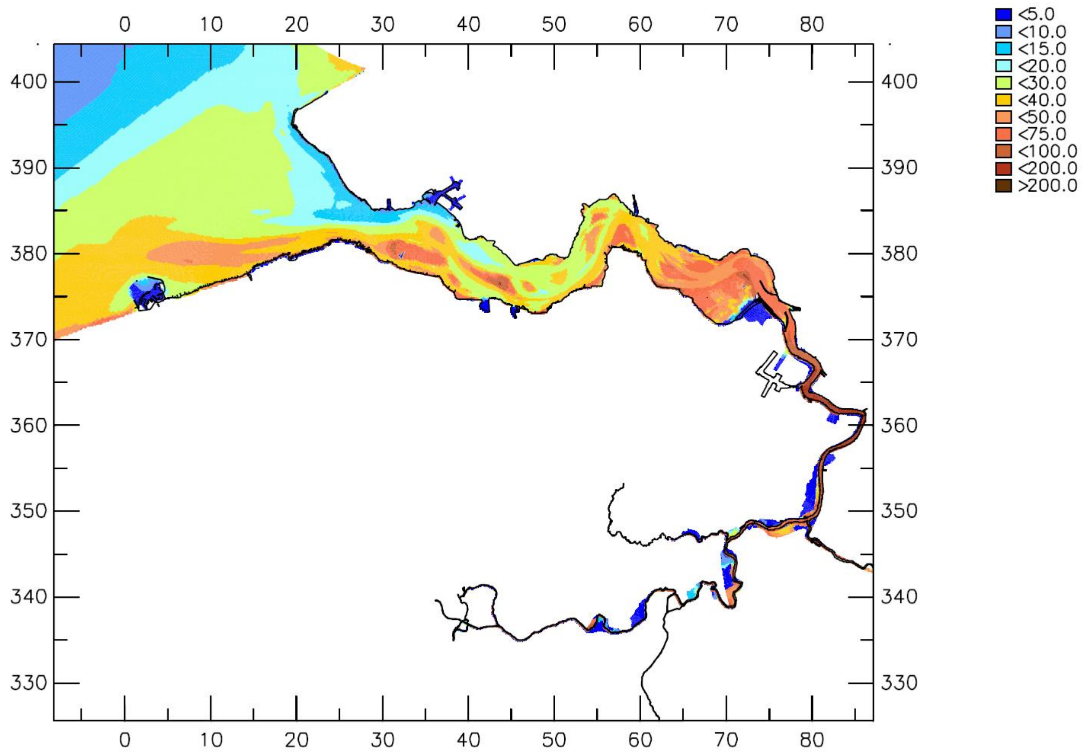

Fig. 4.9b: 14-day winter averaged SPM surface concentration (mg/l), new harbour settings and reduced dumping rate (ws24).

4.7 Effect of shipping traffic

A sensitivity analysis was made on the potential effect of shipping traffic on SPM concentration levels. To this order, two simulations were compared. The first simulation is a simulation without the effect of shipping traffic. In the second simulation the effect of shipping traffic was taken into account by increasing the bed shear stress of each grid cell with a value of $\Delta\tau$ Pa and with a probability p. A new draw was made every 15 min for a period of one day. Fig. B.7a in Appendix B-7 shows a typical example of the total bed shear stress including ship movements for $\Delta\tau$ = 0.5 Pa and p = 1%. Herein the effect of ships appears through the presence of points with enhanced bed shear stress. Fig. B.7b shows the resulting effect on SPM levels. It is concluded that for the applied settings ($\Delta\tau$ = 0.5 Pa and p = 1%) the effect of ship movements is substantial: near Terneuzen, the 14-day average SPM surface concentration increases from 15 to 23 mg/l. However, a more detailed and sophisticated analysis of the navigation density in the Scheldt and its influence on bed shear stress is required to draw more definitive conclusions. Notably, the applied 1% probability of influence of ship movement on the local bed shear stress may not be realistic.

4.8 Validation on 3-month hydrodynamics

Appendix B-7 shows results on a mud transport simulation based on a 3-month hydrodynamic period (Jan – Mar 2000). Preliminary observations based on these model results are:

- Although a number of differences is observed, the results of the simulations do not strongly differ from those based on a 14-day hydrodynamic database;
- The longshore residual mud flux along the Belgian coast is much smaller than for the 14-day simulations. This must be caused by differences in the residual current, as the SPM concentration boundary condition was not changed. The residual currents are steered by the applied boundary conditions. Although the residual longshore flux is much smaller, its influence on SPM levels in the inner estuary appears to be minor.
- Computed SPM levels agree quite well with observed levels, although the variability in the 3-month simulation is still smaller than the available in the available dataset at DOW-jetty. On an intertidal timescale, the computed variations agree well with observed variations.
- The first 3-month simulation does not yet have a good balance between harbour siltation and dredging (=dumping). As a result, a sediment surplus of 3.7 MT/y is entering the Scheldt estuary in the model. Part of this material accretes inside the estuary on tidal flats (0.9 MT/y), but most is exported towards the North Sea (2.8 MT/y). This aspects needs attention prior to application of the model for managerial issues.

A further analysis will be part of the next phase of the project.

5 Conclusions

At a technical level, all model improvements scheduled for 2007 have been implemented. The most important developments are: longer hydrodynamic simulation period (up to one year), more accurate concentration boundary conditions, variable wave effects and biological effects. As mud transport simulations based on these improvements are still in progress, final conclusions on the model performance and its suitability to supporting managerial questions can not yet be drawn. Based on first results the following preliminary conclusions are drawn. More definite conclusions will be drawn in the report of the next phase of the project LTV-mud.

On hydrodynamics

The simulation yields realistic values for water levels and salinities, although it is expected that the modelled velocities will be too high. Three actions are identified that can enhance the simulated hydrodynamics:

1. The high fresh water inflow event in the beginning of March can be modelled more accurately by adding locally more data points in the time series of fresh water inflow in order to increase the volume of fresh water contained in the peak.
2. Furthermore, the time series of fresh water inflow of the Bathse Spuikanaal has to be added in the model.
3. Finally, a different set of boundary conditions, or a new combination of water levels and velocities of the existing set could yield better results for water levels.

Also, a more profound analysis of the hydrodynamics will be carried out. Tidal asymmetry will be assessed using harmonic analysis, and maps of residual currents will be drawn. These additional issues will be discussed in the report of the second phase of 2007.

On mud transport

1. A minor shift of two dumping locations near Antwerp much improves the proper modelling of the estuarine turbidity maximum (ETM).
2. New concentration boundary conditions at sea based on SeaWiFs satellite images result in more realistic SPM concentrations at sea and more realistic longshore SPM fluxes. The turbidity maximum near Zeebrugge is well reproduced.
3. The difference between simulations with 5 and 10 horizontal layers is minor.
4. Variable waves temporarily enhance the SPM concentration in the western part of the Western Scheldt during storms. Towards Antwerp, the computed SPM time series are tide-dominated, but higher concentrations may occur after storms by advection from sea direction.
5. With biological settings taken from a Wadden Sea model, the biological impact on large-scale SPM concentrations in the Scheldt estuary appears to be minor. However, the SPM concentration and mud content of the bed can be significantly affected locally.
6. The SPM levels appear to be rather sensitive to the cycle of harbour siltation and dumping, this aspect should be an integral part of the model calibration. Further optimisation is still required.

7. A first sensitivity analysis suggest that shipping traffic may have a significant impact on SPM levels in the Scheldt estuary, but a more detailed analysis of actual ship movements in the Scheldt and their influence on the bed shear stress is required to prove this.
8. A mud transport simulation based on a 3-month instead of a 14-day hydrodynamic period results in a number of changes, but still does show a similar behaviour and does not lead to strongly different results.

6 References

Borsje, B.W., S.J.M.H Hulscher, M.B. de Vries, G.J. de Boer (2007). Modelling large scale cohesive sediment transport by including biological activity. *Submitted to:*

Bruens, A., J. Vanlede, T. van Kessel (2006). Notitie beheersvragen LTV-slibmodel. WL | Delft Hydraulics report Z4210.75 (in Dutch).

Chen, M.S., S. Wartel, S. Temmerman (2005). Seasonal variation of floc characteristics on tidal flats, the Scheldt estuary. *Hydrobiologia* 540, pp. 181–195.

Fettweis, M., Nechad, B. & Van den Eynde, D (2007). An estimate of the suspended particulate matter (SPM) transport in the southern North Sea using SeaWiFS images, in-situ measurements and numerical model results. Continental Shelf Research (submitted).

Jong, D.J. de, V.N. de Jonge (1995). Dynamics and distribution of microphytobenthic chlorophyll-a in the Western Scheldt estuary (SW Netherlands). *Hydrobiologia* 311, pp. 21–30.

Kessel, T. van, J. Vanlede, A. Bruens (2006). Development of a mud transport model for the Scheldt estuary in the framework of LTV. WL | Delft Hydraulics & WL Borgerhout report Z4210.

McManus, J.P. and D. Prandle (1997). Development of a model to reproduce observed suspended sediment distributions in the North Sea using Principle Component Analysis and Multiple Linear Regression. Continental Shelf Research, Vol. 17, No. 7, pp. 761–778.

Winterwerp, J.C. en De Kok, J. (2006). Plan van aanpak LTV-slib: modelinstrumentarium t.b.v. beheersproblematiek slib. Intern document no. Z4210.95 – M756/01.

A Figures on hydrodynamic model

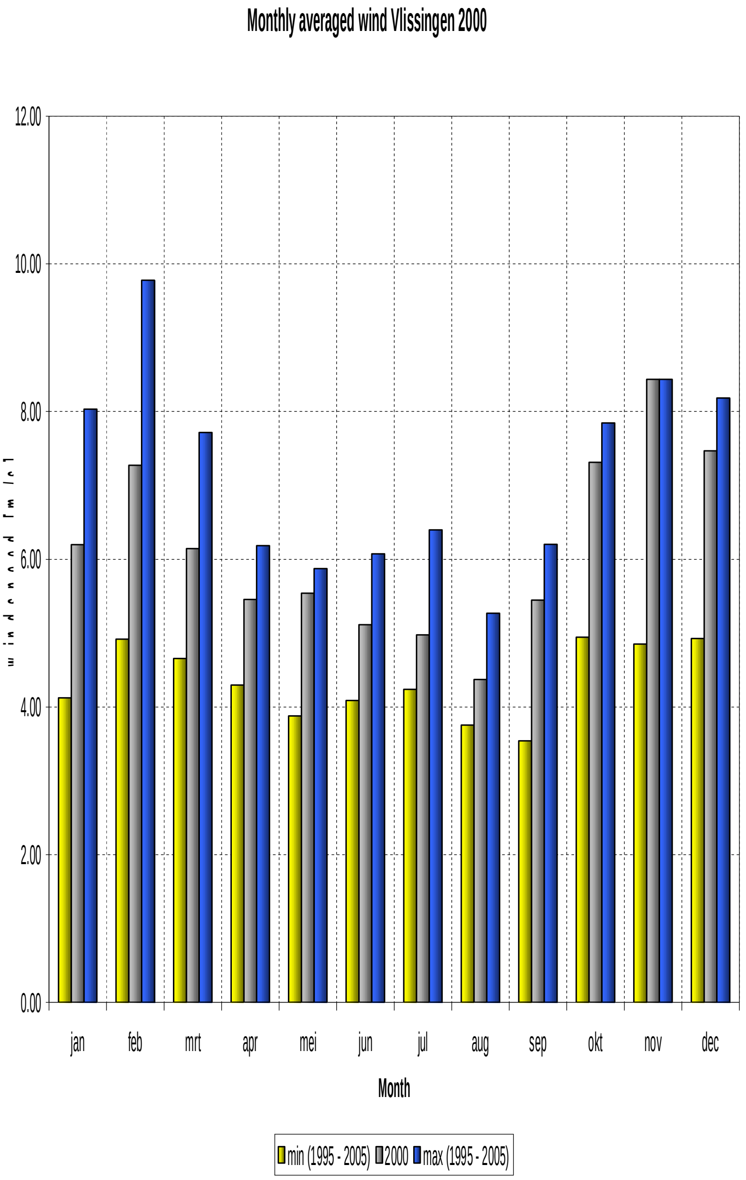

Figure A.1: Monthly averaged wind at Vlissingen	**M.756/02**
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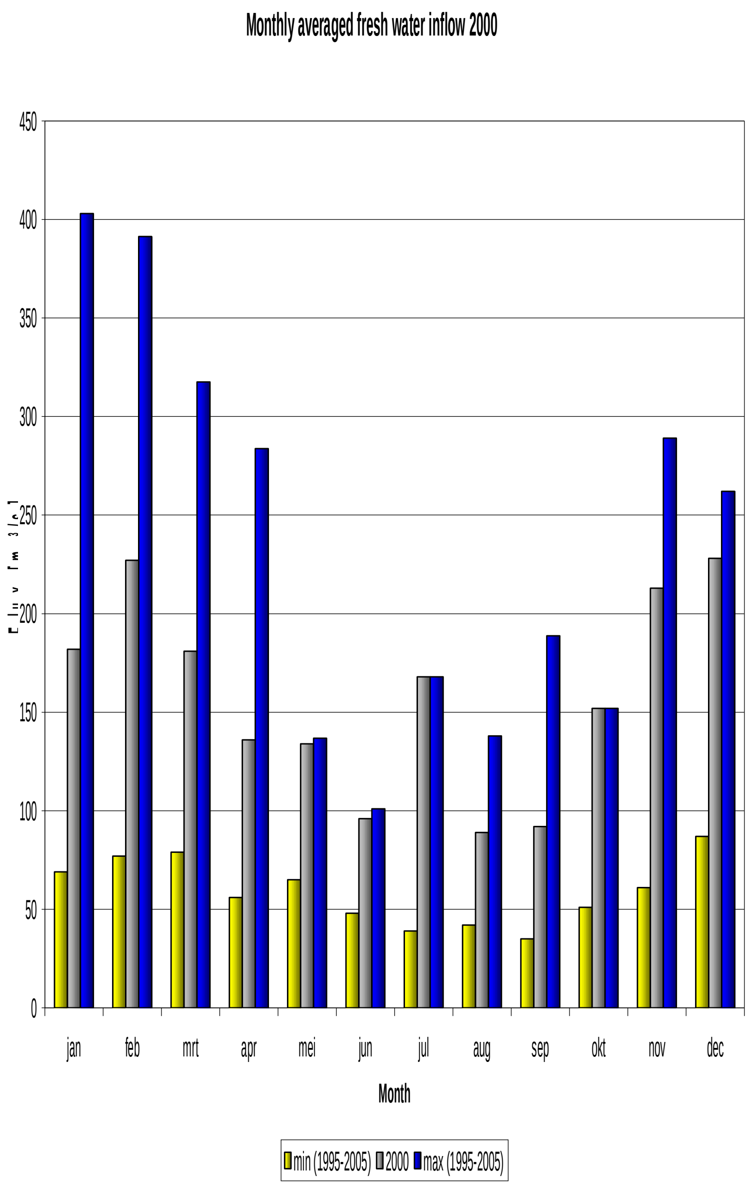

Figure A.2: Monthly averaged fresh water inflow	**M.756/02**
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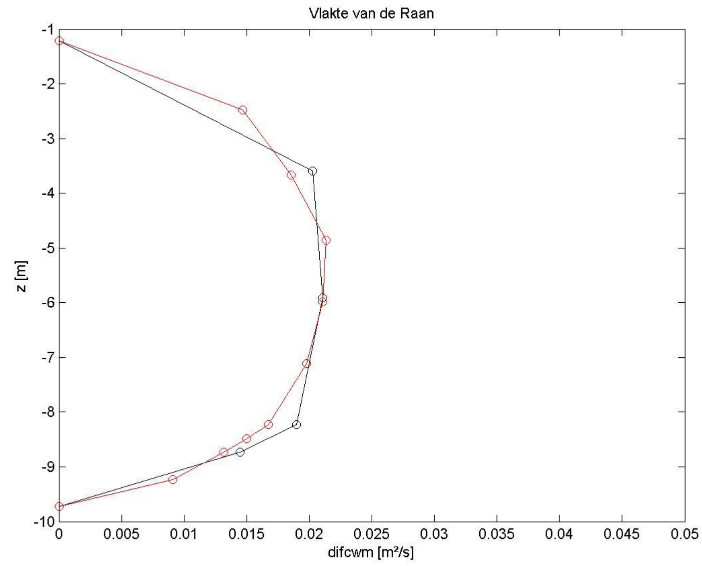

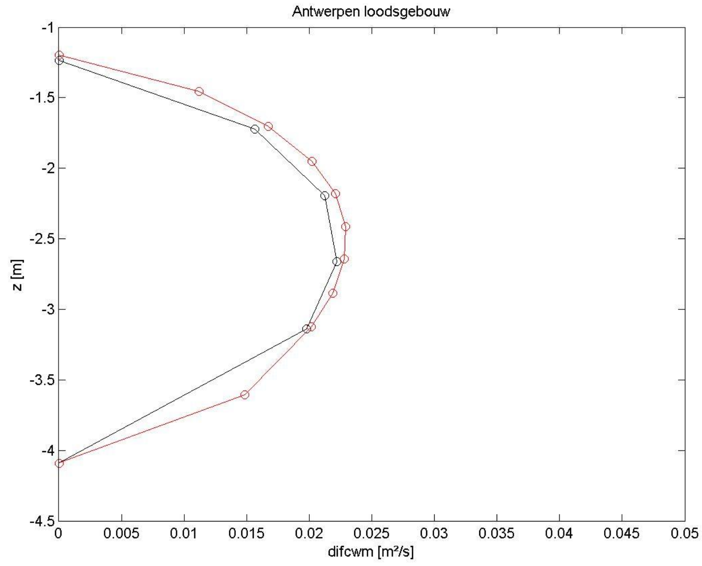

Figure A.3: Profiles of diffusivity: 5 layer model and 10 layer model	**M.756/02**
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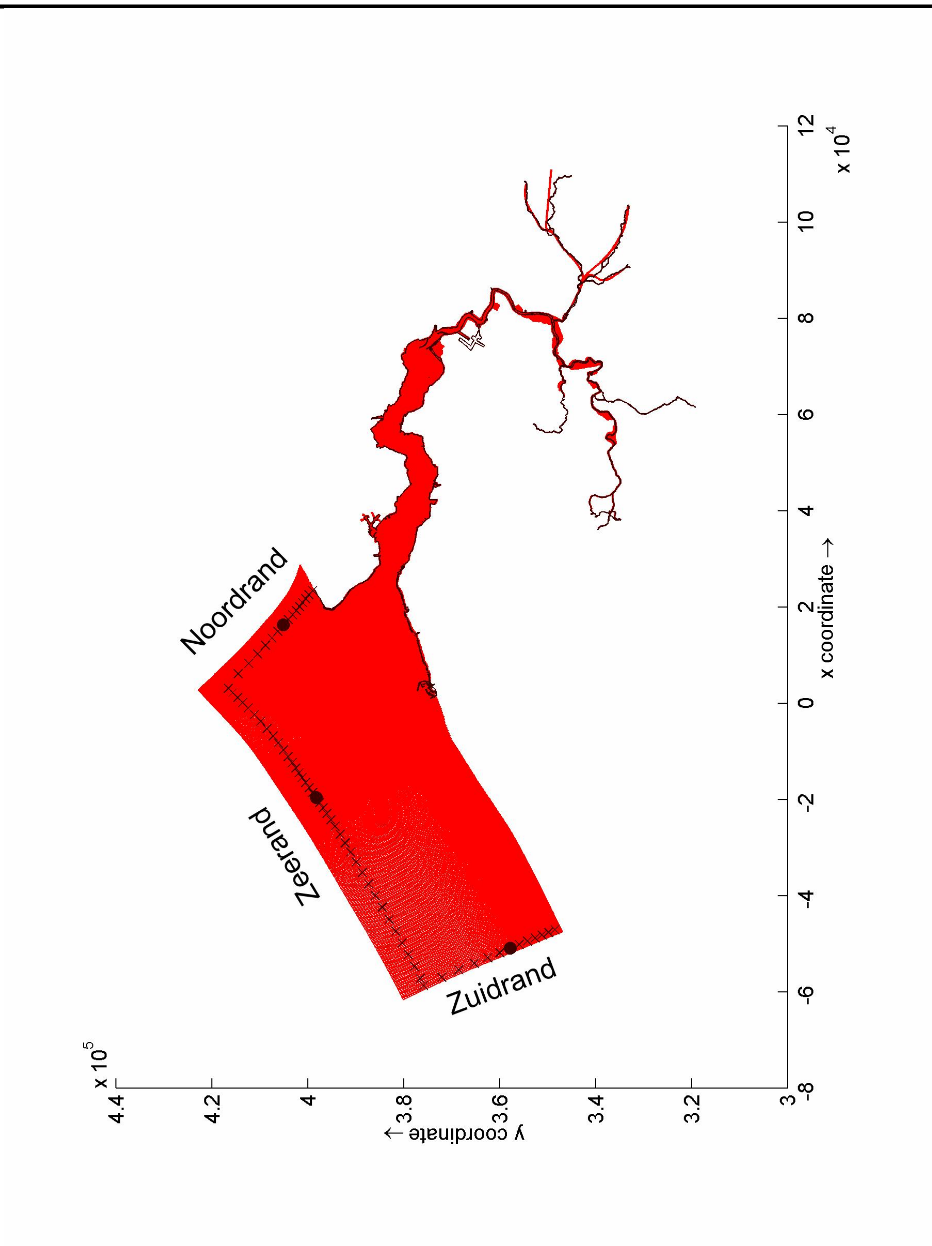

Figure A.4: Downstream boundaries of the model “+” indicates the boundary of the 2007 model. The 2006 HD model covered the entire red area.	**M.756/02**	
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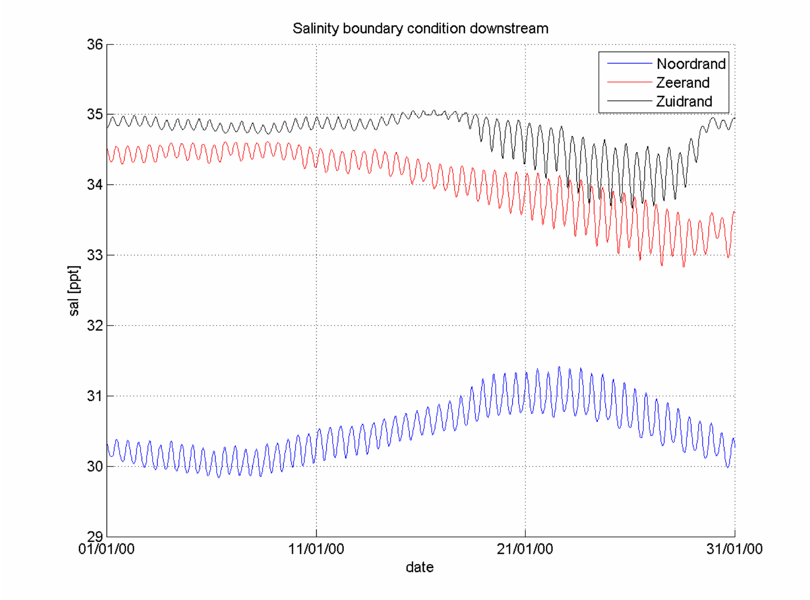

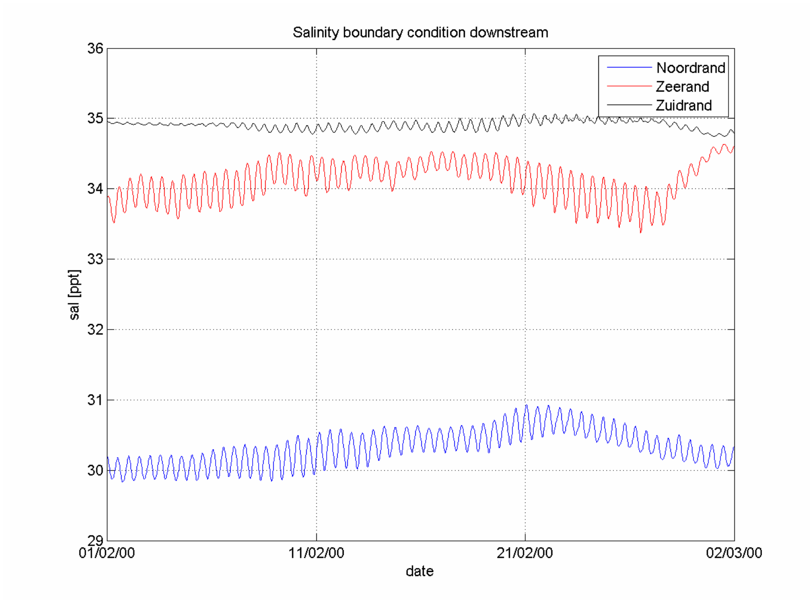

Figure A.5: Salinity boundary condition	**M.756/02**
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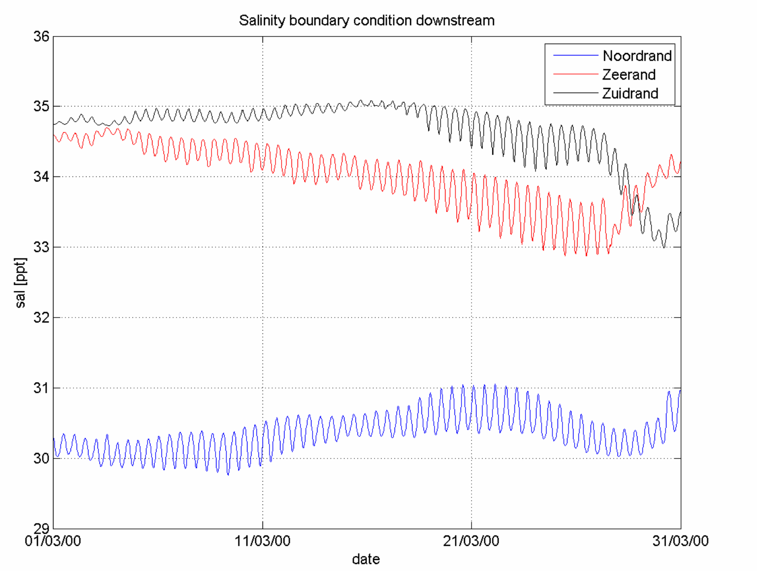

Figure A.6: Salinity boundary condition

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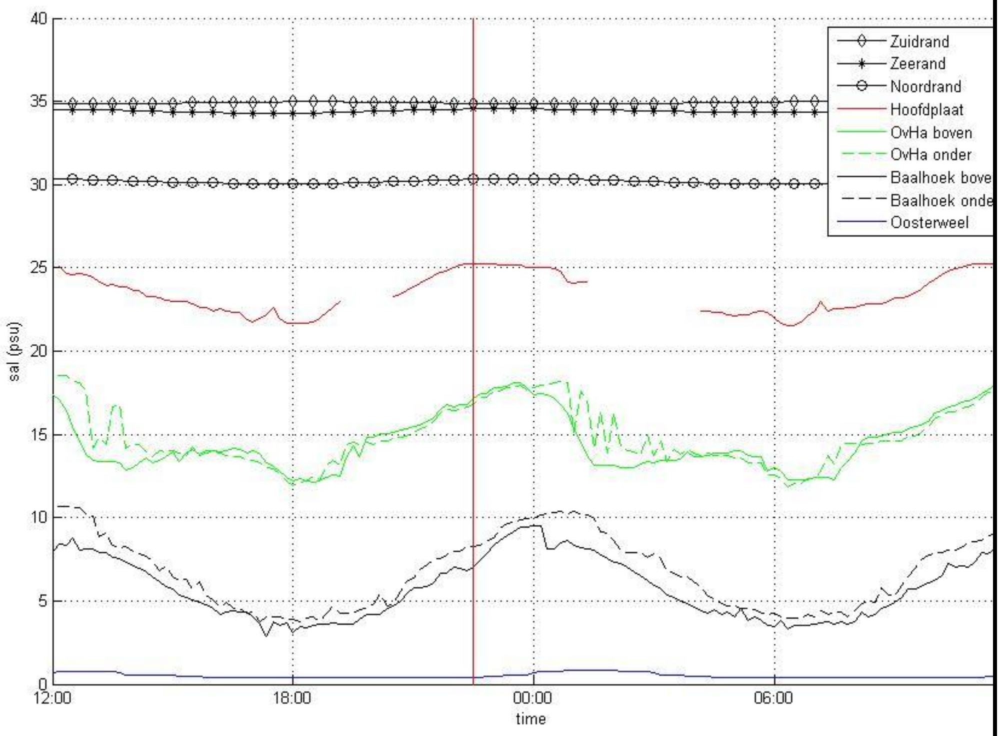

Figure A.7: Selection of initial salinity values	**M.756/02**	
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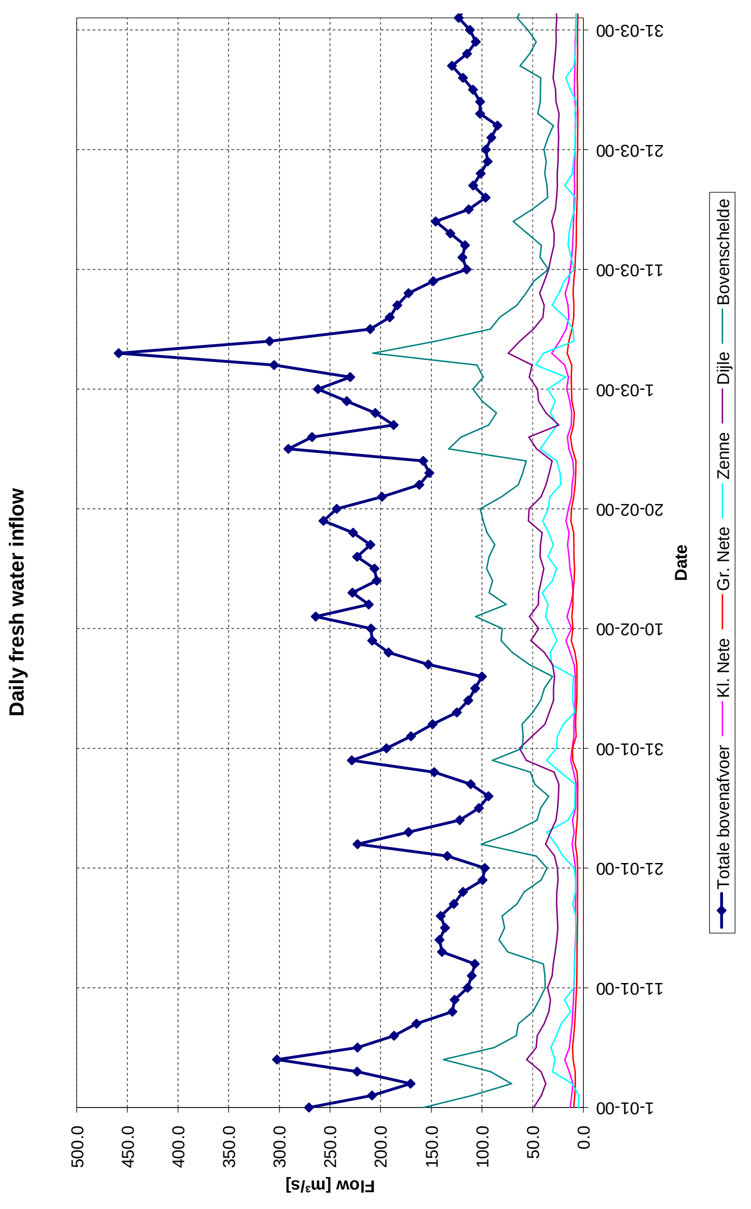

Figure A.8: Daily fresh water inflow	**M.756/02**
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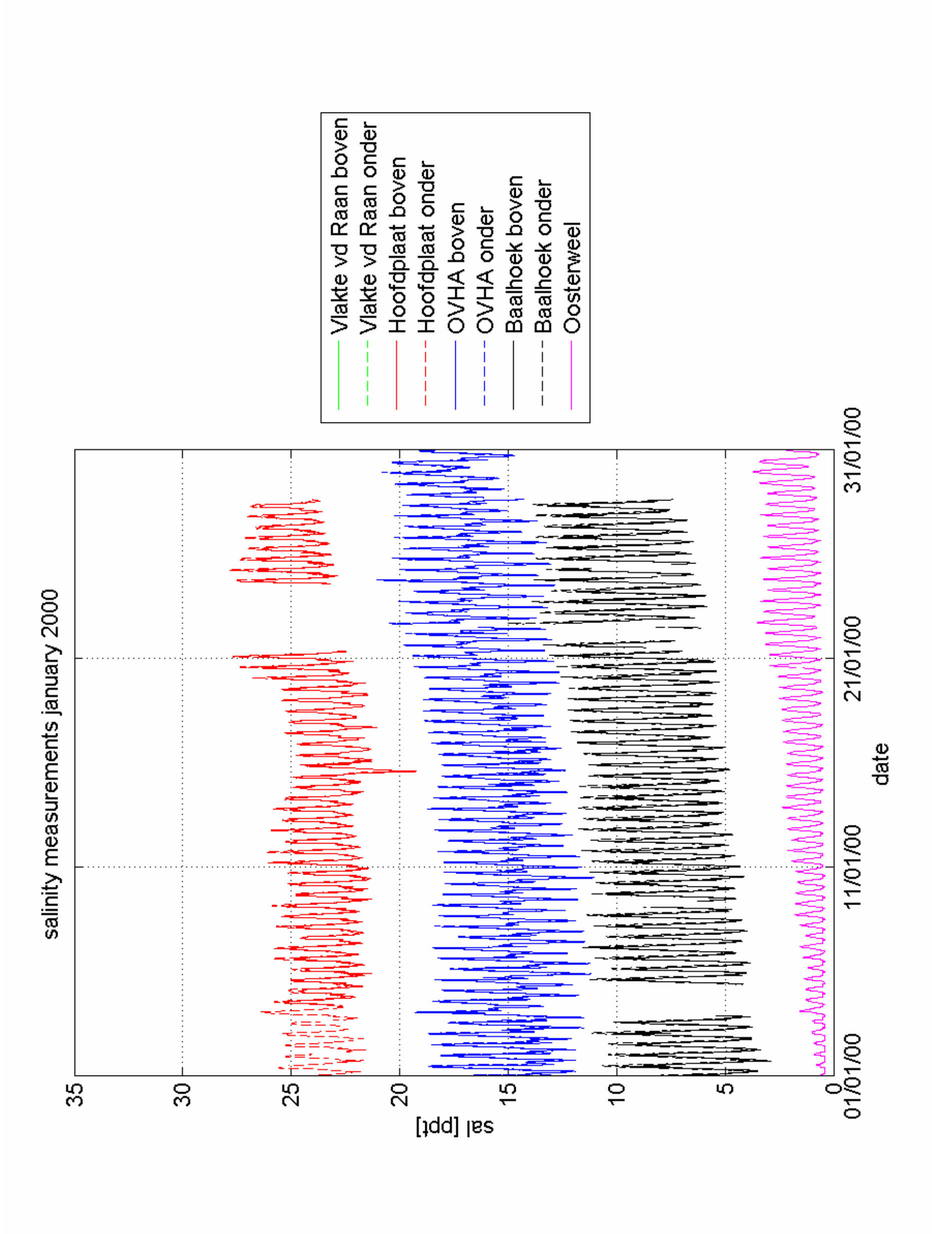

Figure A.9: Salinity measurements january	**M.756/02**
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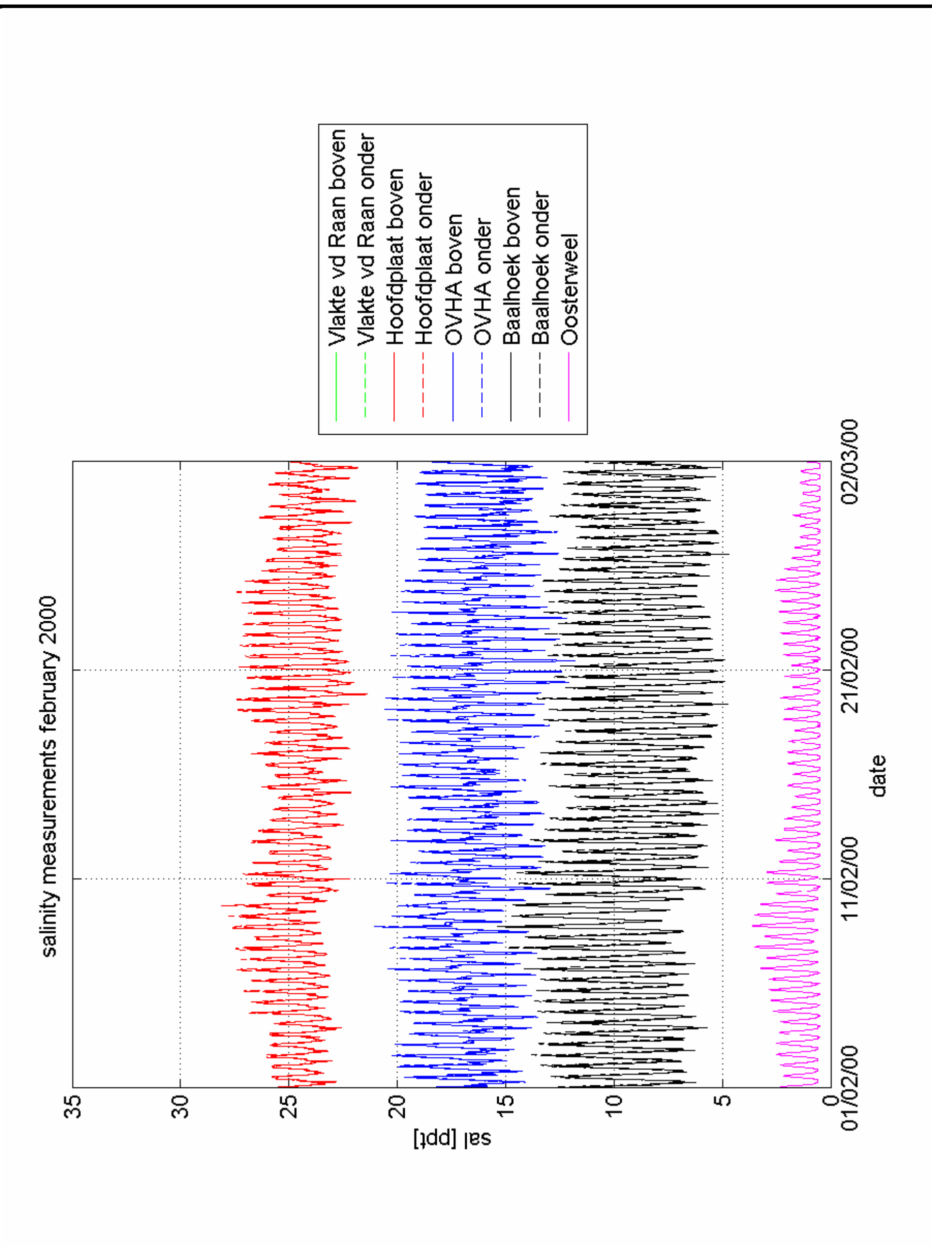

Figure A.10: Salinity measurements february

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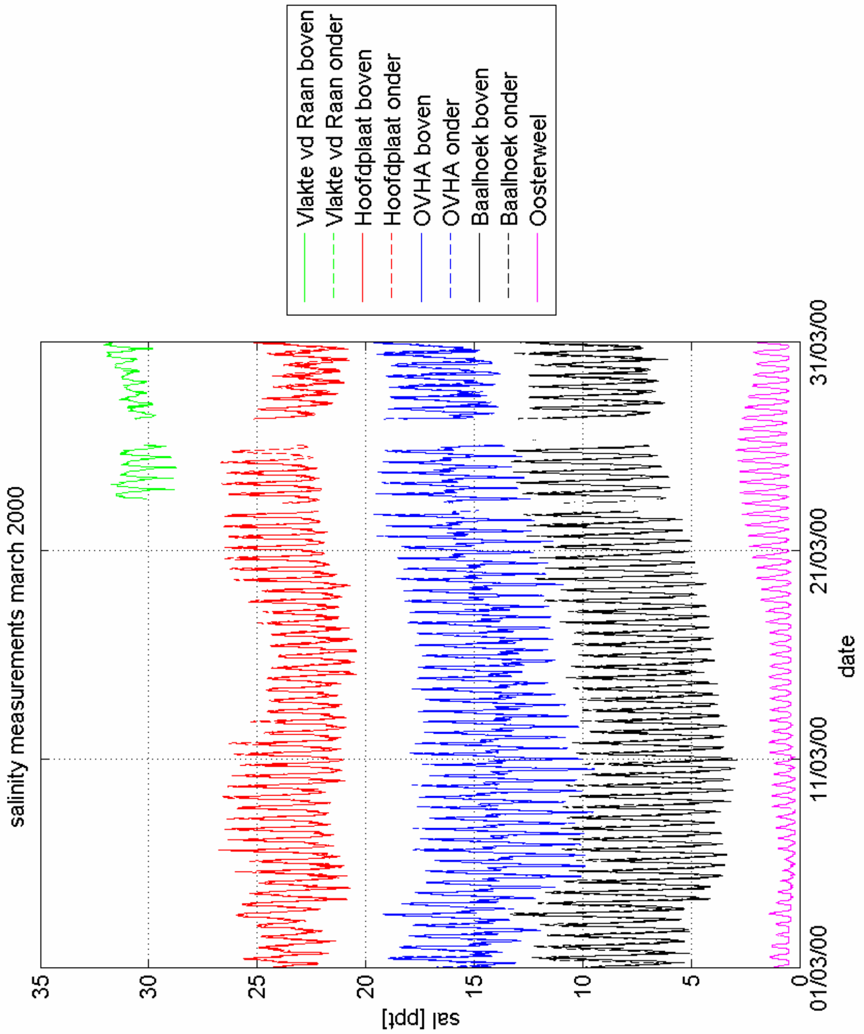

Figure A.11: Salinity measurements march	**M.756/02**	
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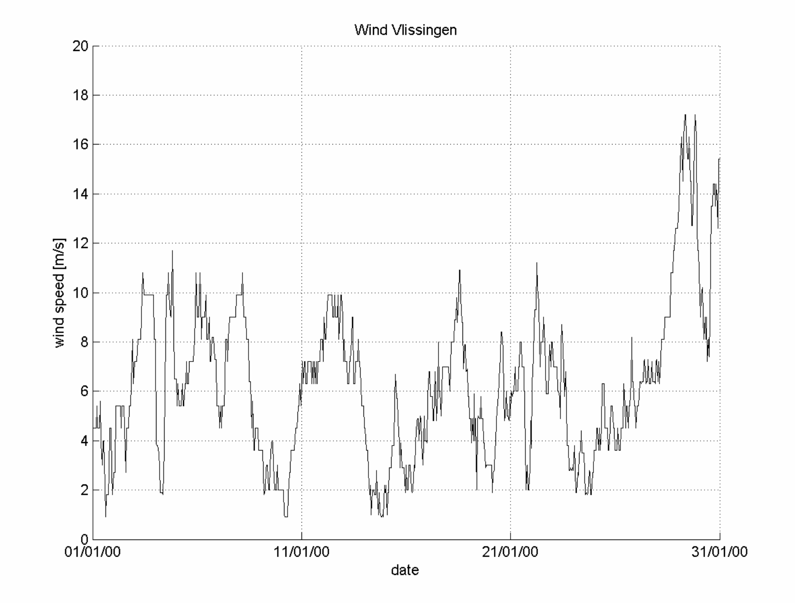

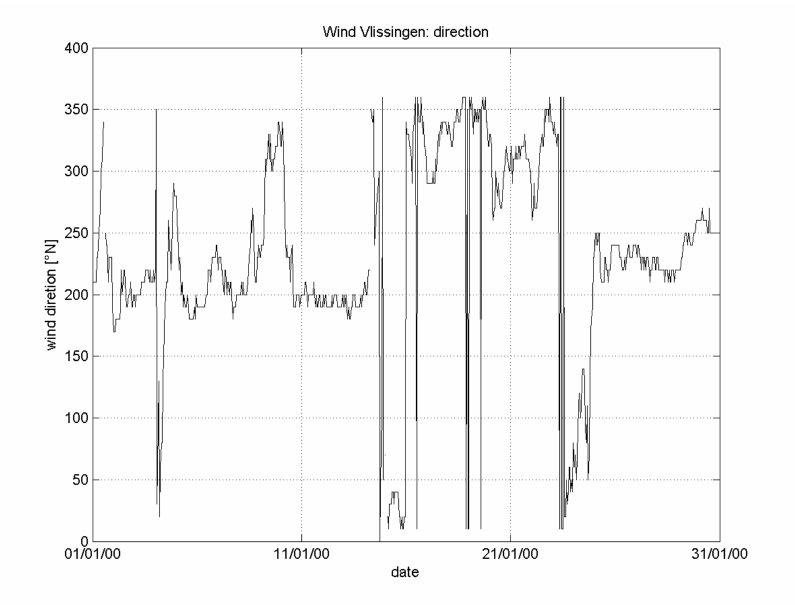

Figure A.12: Wind Vlissingen. Wind speed (top) and direction (bottom)

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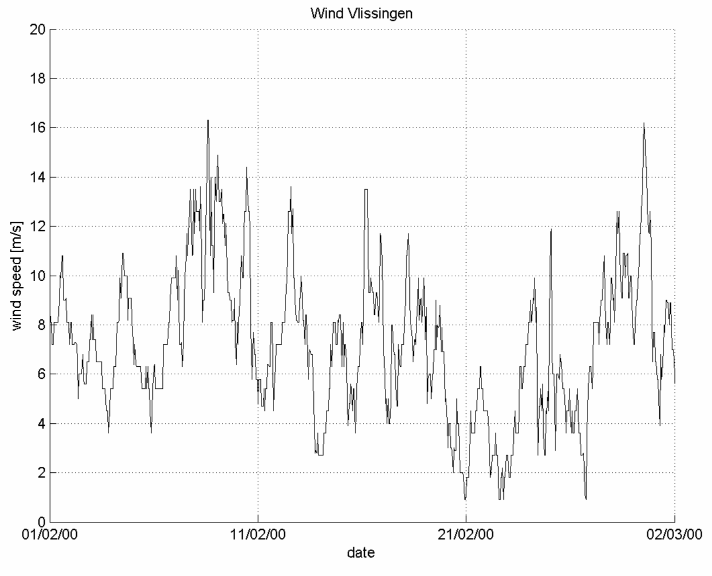

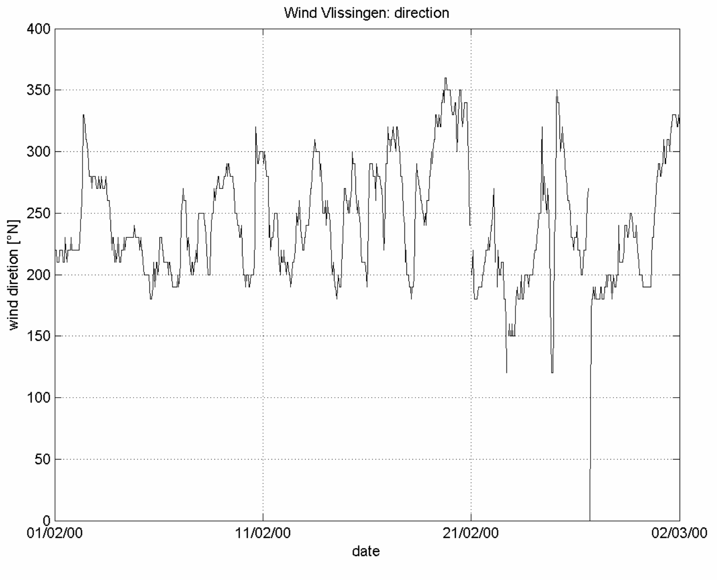

Figure A.13: Wind Vlissingen. Wind speed (top) and direction (bottom)

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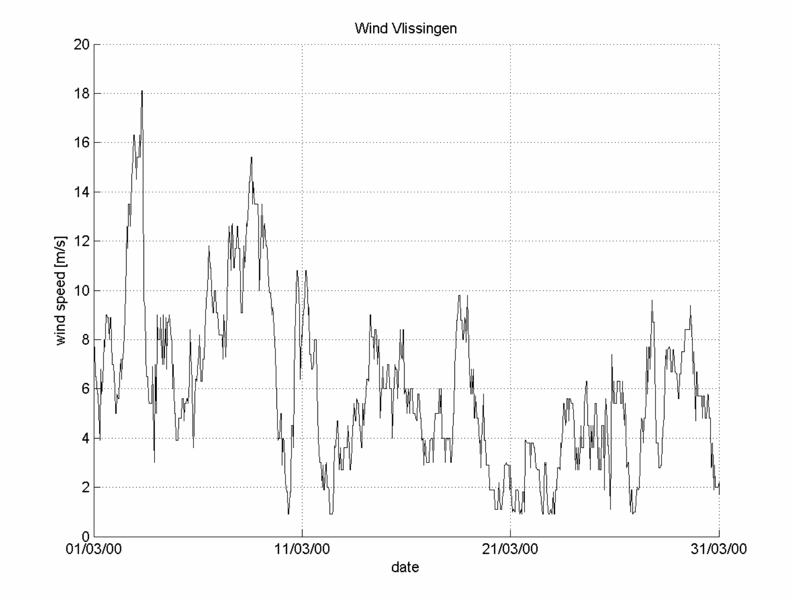

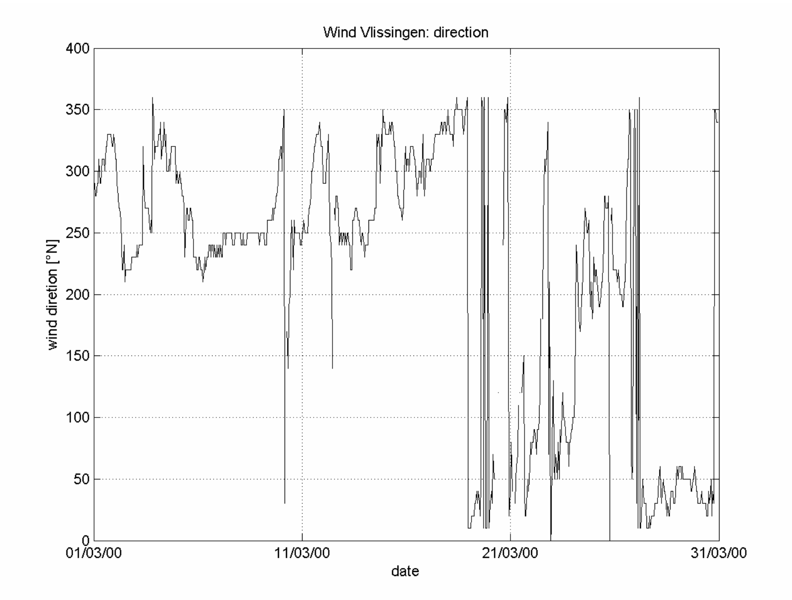

Figure A.14: Wind Vlissingen. Wind speed (top) and direction (bottom)	**M.756/02**
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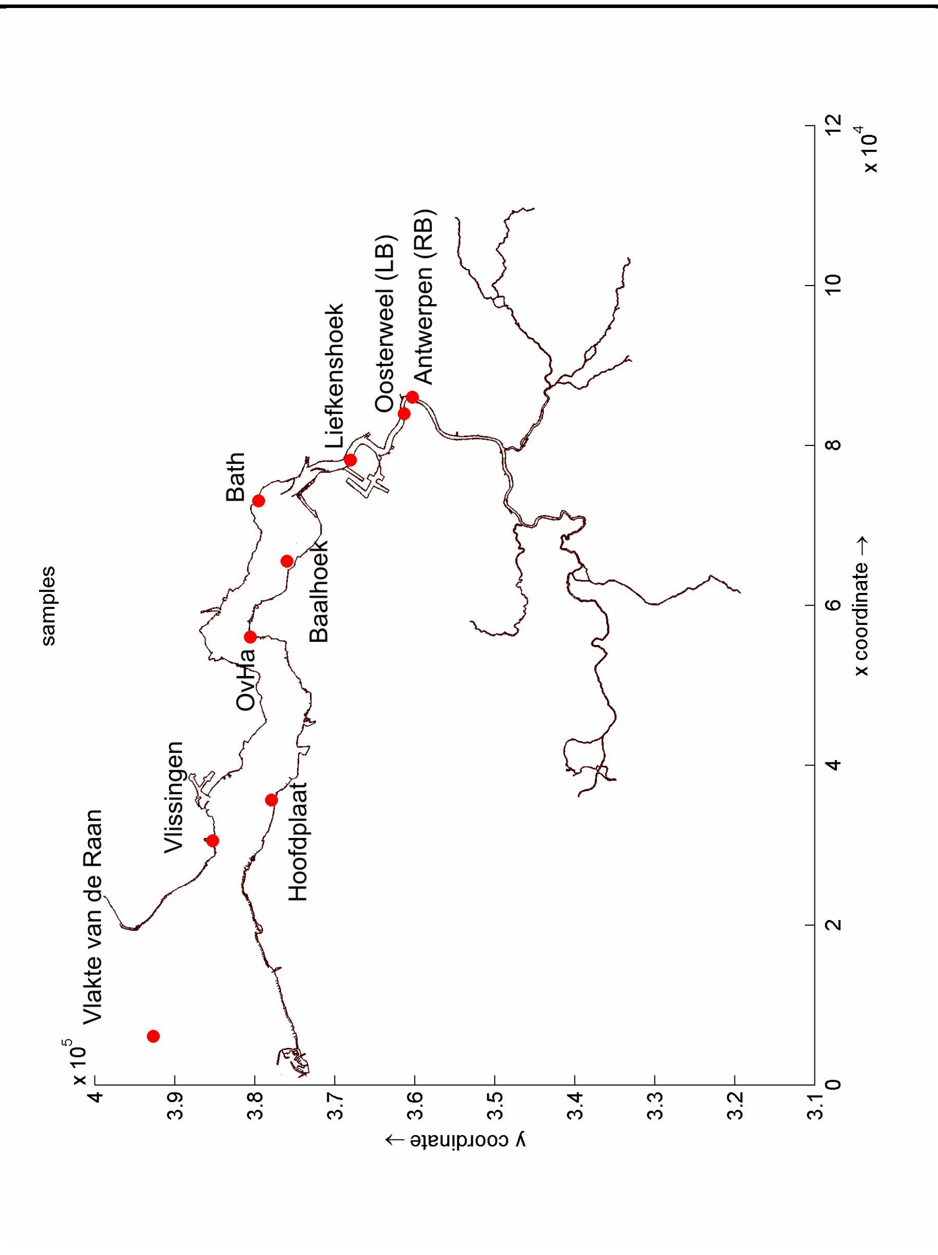

Figure A.15: Output locations

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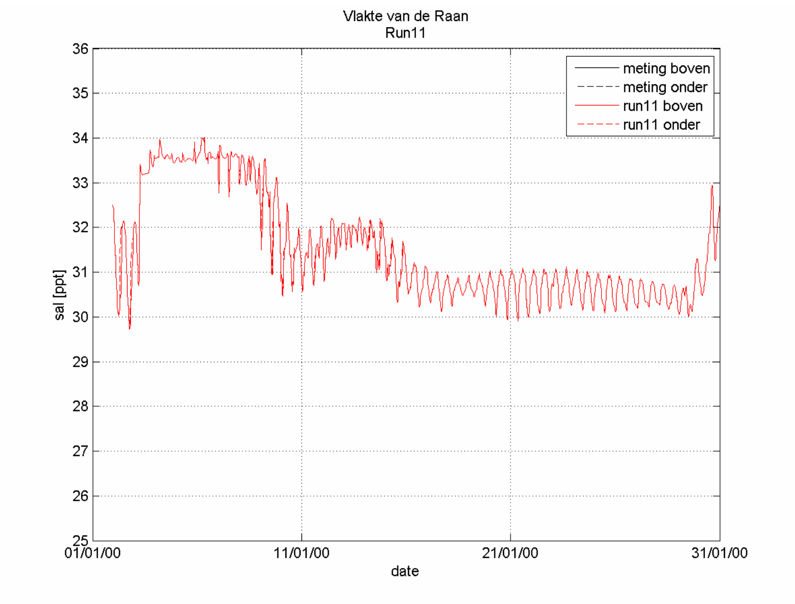

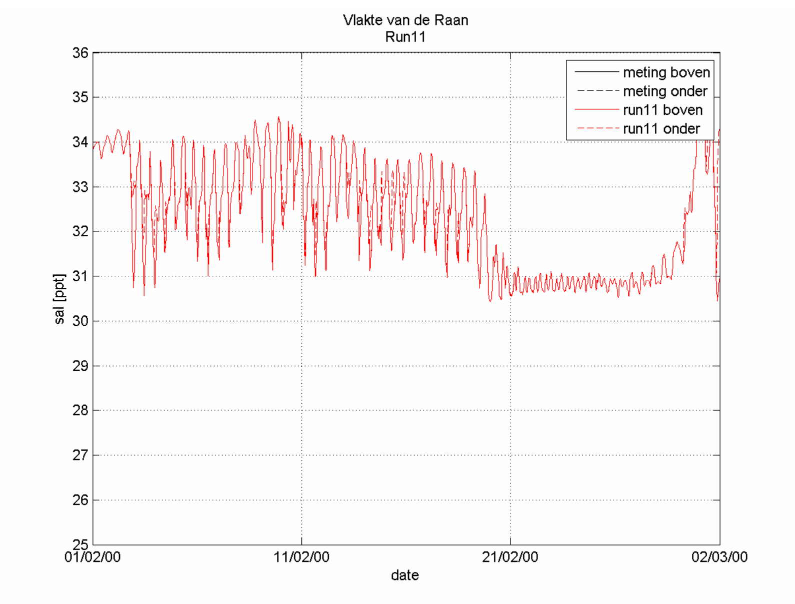

Figure A.16: Salinity: computed results and measurements	**M.756/02**
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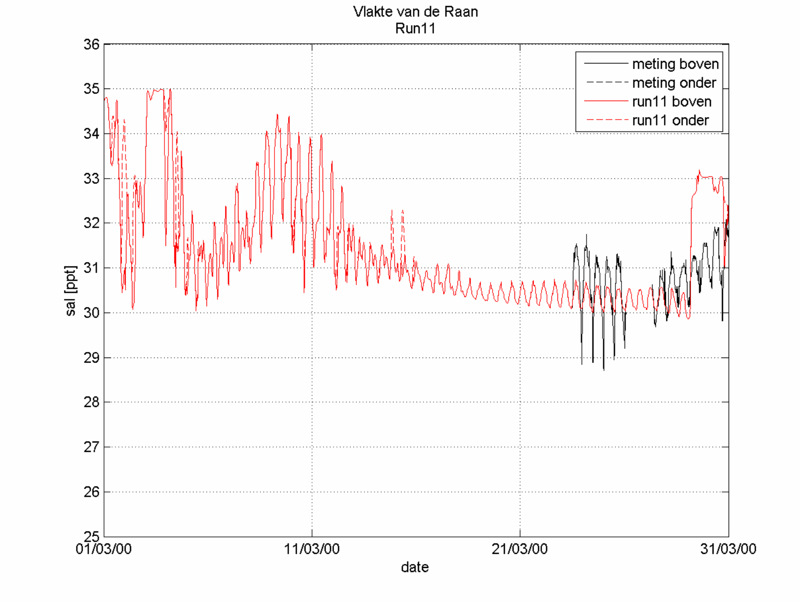

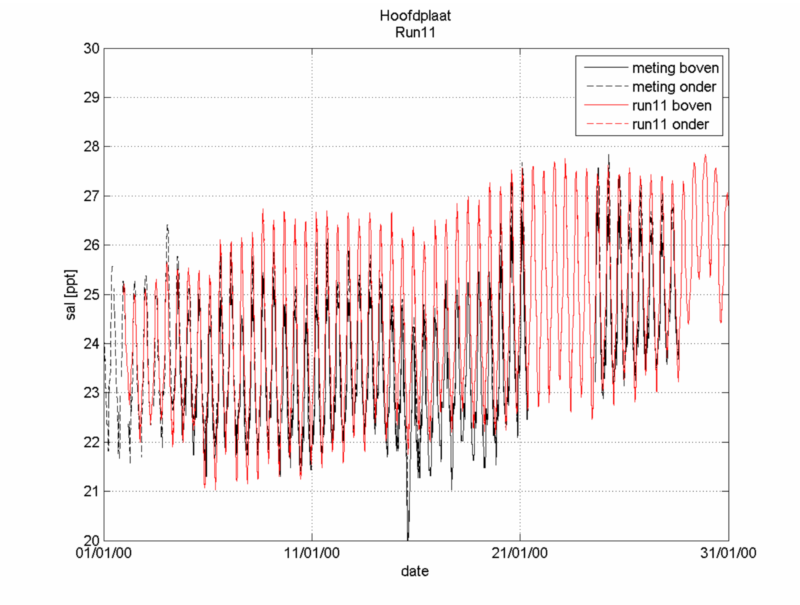

Figure A.17: Salinity: computed results and measurements

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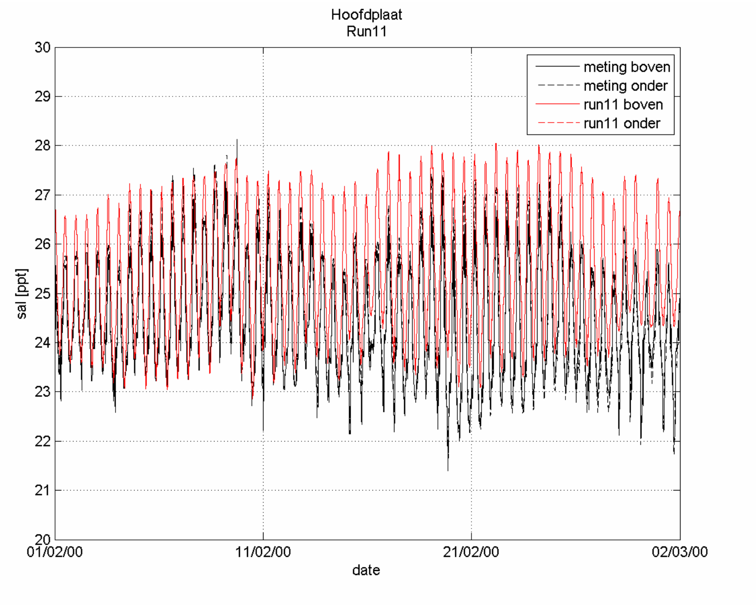

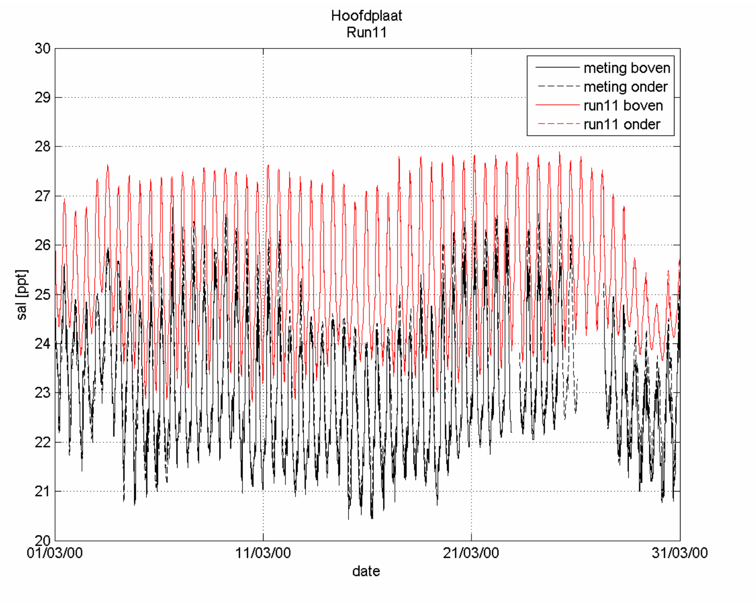

Figure A.18: Salinity: computed results and measurements

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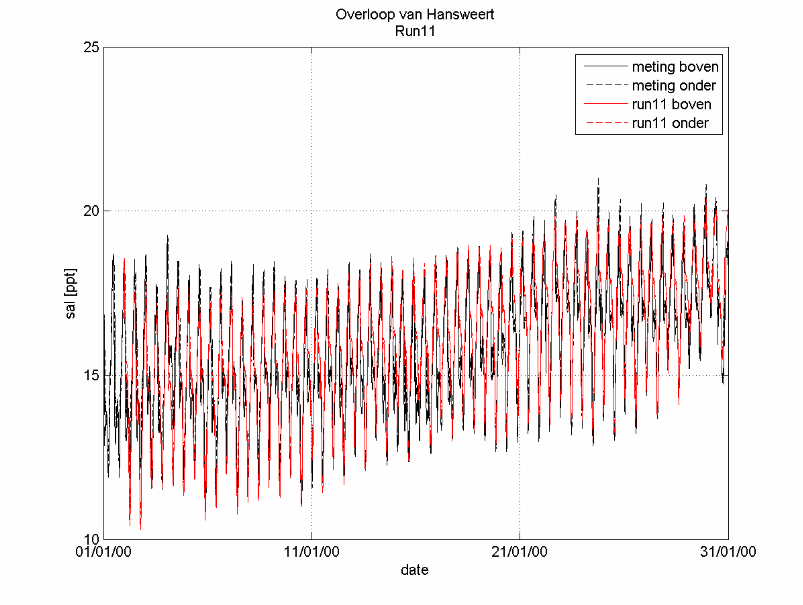

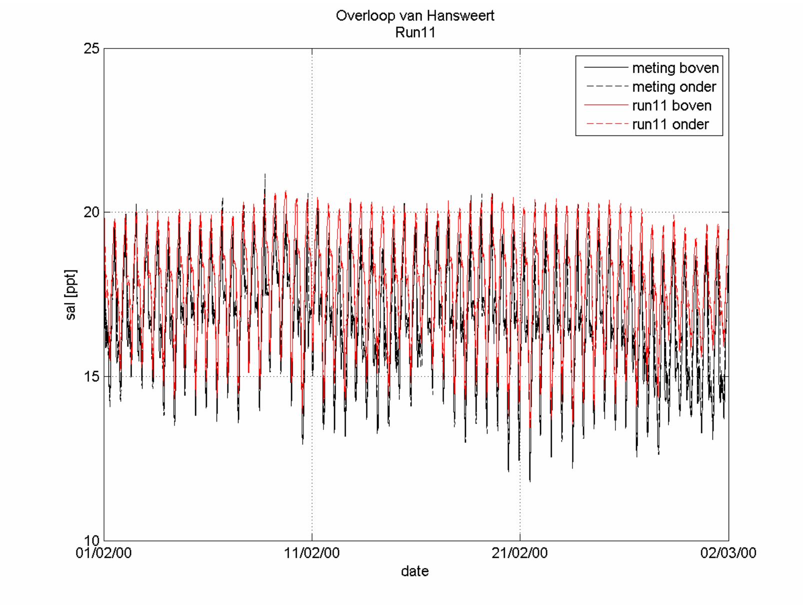

Figure A.19: Salinity: computed results and measurements	**M.756/02**
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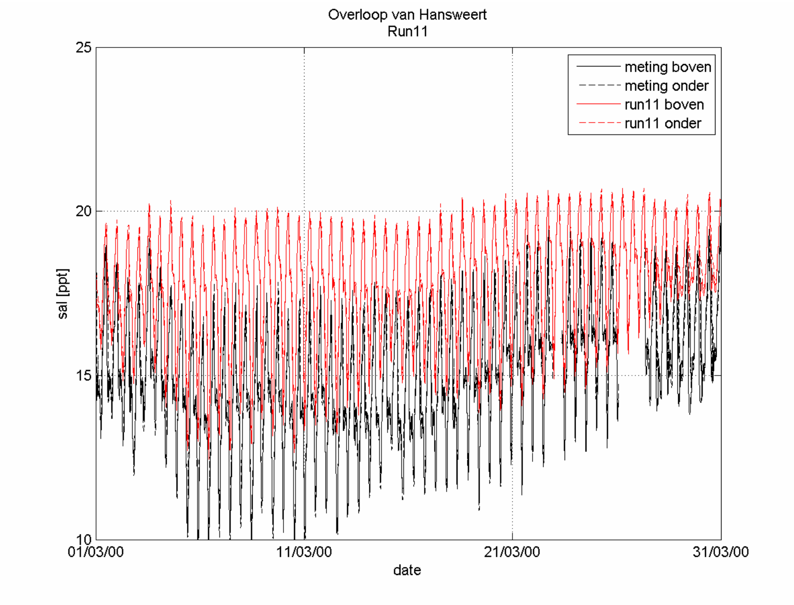

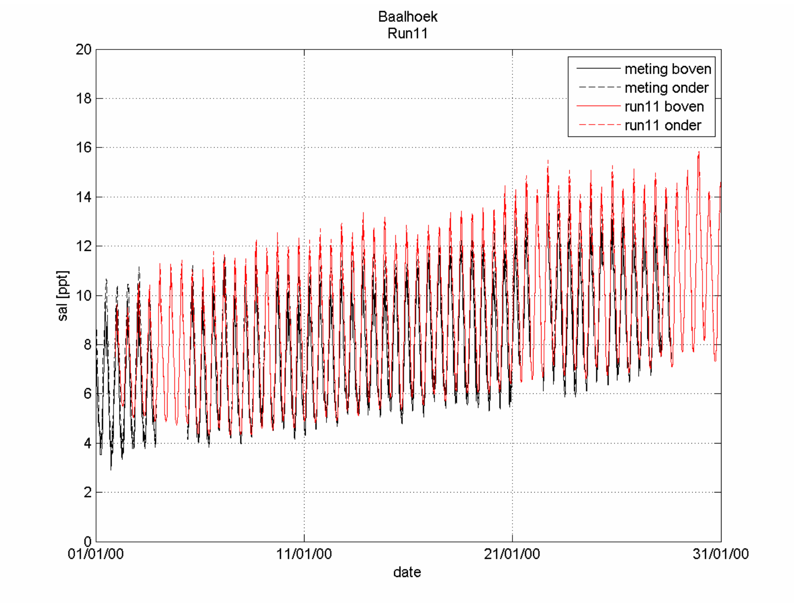

Figure A.20: Salinity: computed results and measurements	**M.756/02**
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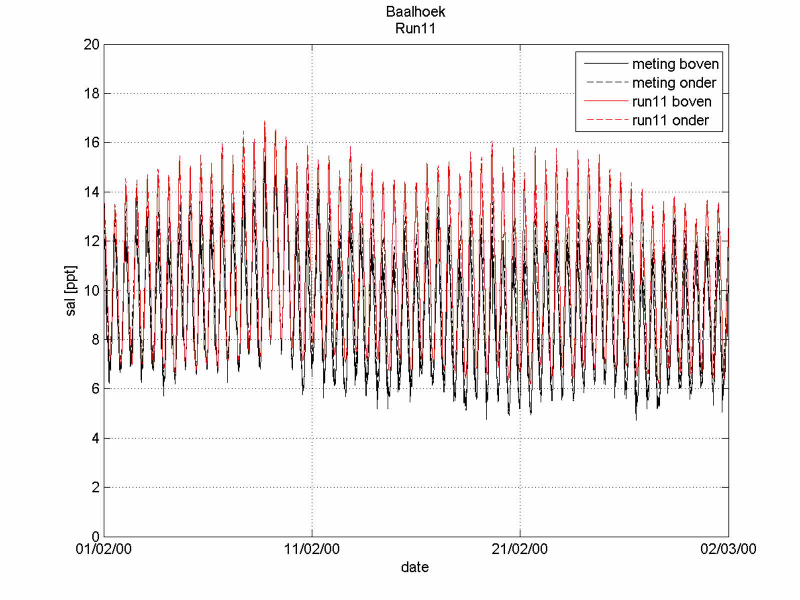

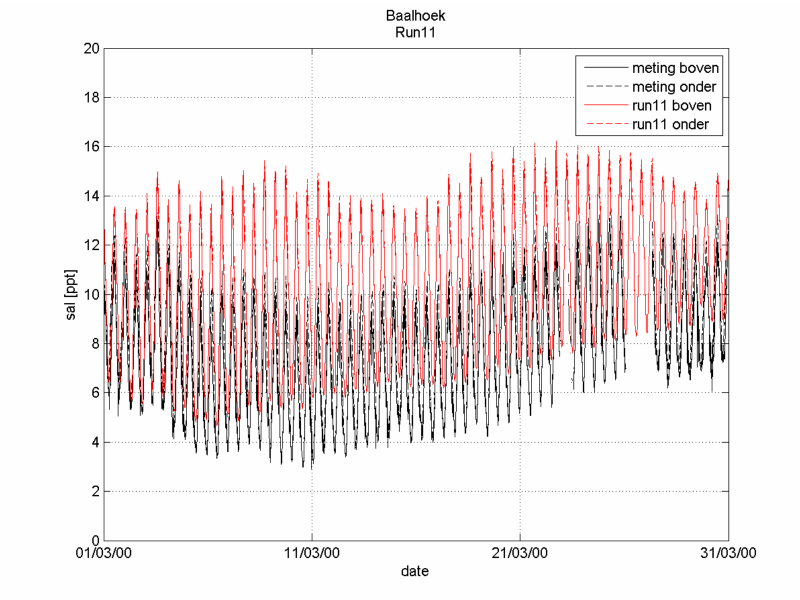

Figure A.21: Salinity: computed results and measurements	**M.756/02**
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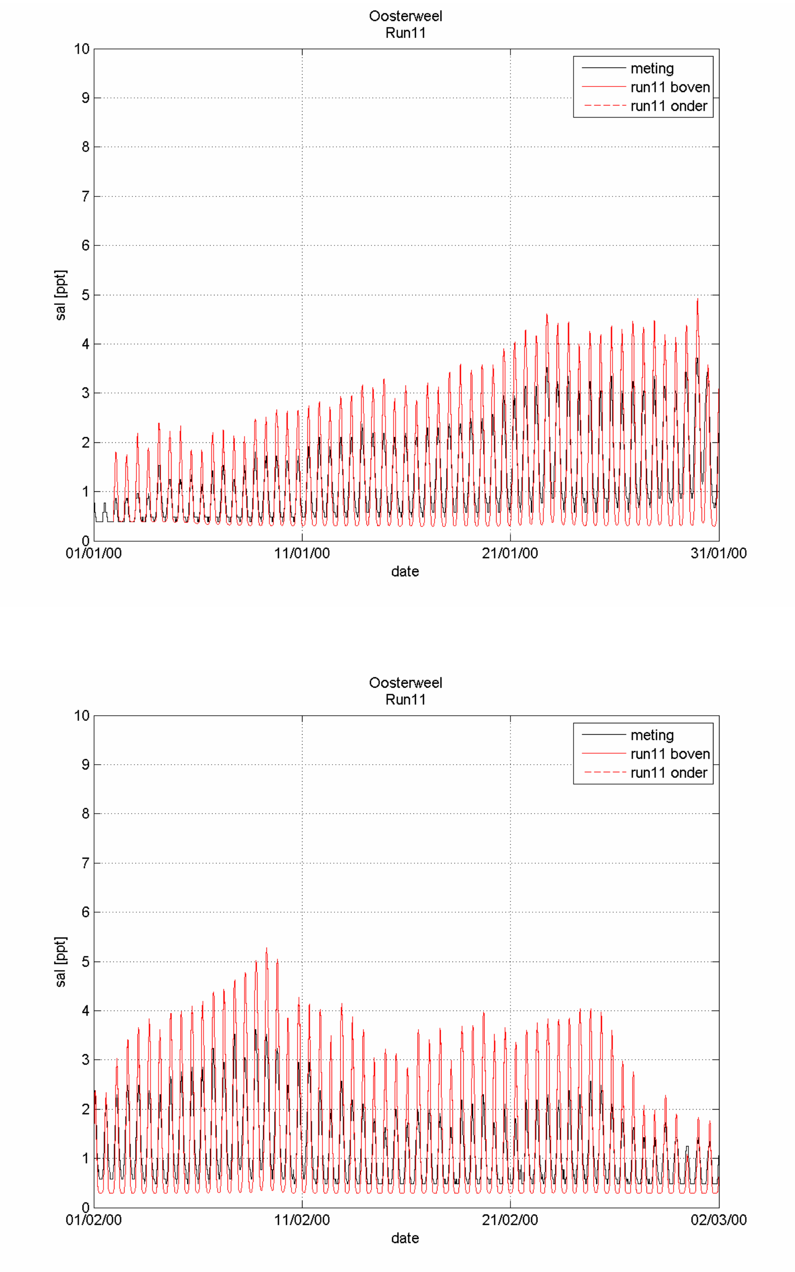

Figure A.22: Salinity: computed results and measurements

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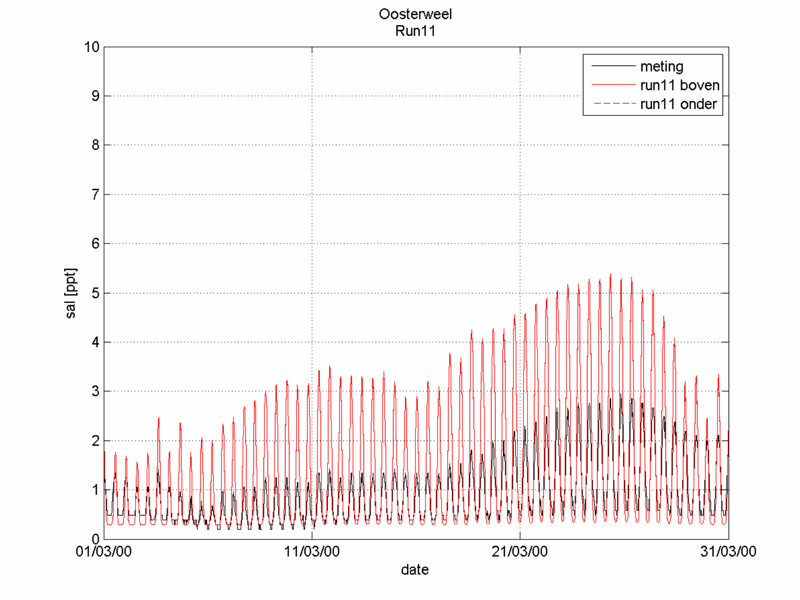

Figure A.23: Salinity: computed results and measurements	**M.756/02**	
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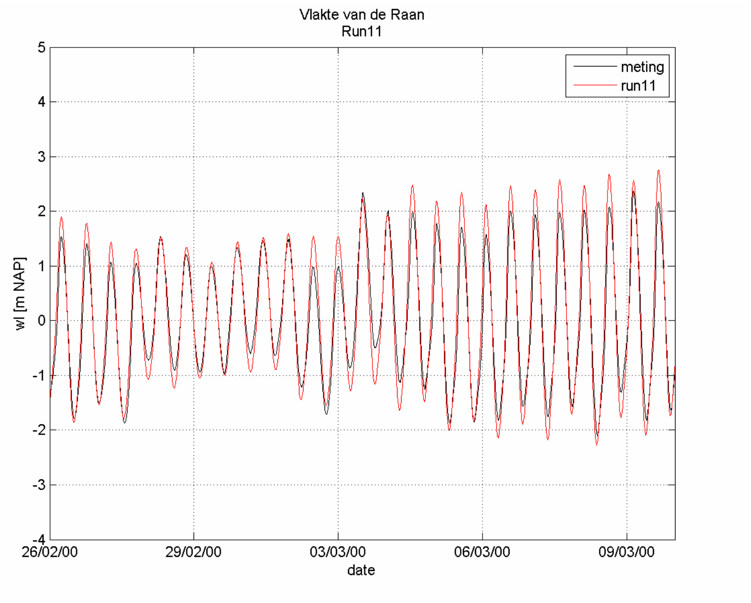

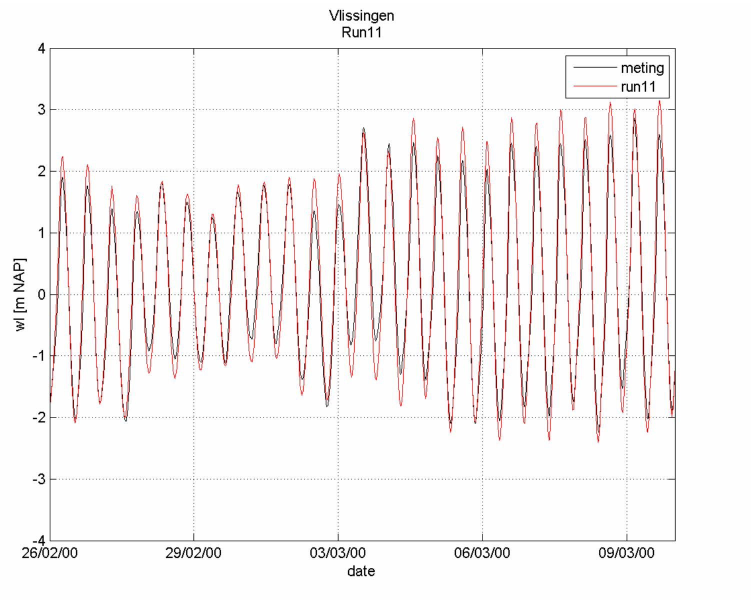

Figure A.24: Water level: computed results and measurements (26/02 to 09/03)

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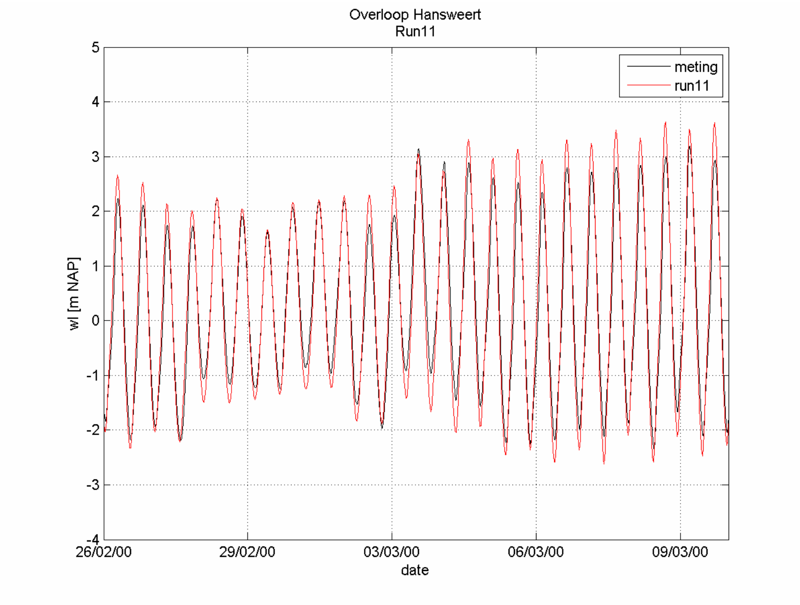

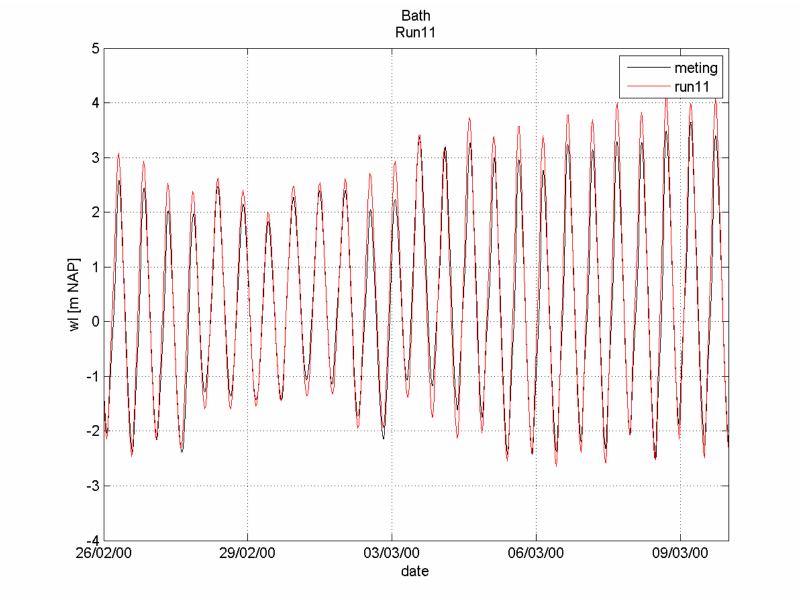

Figure A.25: Water level: computed results and measurements (26/02 to 09/03)

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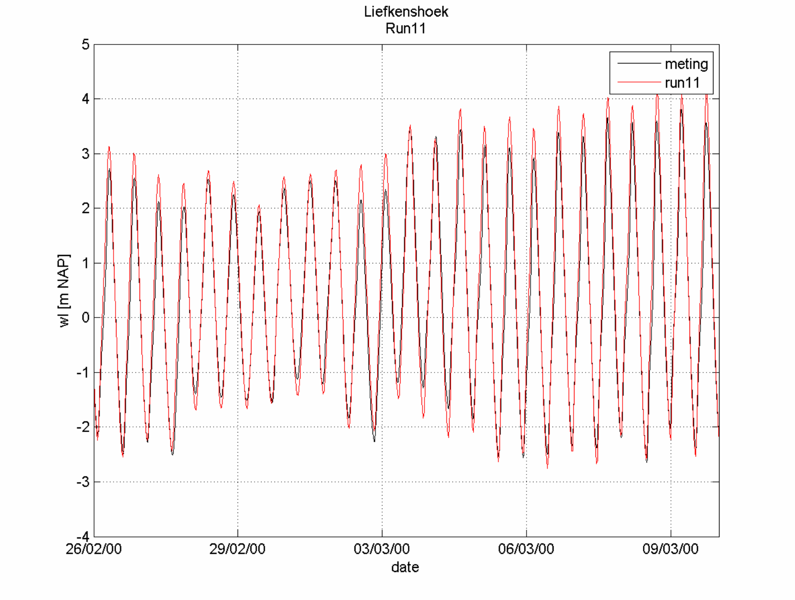

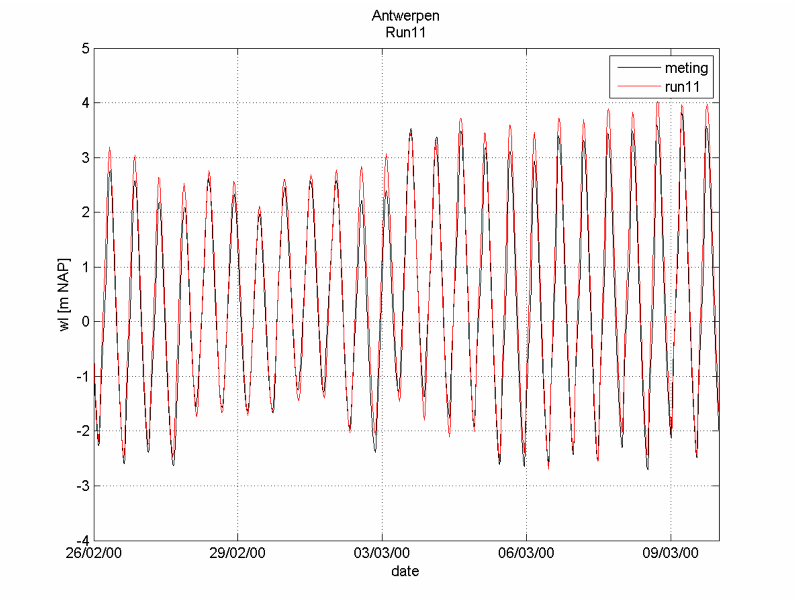

Figure A.26: Water level: computed results and measurements (26/02 to 09/03)

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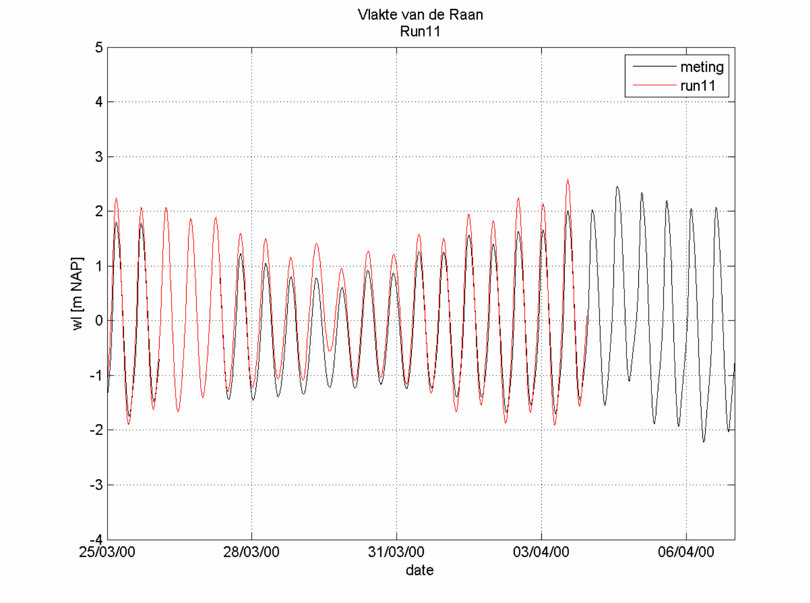

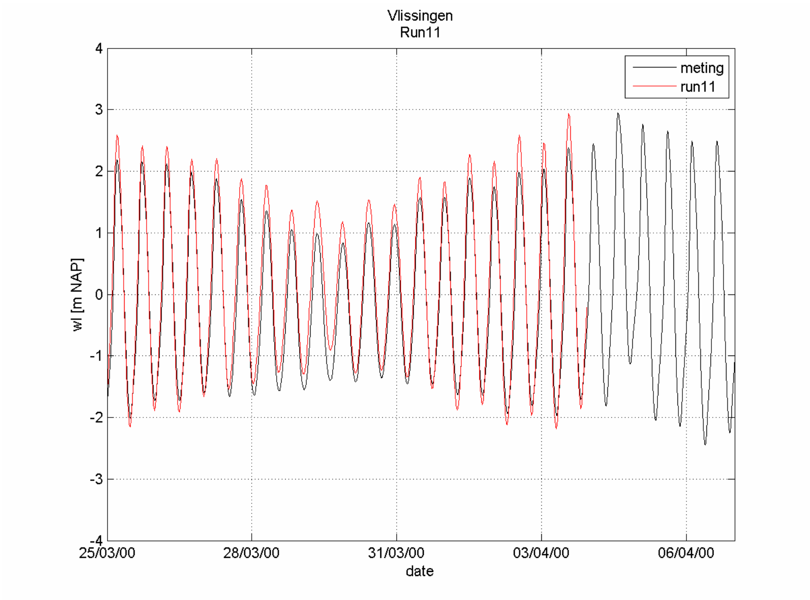

Figure A.27: Water level: computed results and measurements (25/03 to 06/04)	M.756/02
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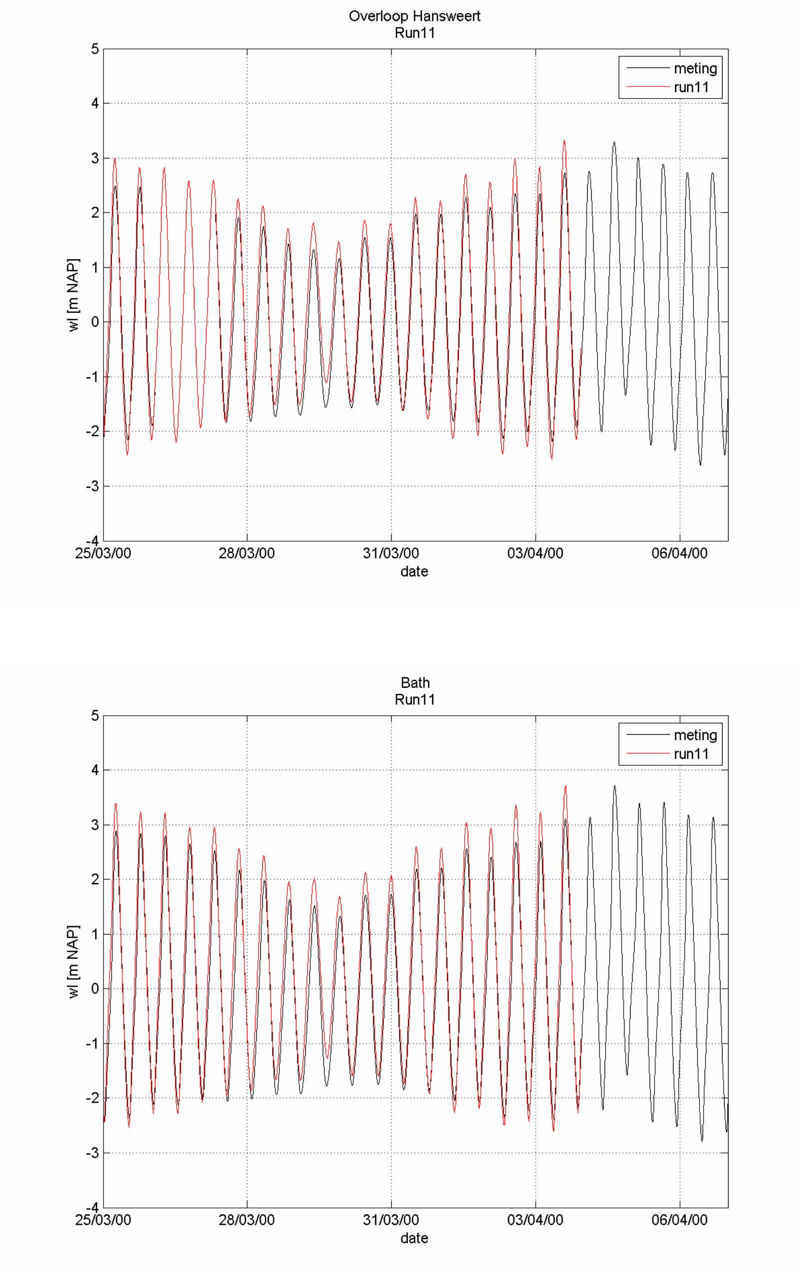

Figure A.28: Water level: computed results and measurements (25/03 to 06/04)

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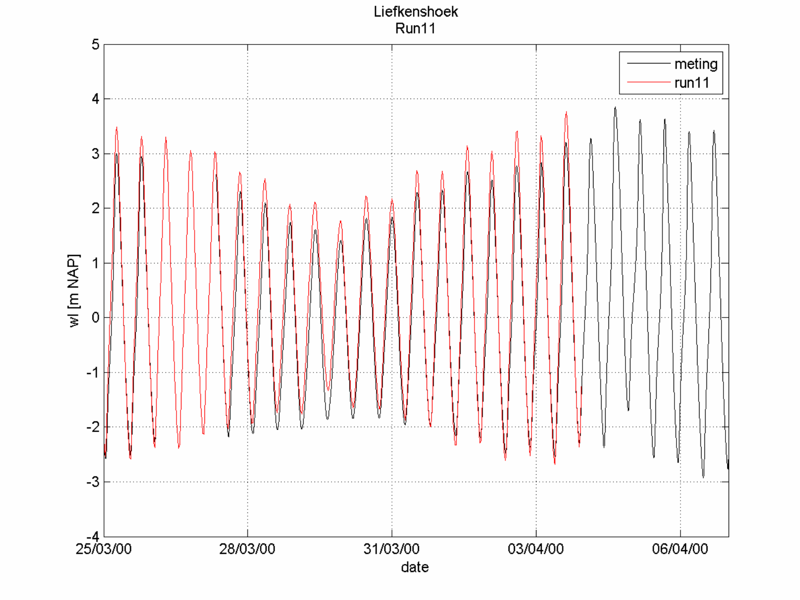

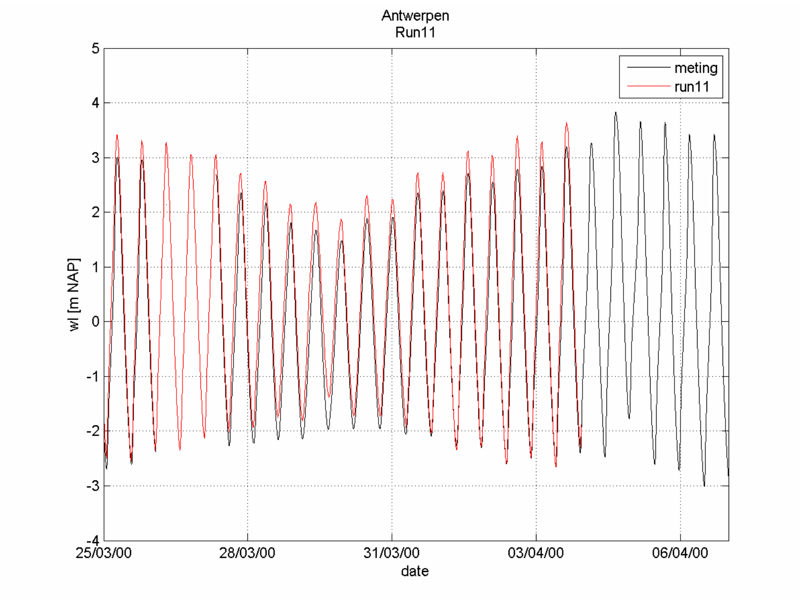

Figure A.29: Water level: computed results and measurements (25/03 to 06/04)	**M.756/02**
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B Figures on mud transport model

B.1 New dumping locations near Antwerp

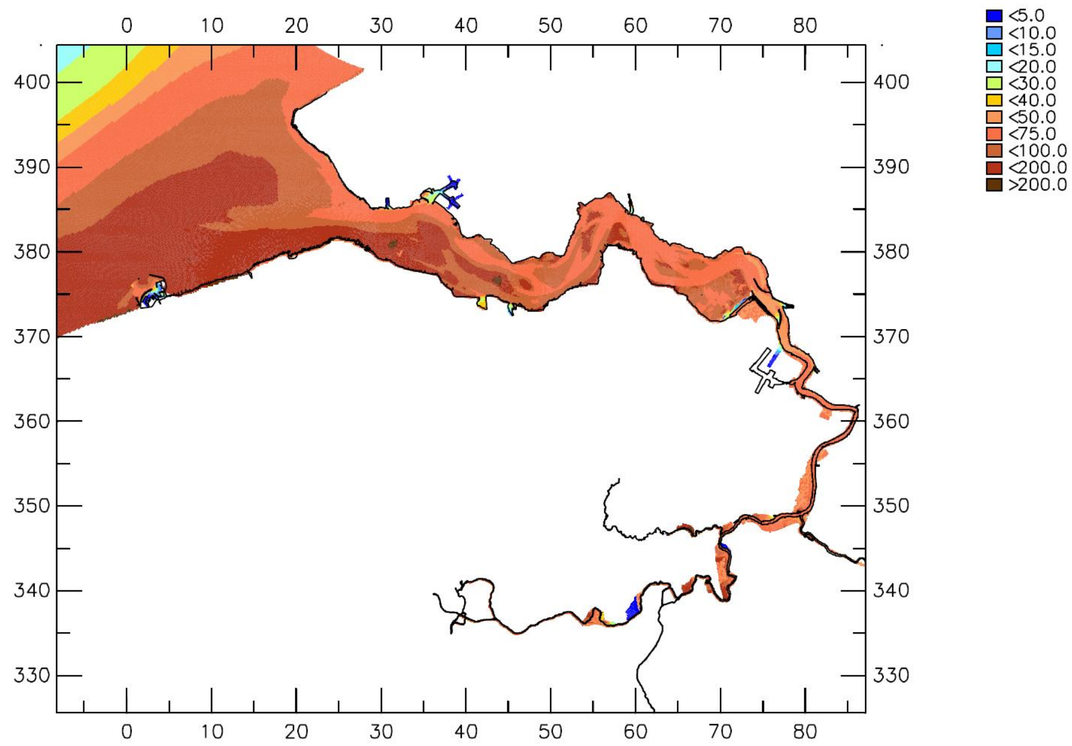


Fig. B.1a: 14-day winter averaged SPM surface concentration (mg/l), original dumping locations (ws15)

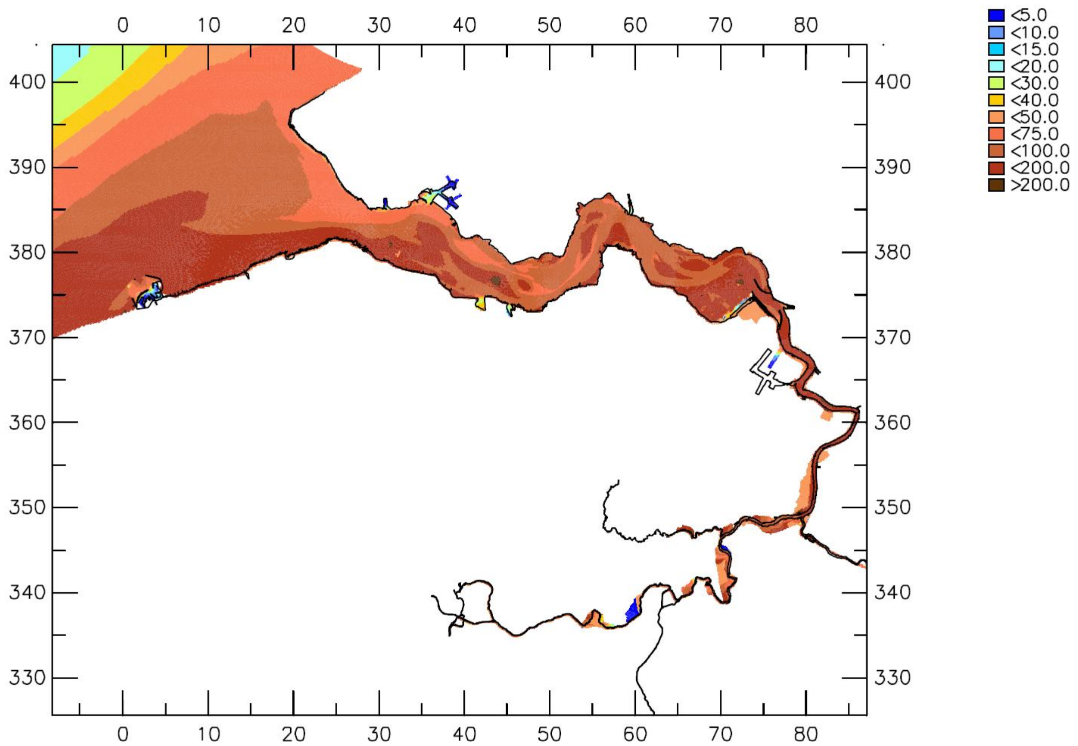


Fig. B.1b: 14-day winter averaged SPM surface concentration (mg/l), new dumping locations (ws15new)

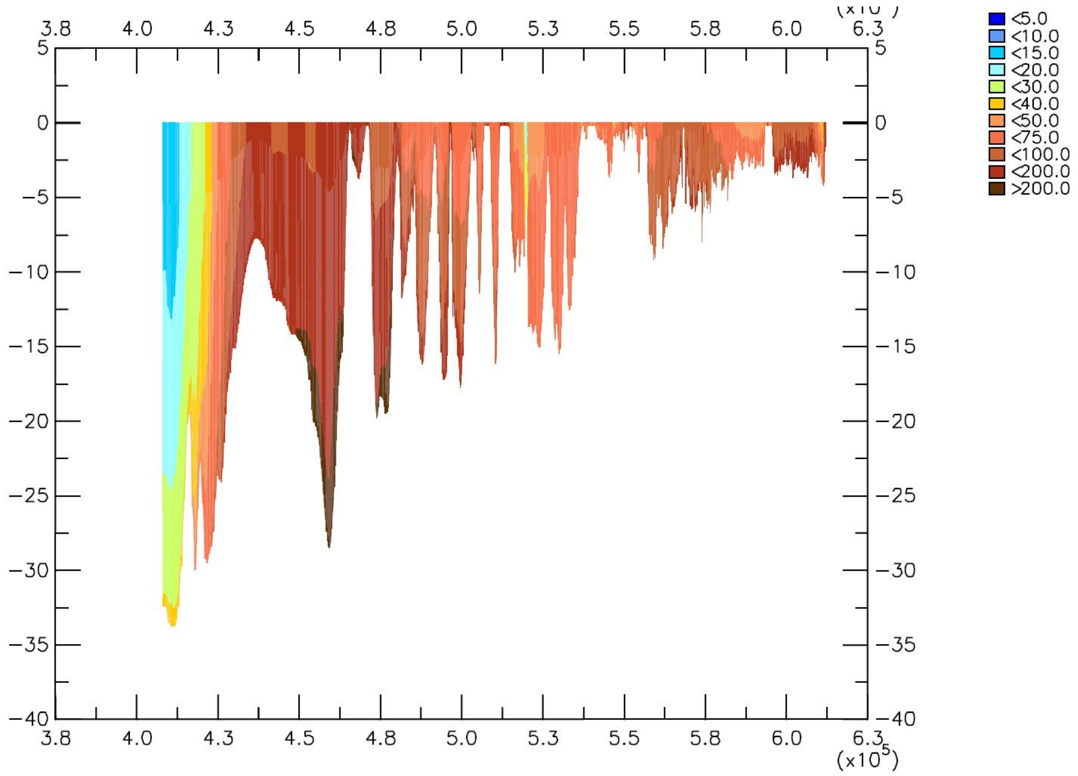


Fig. B.1c: 14-day winter averaged vertical SPM concentration transect (mg/l), original dumping locations (ws15)

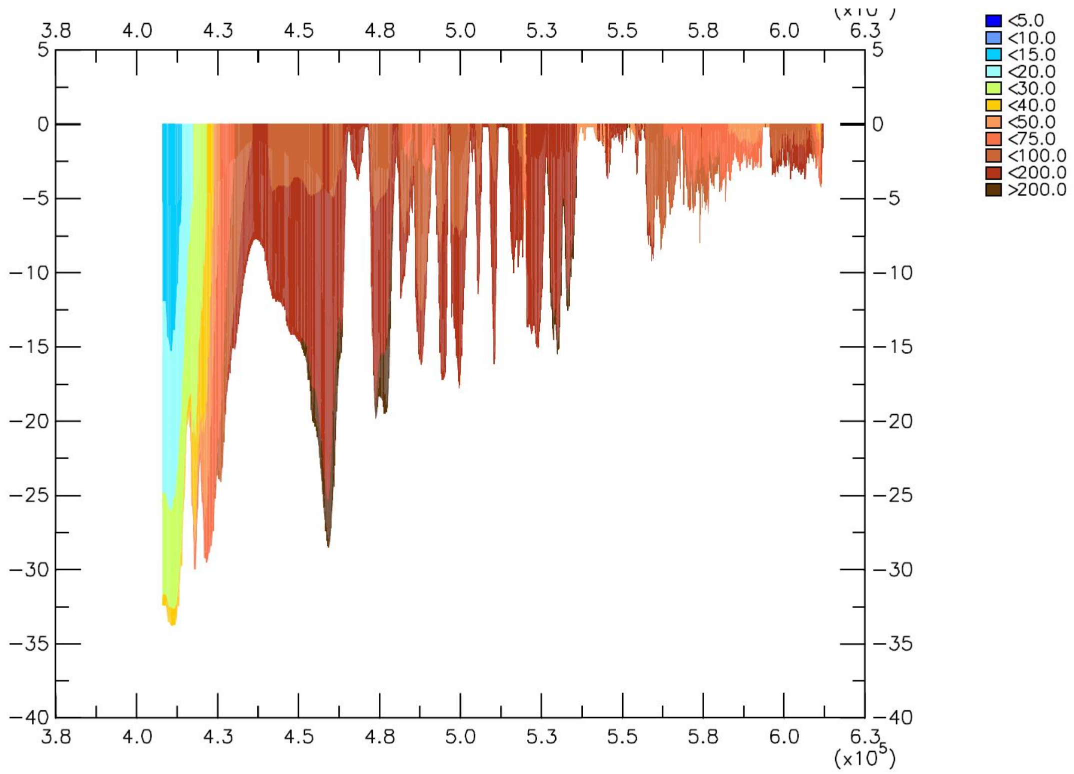
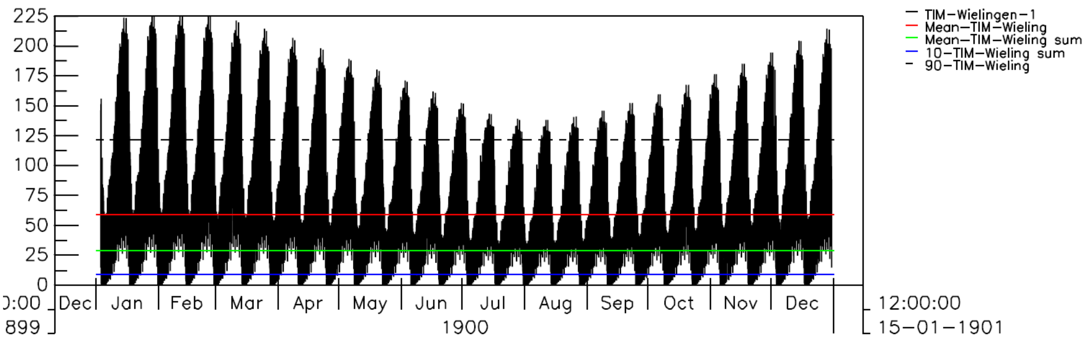
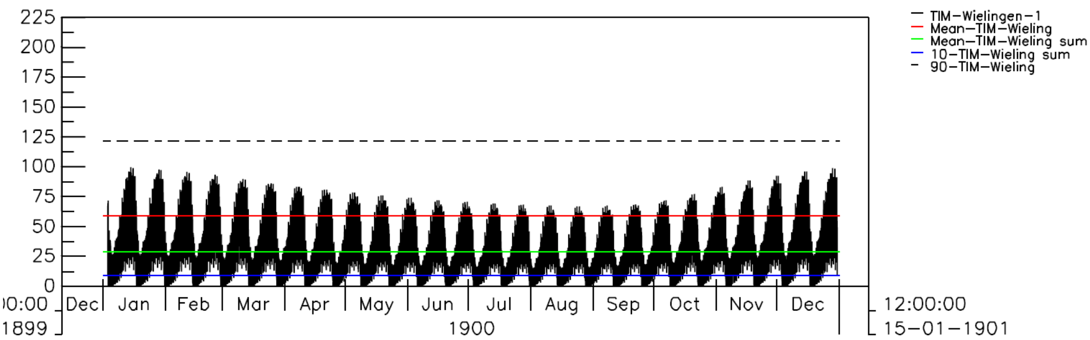


Fig. B.1d: 14-day winter averaged vertical SPM concentration transect (mg/l), new dumping locations (ws15new)

B.2 Effect of new SeaWiFs boundary conditions



a)



b)

Figure B.2: Computed SPM surface concentration at Wielingen. a) original boundary conditions; b) new boundary conditions based on SeaWiFs images. Observed mean levels are indicated with horizontal lines. In blue: 10-percentile level; in green: mean summer level; in red: mean winter level; dashed black: 90-percentile level.

B.3 Comparison between 5L and 10L

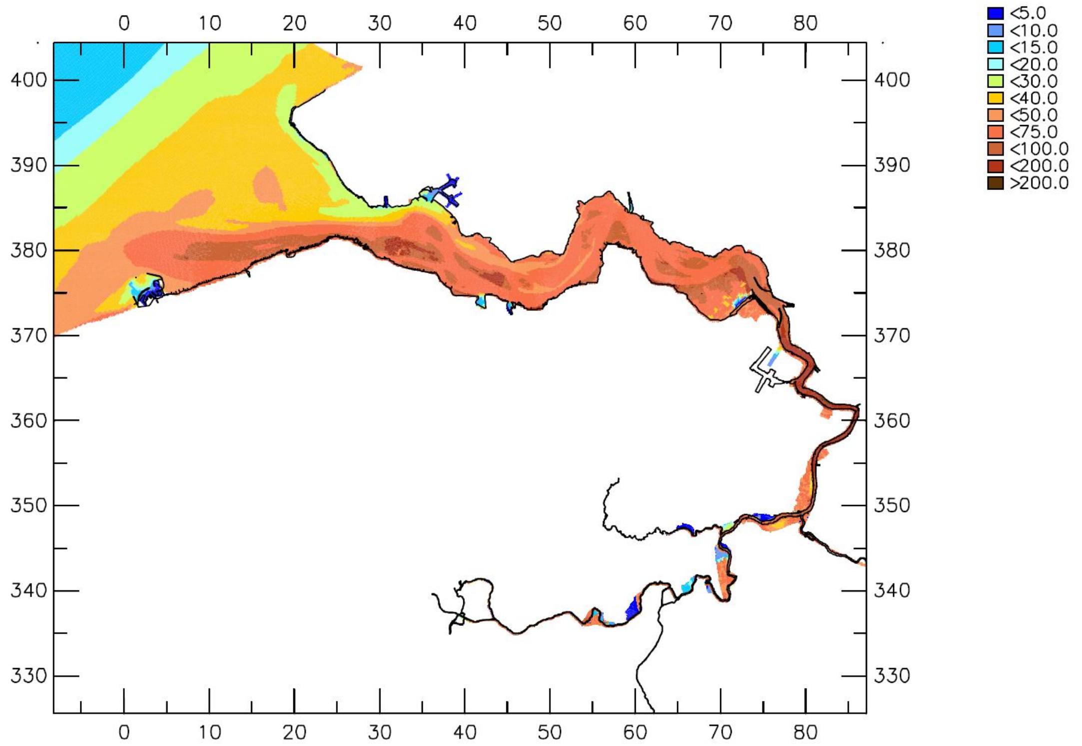


Fig. B.3a: 14-day winter averaged SPM surface concentration (mg/l), 5 horizontal layers (05L01).

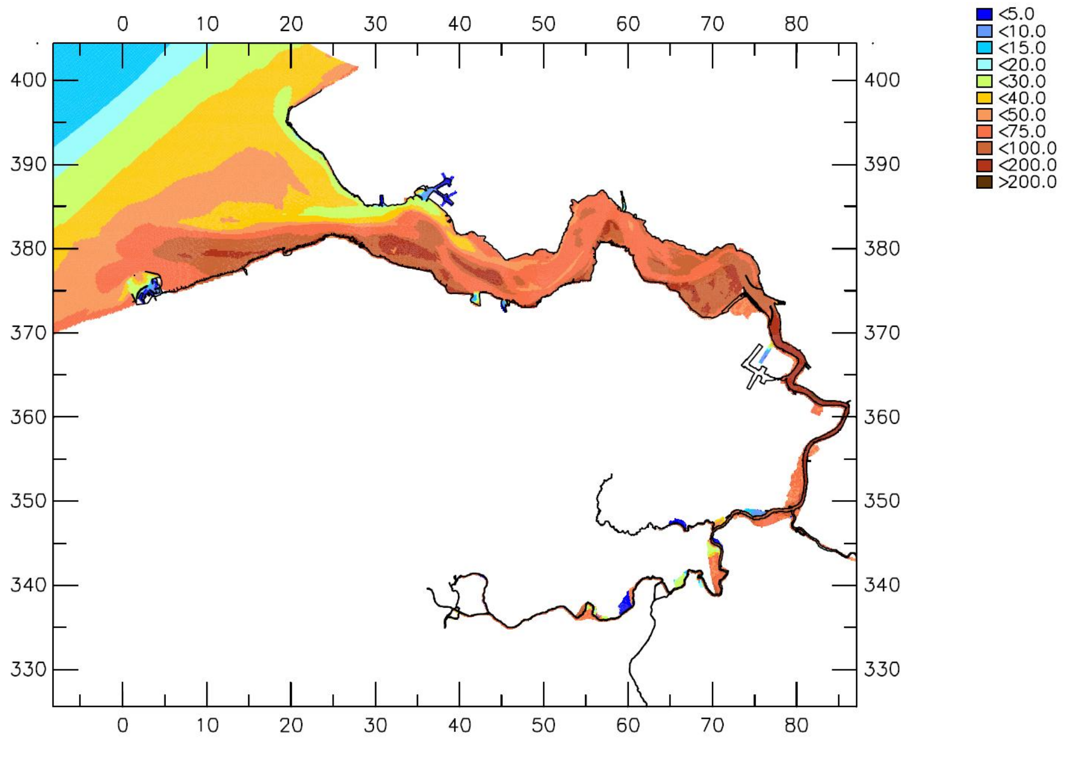


Fig. B.3b: 14-day winter averaged SPM surface concentration (mg/l), 10 horizontal layers (10L01).

B.4 Comparison between constant and variable wave forcing

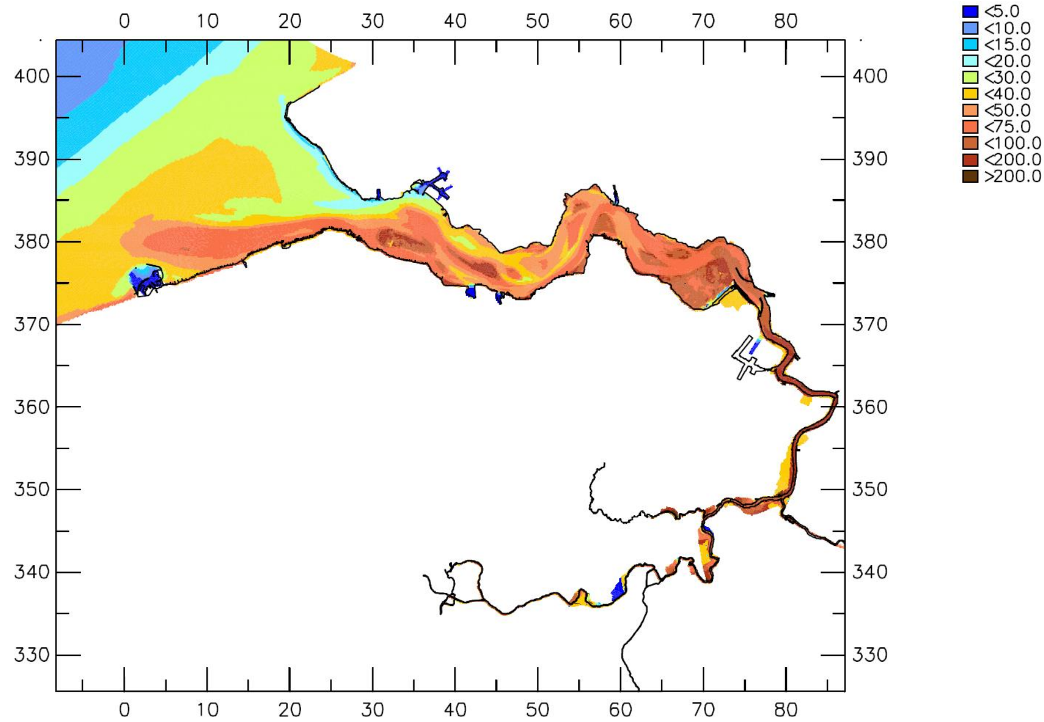


Fig. B.4a: 14-day winter averaged SPM surface concentration (mg/l), constant waves (ws22).

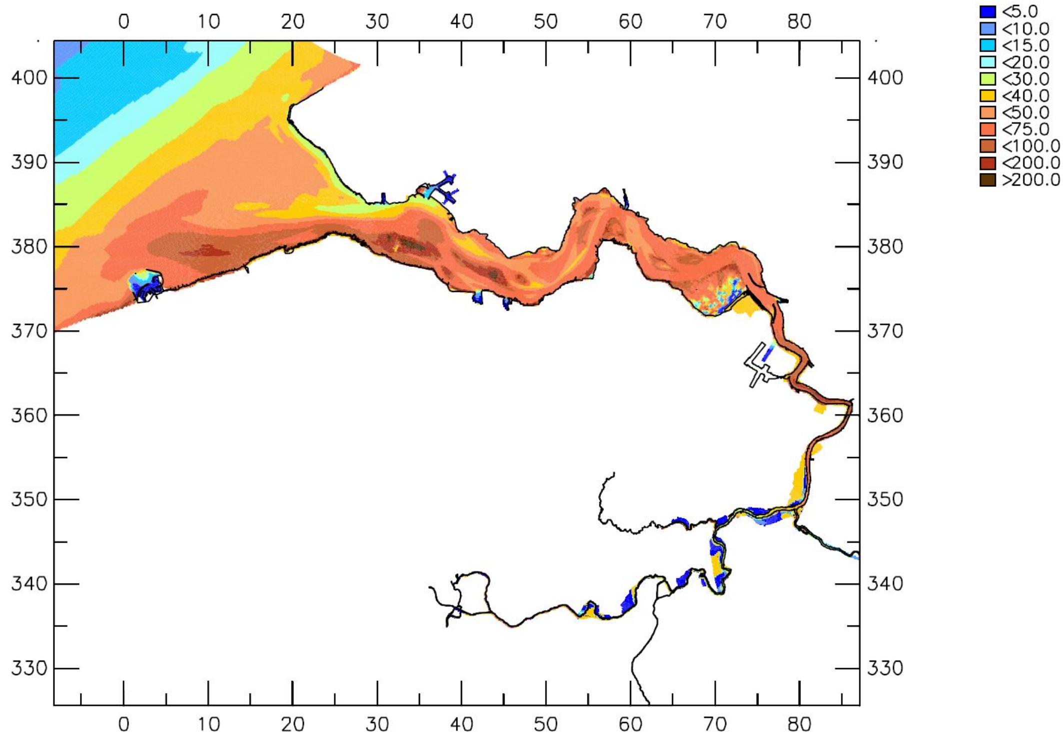


Fig. B.4b: 14-day winter averaged SPM surface concentration (mg/l), variable waves (ws21).

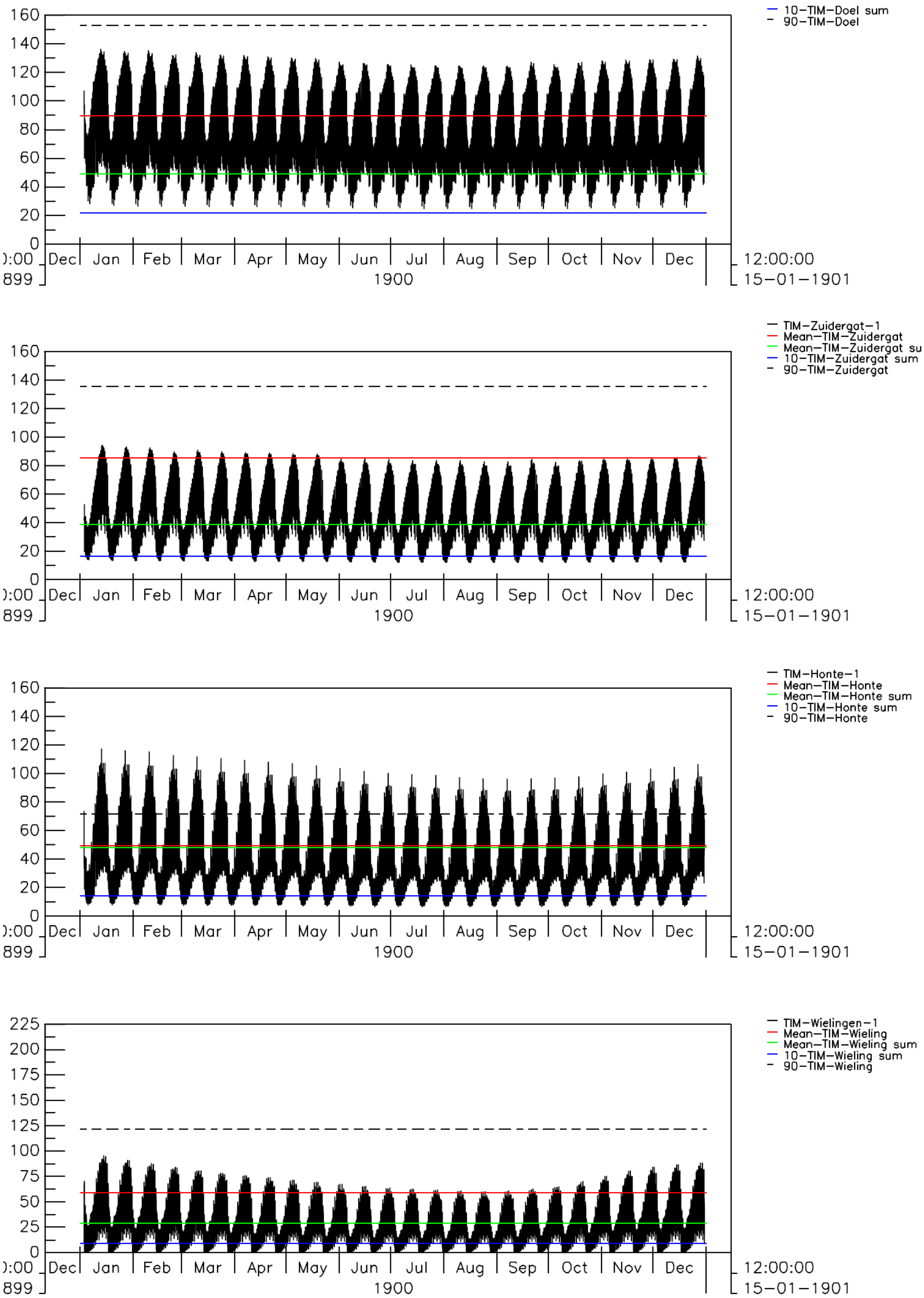


Figure B.4c: Computed SPM surface concentration at 4 stations along the Scheldt estuary for a simulation with constant waves (ws22). Observed mean levels are indicated with horizontal lines. In blue: 10-percentile level; in green: mean summer level; in red: mean winter level; dashed black: 90-percentile level.

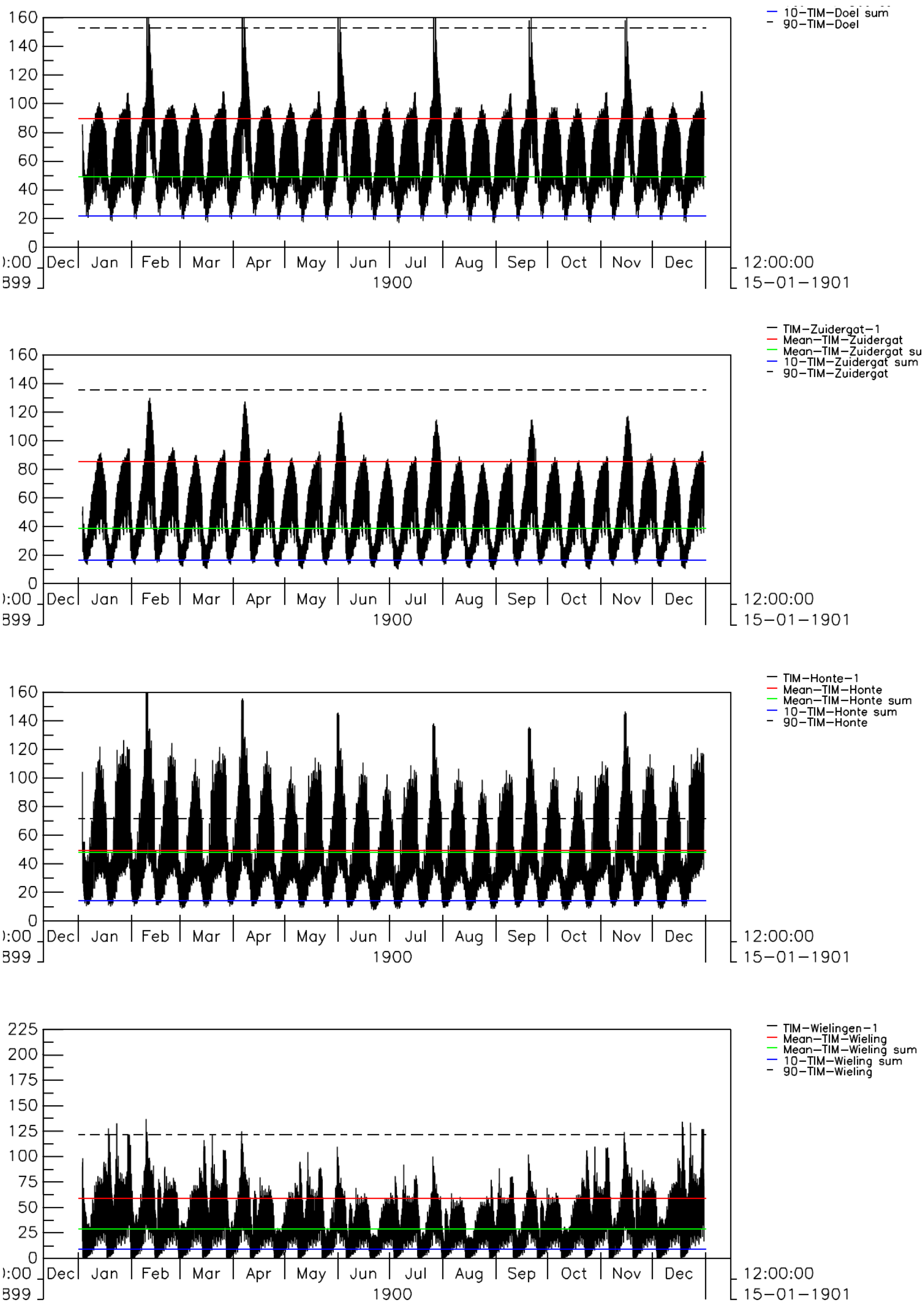


Figure B.4d: Computed SPM surface concentration at 4 stations along the Scheldt estuary for a simulation with variable waves (ws21). Observed mean levels are indicated with horizontal lines. In blue: 10-percentile level; in green: mean summer level; in red: mean winter level; dashed black: 90-percentile level.

B.5 Influence of biology

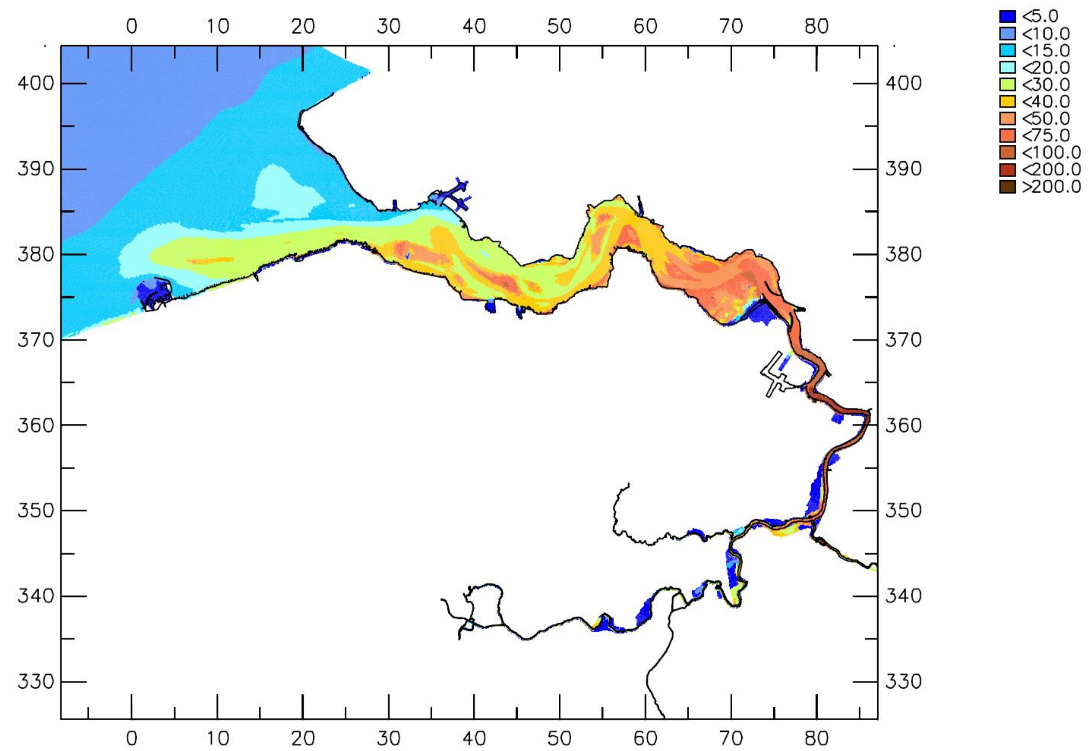


Fig. B.5a: 14-day summer averaged SPM surface concentration (mg/l), without biology, (ws27).

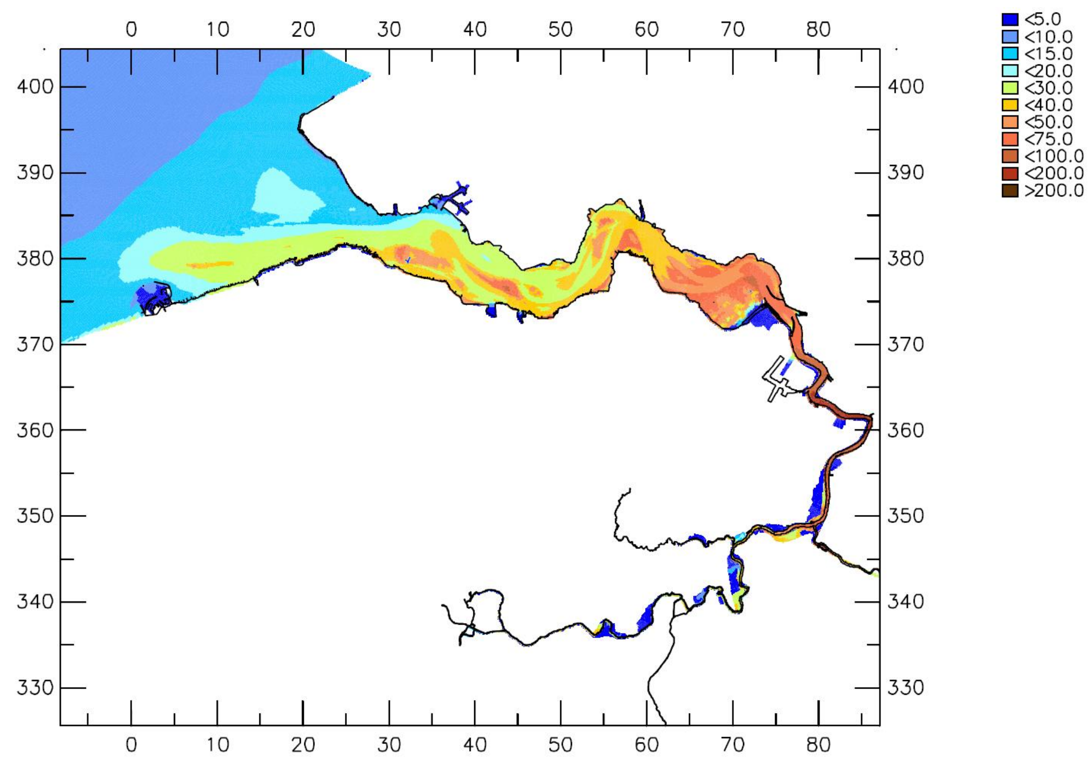


Fig. B.5b: 14-day summer averaged SPM surface concentration (mg/l), with biology, (ws26).

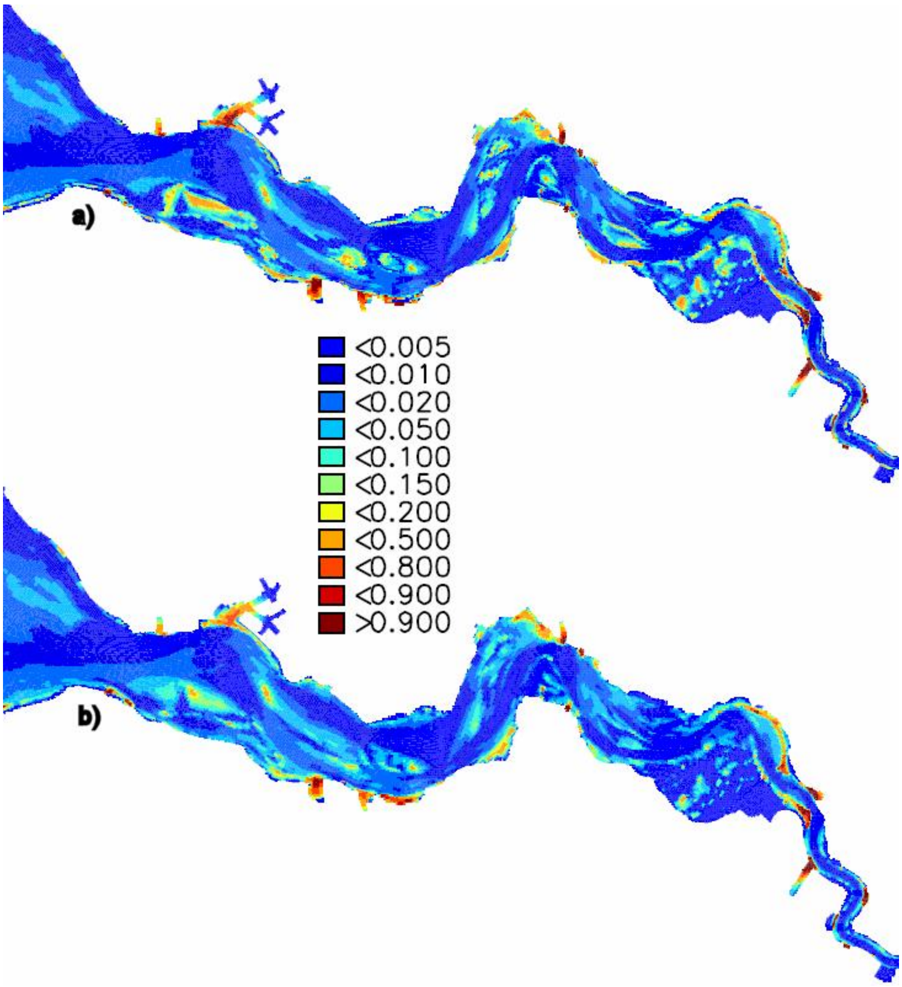


Fig. B.5c: Mud fraction in seabed in summer a) with biology; b) without biology.

B.6 Matching siltation and dumping flux

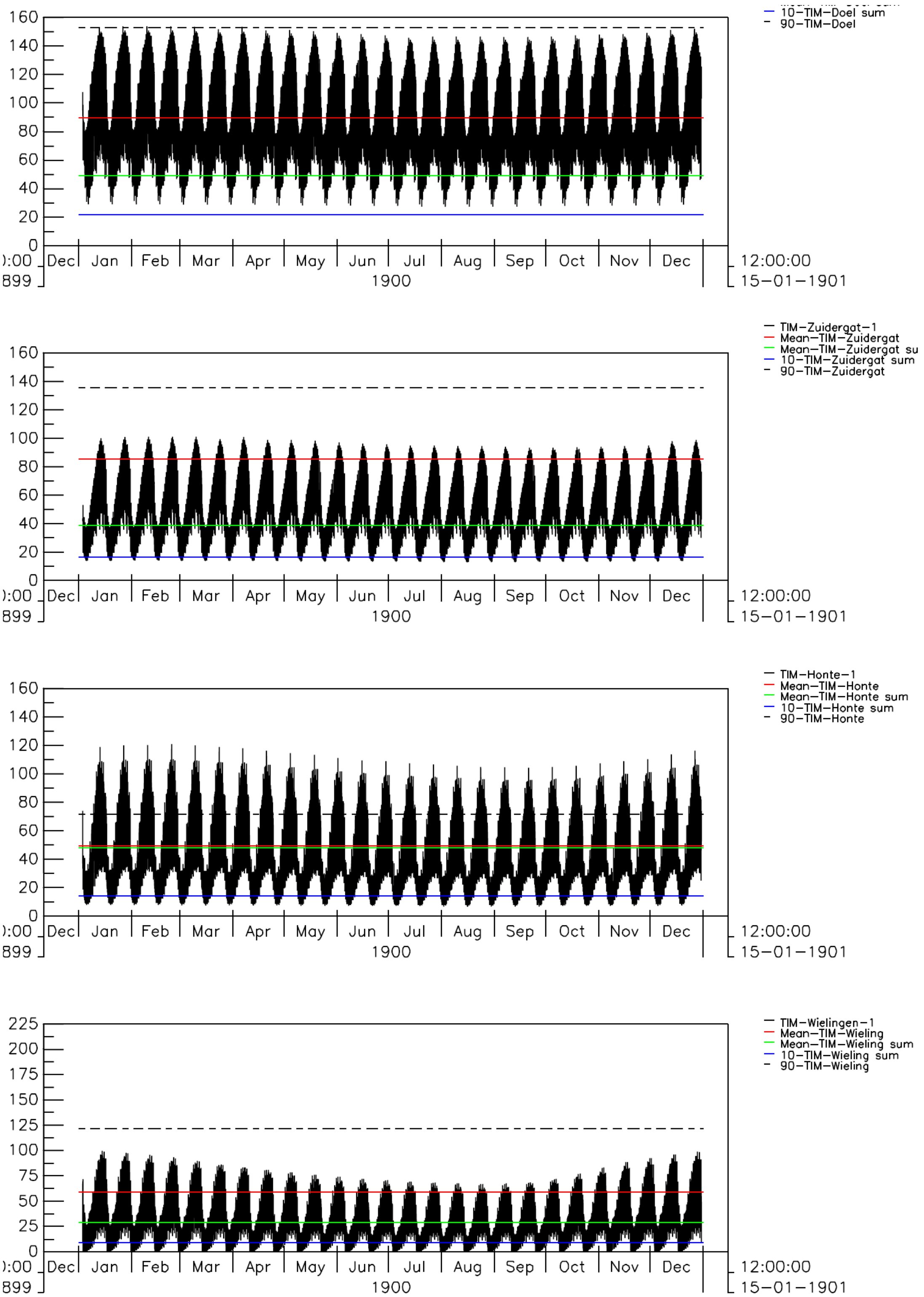


Figure B.6a: Computed SPM surface concentration at 4 stations along the Scheldt estuary for a simulation with original sediment loads (ws20). Observed mean levels are indicated with horizontal lines. In blue: 10-percentile level; in green: mean summer level; in red: mean winter level; dashed black: 90-percentile level.

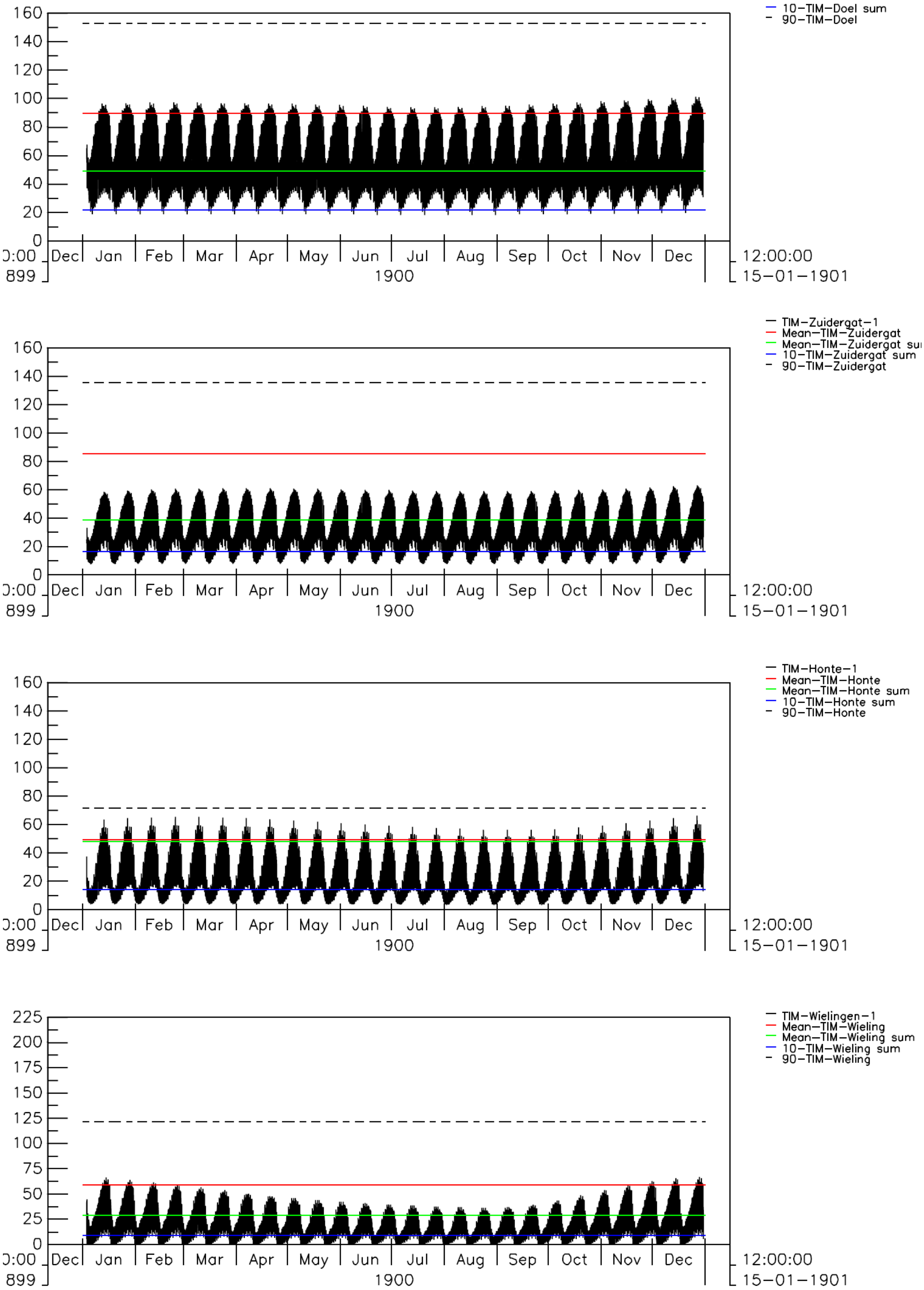


Figure B.6b: Computed SPM surface concentration at 4 stations along the Scheldt estuary for a simulation with reduced sediment loads and enhanced harbour siltation (ws24). Observed mean levels are indicated with horizontal lines. In blue: 10-percentile level; in green: mean summer level; in red: mean winter level; dashed black: 90-percentile level.

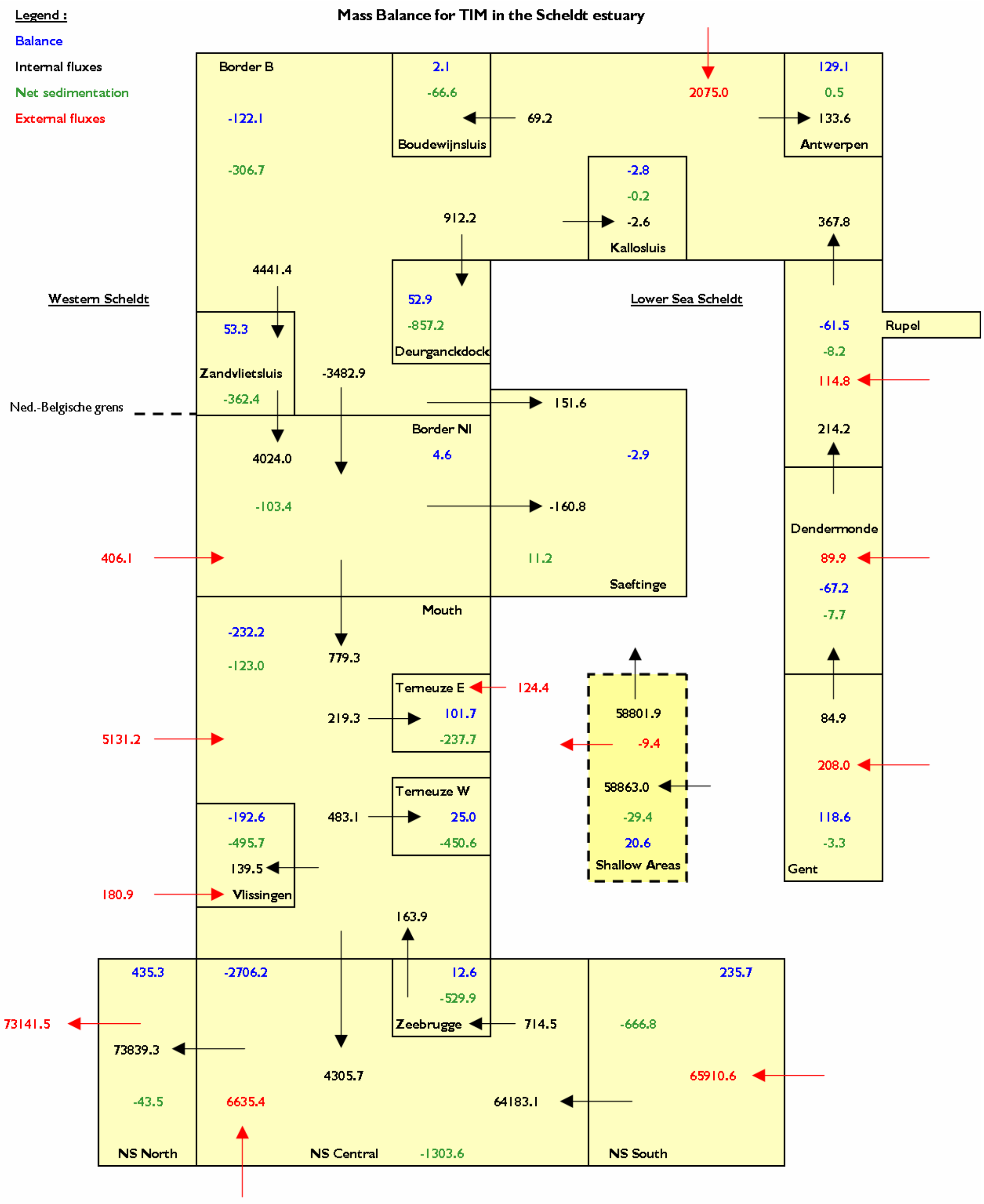


Figure B.6c: Mud balance for simulation with original loads (ws20)

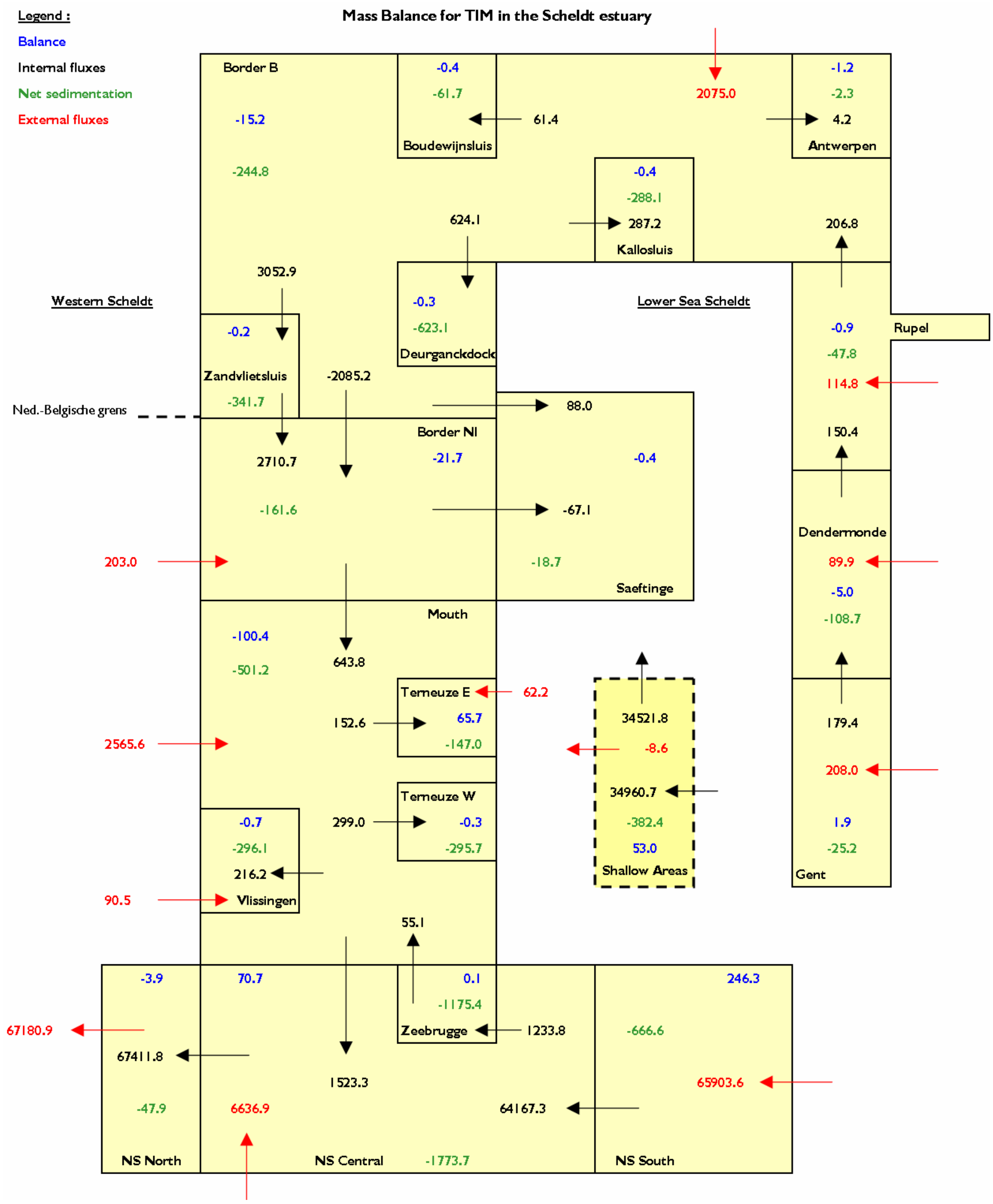


Figure B.6c: Mud balance for simulation with reduced loads and enhanced harbour siltation (ws24)

B.7 Potential effect of shipping traffic

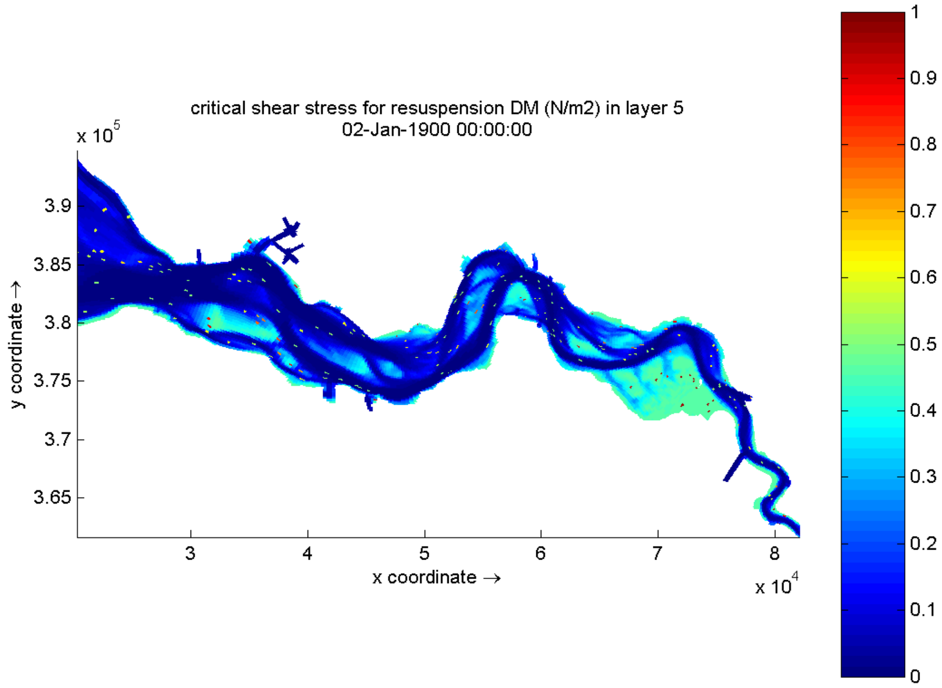


Fig. B.7a: Example of the actual total bed shear stress including ship movements (ws27). Dots signify the presence of ships. $\Delta\tau$ = 0.5 Pa and p = 1%.

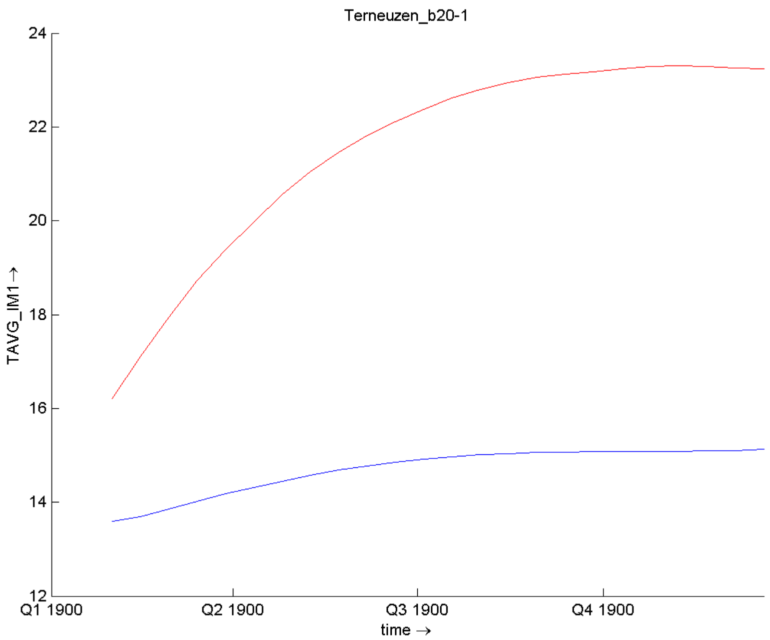


Fig. B.7b: 14-day average SPM surface concentration levels at DOW jetty, Terneuzen for a simulation without (ws36, blue line) and with (ws37, red line) ship movement (. $\Delta\tau$ = 0.5 Pa and p = 1%).

B.8 3-month simulation

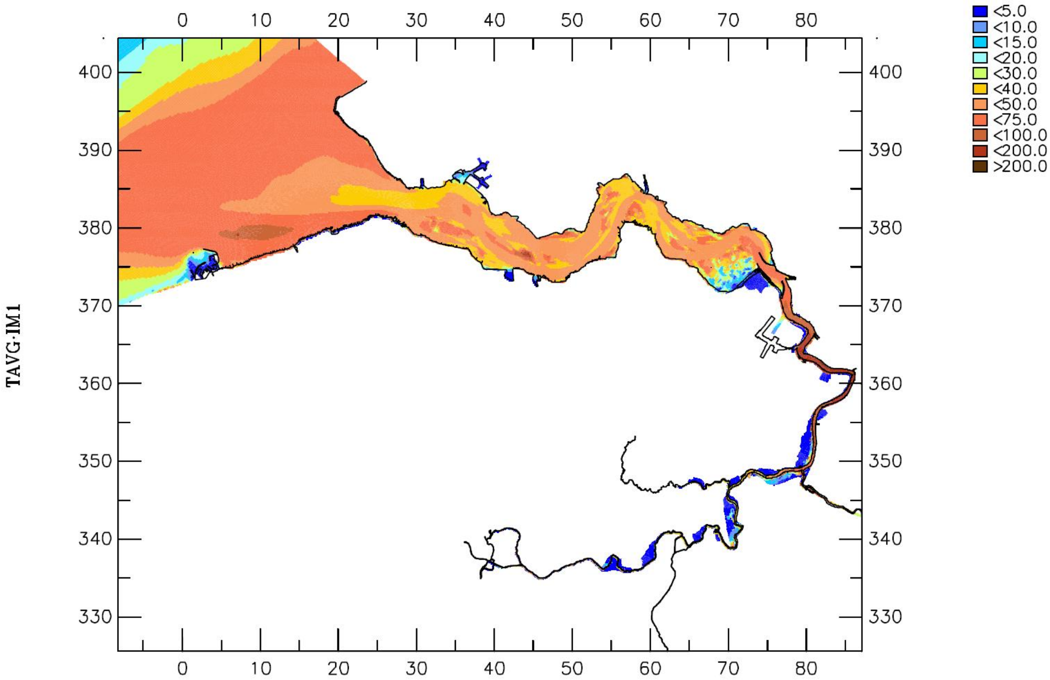


Figure B.7a: 14-day averaged SPM surface concentration (mg/l) at end of 3-month simulation (q03).

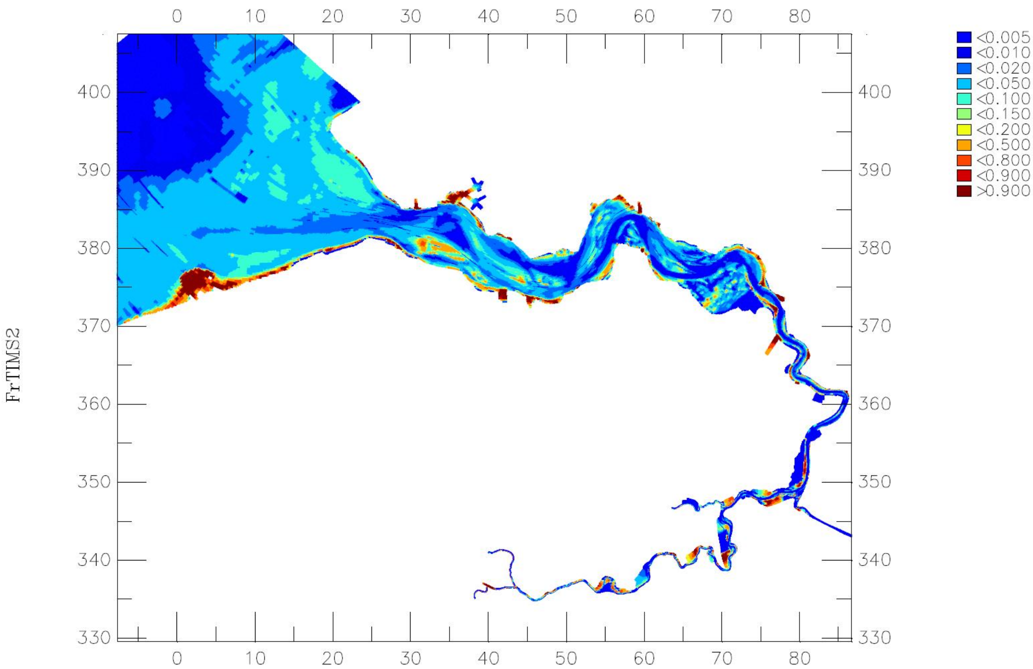
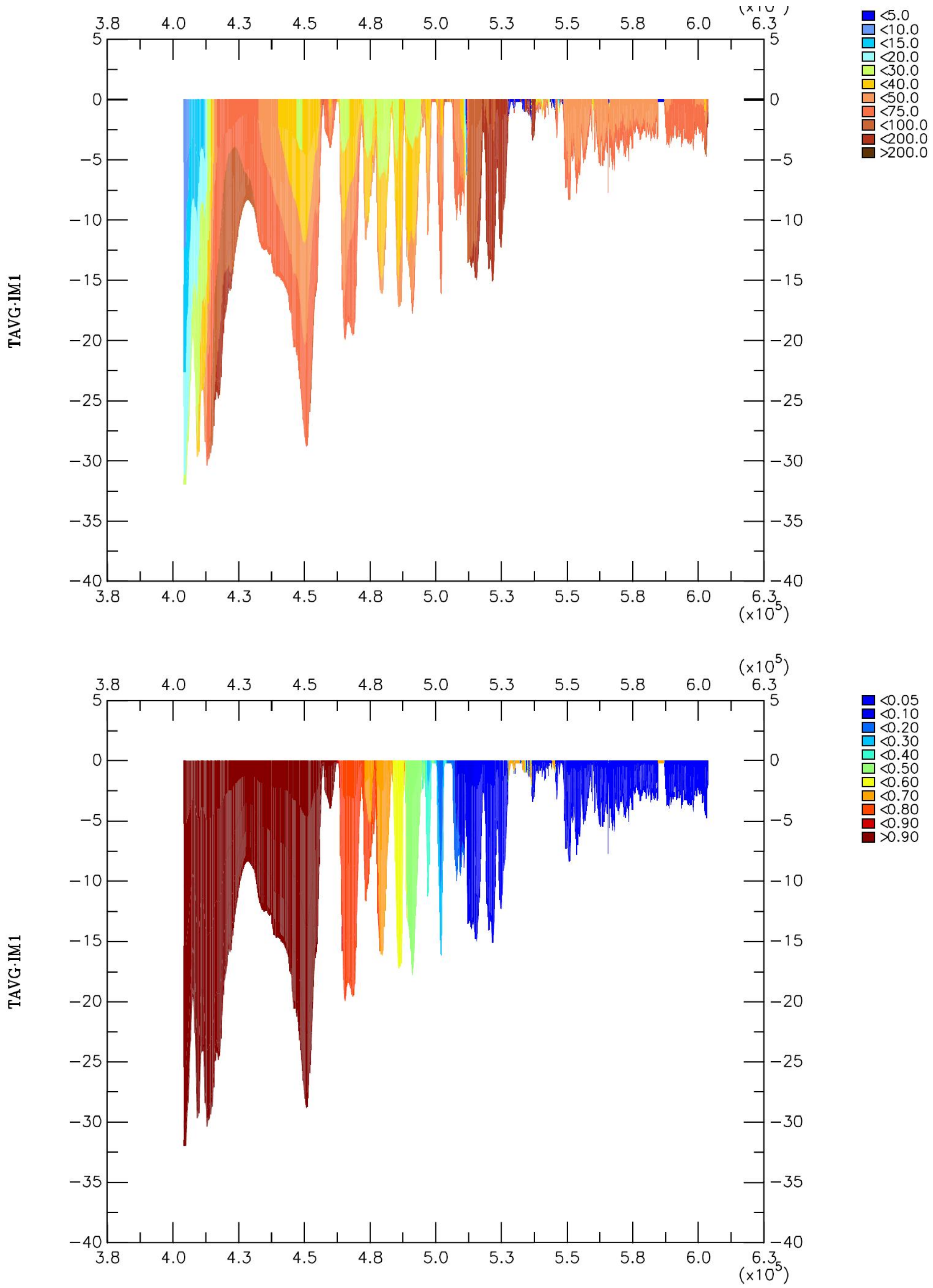


Figure B.7b: Mud fraction in sediment bed for 3-month simulation (q03).



B.7c: surface: 14-day winter averaged vertical SPM concentration transect (mg/l) for 3-month simulation (q03);
bottom: fraction marine mud.

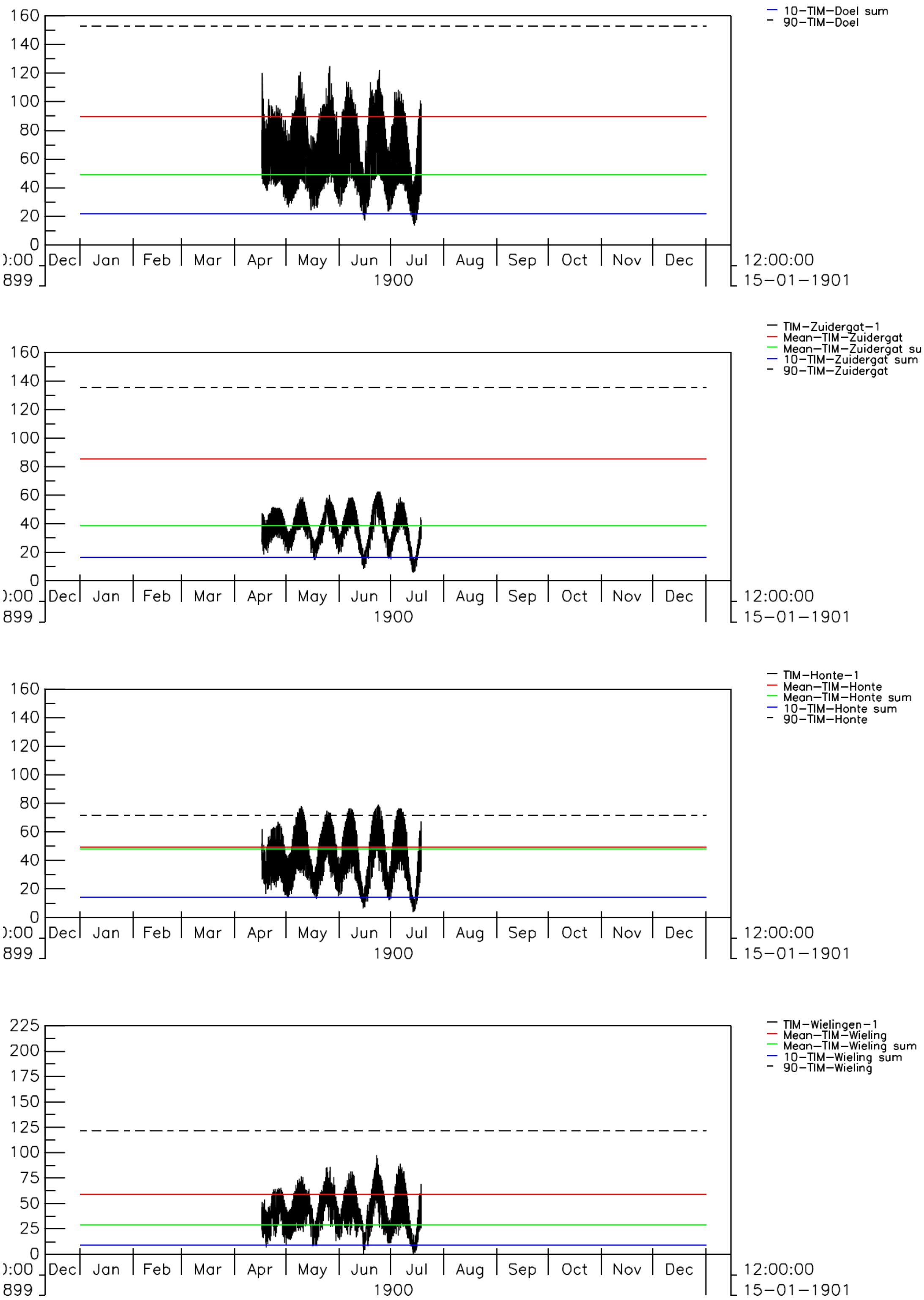


Figure B.7d: Computed SPM surface concentration at 4 stations along the Scheldt estuary for a 3-month simulation (q03). Observed mean levels are indicated with horizontal lines. In blue: 10-percentile level; in green: mean summer level; in red: mean winter level; dashed black: 90-percentile level..

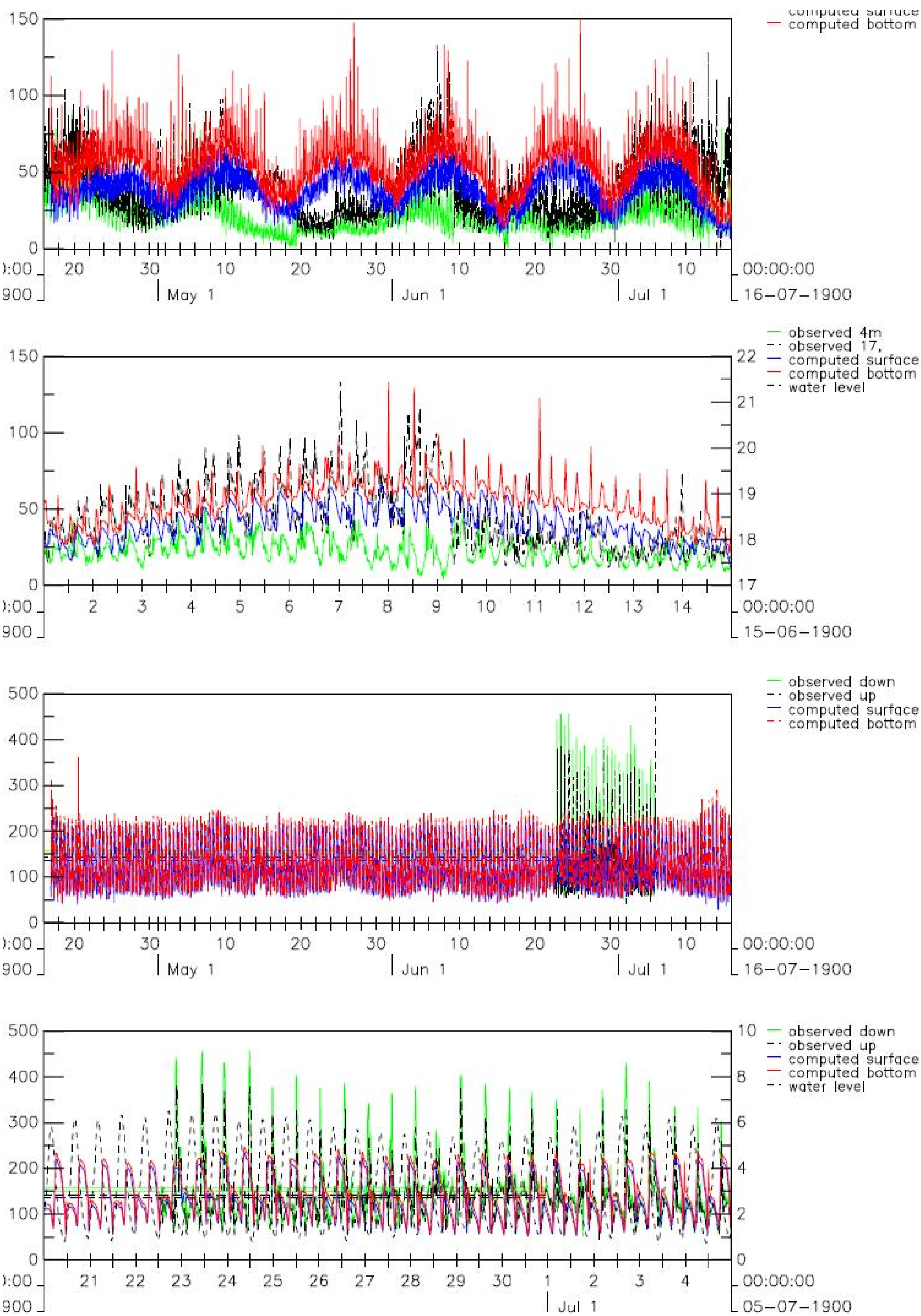


Figure B.7e: Mud : Computed SPM surface concentration at 2 stations along the Scheldt estuary for a 3-month simulation (q03). Upper two panels: at DOW-jetty; lower two panels: at Oosterweel. Observations are included in green (surface) and black (bottom).

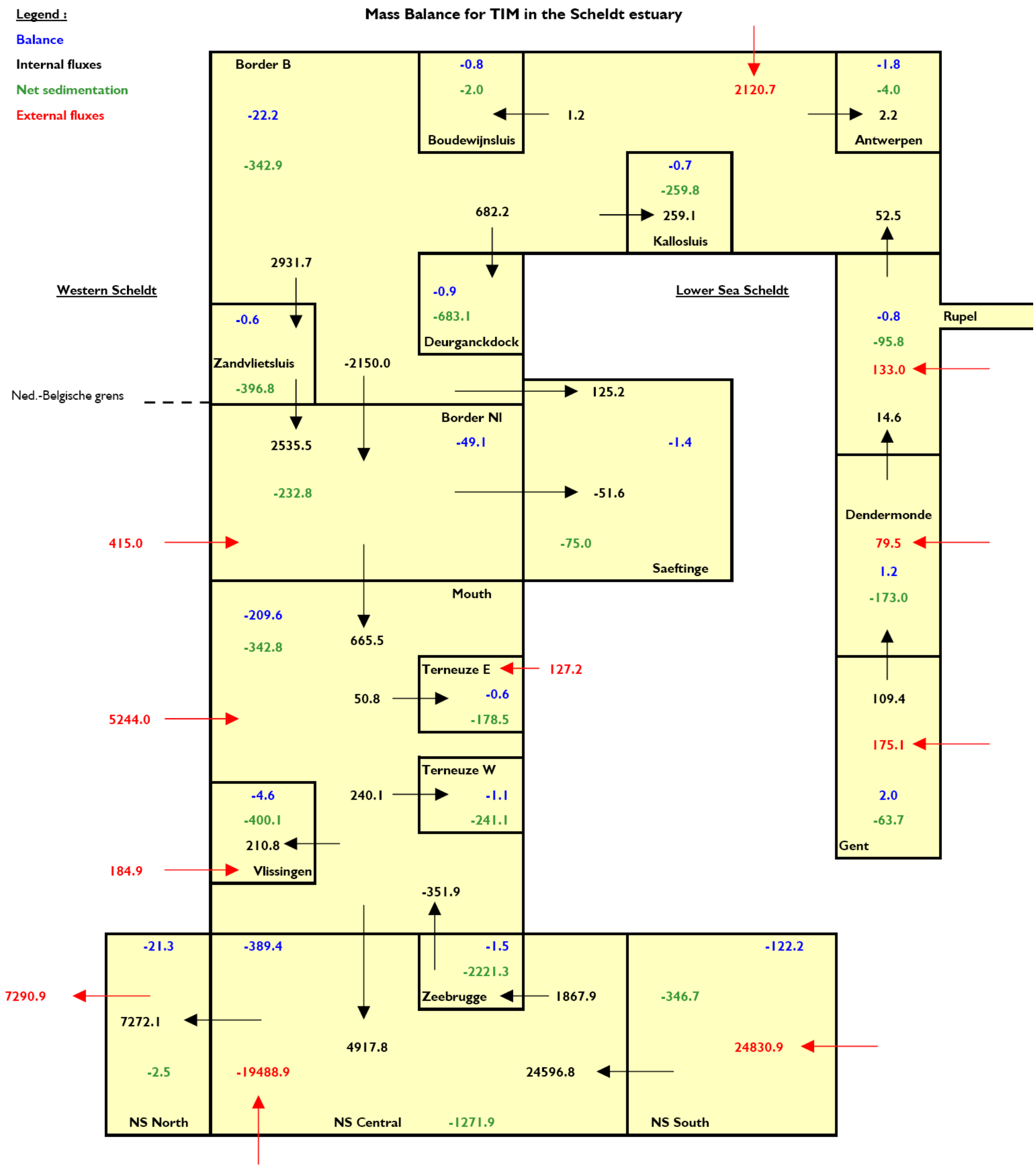


Figure B.7f: Mud balance for simulation Jan – Mar 2003 (q03), expressed in kton/year.