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Mud dynamics in the Eems-Dollard, phase 2

Setup sediment transport models

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Title
Mud dynamics in the Eems-Dollard, phase 2

Client	Project	Reference	Pages
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Summary
The Water Framework Directive (WFD) obliges the EU member states to achieve good status of all designated water bodies (rivers, lakes, transitional and coastal waters) by 2015. In the management plan for the implementation of the WFD (and Natura 2000) in the Netherlands, the context, perspectives, targets and measures for each designated water body (also including the Ems-Dollard) have been laid out. To achieve a good status of the Ems-Dollard Estuary (as the WDF obliges), knowledge on the mud dynamics in this region has to be improved, and the reasons for the increase in turbidity have to be identified before 2015. Therefore Rijkswaterstaat has initiated the project "Onderzoek slibhuishouding Eems-Dollard" (Research mud dynamics Ems-Dollard). This project explores the reasons for the historic increase in turbidity, and which measures can be designed to improve the water quality in the area.

Part of this research is the development of numerical models. This report describes the set up of the sediment transport models, using the hydrodynamic models developed earlier in the project. One of these models is part of an effect-chain model, for which the sediment transport model provides input to a water quality model. Dredging from ports and access channels is an integral part of the model setup and therefore the calibration. The model is calibrated against 2 permanent stations located in the outer estuary, long-term MWTL observations carried out at 3 stations, and 6 stations monitored in 2012 and 2013 as part of this project. In a later stage of the project this model is used to explain the current state of turbidity in the Ems Estuary and quantify the effects of mitigating measures. A second model is developed specifically for the lower Ems River, calibrated against several permanent monitoring stations located in the lower Ems River, but also set up for a range of historic scenarios. This model is developed to quantify historic changes in the lower Ems River and its impact on the lower Ems Estuary.

References
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1.0	April 2013	Bas van Maren		Thijs van Kessel			
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3.0	June 2014	Bas van Maren		Han Winterwerp			
4.0	Sep 2014	Bas van Maren	BM	Marcel Taal		Frank Hoozemans	

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final

Contents

1 Introduction

The Water Framework Directive (WFD) requires EU member states to achieve good ecological and chemical status of all designated water bodies (rivers, lakes, transitional and coastal waters) by 2015. In the management plan (Rijkswaterstaat, 2009) for the implementation of the WFD (and Natura 2000) in the Netherlands, the context, perspectives, targets and measures for each designated water body have been defined. The requirements for the Ems Estuary (see Figure 1.1 for location) are that the mud dynamics need to be better understood (before 2015), and driving forces for increase in turbidity need to be identified. Therefore Rijkswaterstaat has initiated the project 'Research mud dynamics Ems Estuary' (*Onderzoek slibhuishouding Eems-Dollard*). The aim of this project is to (I) determine if and why the turbidity in the Ems Estuary has changed, (II) to determine how the turbidity affects primary production, and (III) to investigate and quantify measures to reduce turbidity and improve the ecological status of the estuary – see also the flow chart of the project structure (Figure 1.2).

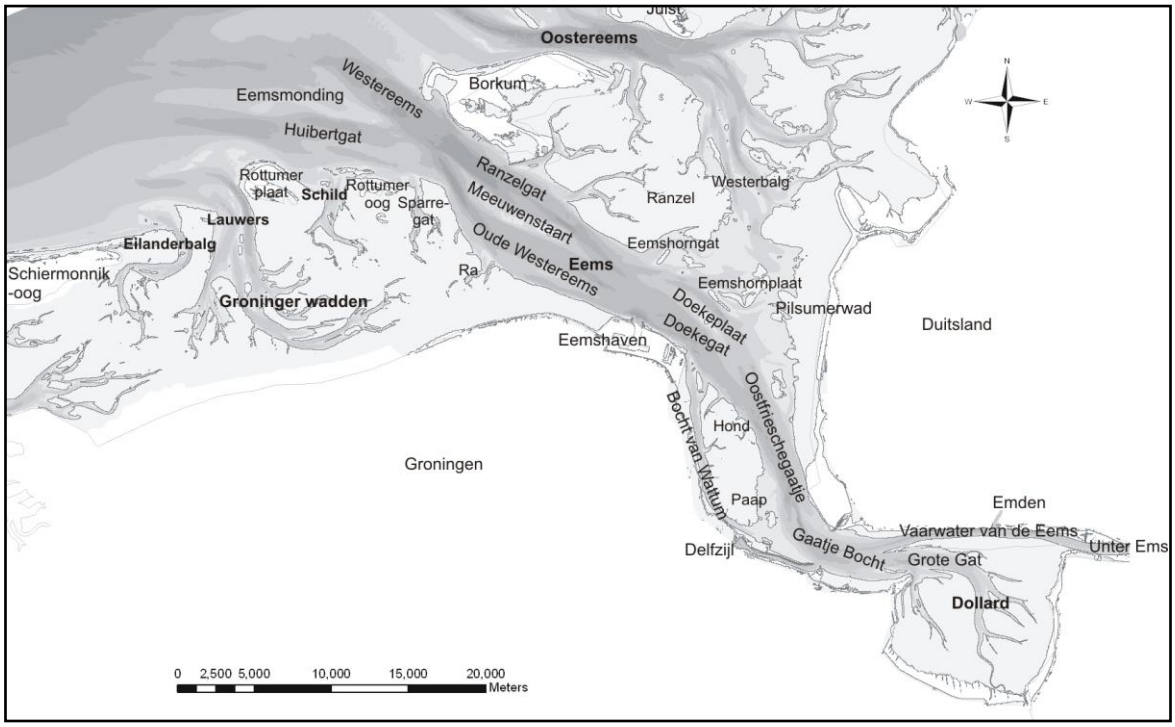

Figure 1.1 Map of Ems Estuary with names of the most important channels and flats (Cleveringa, 2008) in Dutch and German. The English name of the 'Vaarwater van de Eems' is the Emden navigation channel or Emden Fairway. The English name of 'Unter Ems' is the lower Ems River.

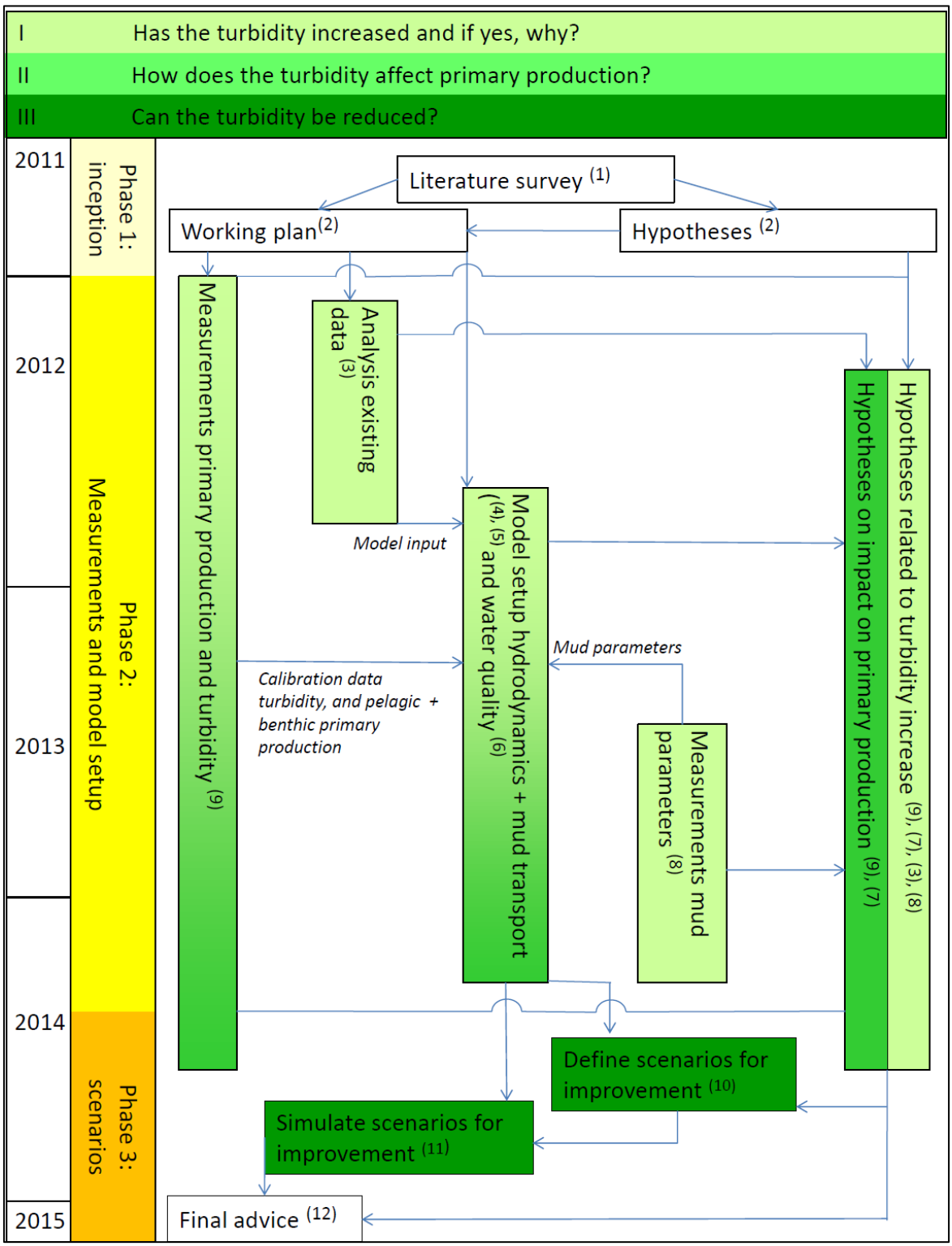

Figure 1.2 Flow chart for the structure and timetable of the study. Green colouring of the phase 2 activities relates to the colour of the main research questions I, II, and III. See Box 1 for a description and Table 1.1 for the references (1) – (12)

This research project explores mechanisms that may be responsible for the present-day turbidity of the estuary and identifies measures to reduce the turbidity. The long-term effect of human interventions on suspended sediment dynamics in an estuary such as the Ems Estuary is complex, and data supporting such an analysis is limited or non-existent. As an alternative to historic data analysis, an effect-chain model (relating human interventions to changes in hydrodynamics, sediment transport, and water quality) has been set up. Hereby maximal use was made of data that were already available and new data, collected within this project. Although the absolute values of the model predictions should be carefully interpreted, an effect-chain model provides a tool to investigate trends in system response to human interventions. This work provides indicative explanations for the current turbidity patterns and a first exploration of restoration options, but also reveals important gaps in knowledge and next steps to be taken. Additional research is required to further substantiate the results of this project.

The overall study is divided into three stages: an inception phase (phase 1) in which gaps in knowledge are identified and a research approach is defined; phase 2, in which measurements are done and models are set up and calibrated; and phase 3 in which the models are applied to investigate measures to improve the ecological and chemical status of the estuary. The overall structure and timeline of this study is summarized in Figure 1.2 and Box 1. An overview of the deliverables (reports and memos) produced during the project is given in Table 1.1. The numbers 1 to 12 of the deliverables are part of the project layout in Figure 1.2.

BOX 1: SET UP OF THE STUDY (with Figure 1.2; references in Table 1.1)

The primary objective of this study is to address the following:

q1: Has the turbidity increased and why?

q2: If yes, what is the impact on primary production?

q3: Can the turbidity be reduced?

These questions are presented in a flow chart (see Figure 1.2). During phase 1, existing gaps in knowledge were identified (see report 1 in Table 1.1), and a number of hypotheses were formulated related to q1 and q2 (report 2 in Table 1.1), to be addressed during phase 2 of the study.

Phase 2 consists of measurements, model set up and analysis. Measurements of primary production and turbidity are carried out from January 2012 to December 2013, and reported mid 2014 (report 9 in Table 1.1). These measurements are carried out to address hypotheses related to q1 and q2, and to calibrate the sediment transport and water quality models. Existing abiotic data (such as water levels, bed level, dredging, and sediment concentration) are analysed in this phase to address hypotheses related to q1 and to provide data for model calibration (report 3 in Table 1.1). Soil samples in the Ems estuary and Dollard basin have been collected to determine changes in mud content (hypotheses relates to q1) and determine parameter settings of the sediment transport model (report 8 in Table 1.1).

The effect-chain model set up for this study consist of three modules: a hydrodynamic module (report 4 in Table 1.1), a sediment transport module (report 5), and a water quality module (report 6). These models are applied to address the hypotheses related to q1, q2, and q3 (report 7 in Table 1.1).

In phase 3, a number of scenarios are defined to reduce turbidity / improve the water quality (q3) of the estuary (report 10 in Table 1.1). Their effectiveness is tested in reference (report 11). A final report, synthesizing the most important findings and recommendations (report 12) concludes the project.

Table 1.1 Reports / memos delivered during phase 1 to 3 of the Mud dynamics in the Ems estuary project (with numbers referencing to Figure 1.2). The current report is in bold.

Number	Year	Phase	Main research question	Report
1	2011	1	-	Literature study
2	2011	1	-	Working plan phase 2 and 3
3	2012	2	1	Analysis existing data
4	2014	2	-	Set up hydrodynamic models
5	**2014**	**2**	**-**	**Set up sediment transport models**
6	2014	2	-	Set up water quality model
7	2014	2	1, 2	Model analysis
8	2014	2	1	Analysis soil samples
9	2014	2	1, 2	Measurements primary production
10	2014	3	3	Scenario definition (memo)
11	2014	3	3	Model scenarios
12	2015	3	1, 2, 3	Final report

Part of phase 2 of the project is the set-up and analysis of numerical models. The models are used to better understand the historic changes and present-day conditions in the Ems Estuary (report 7 in Table 1.1) and to quantify the effect of measures to improve the functioning of the estuary (Phase 3; Report 11). The research questions to be addressed with the models cover a range of processes to be addressed, which have led to the development of multiple hydrodynamic and sediment transport models. This will be explained in more detail in Chapter 2. Chapter 3 provides a short analysis of data needed for the set-up and calibration / validation of the sediment transport model. These data are analysed and translated into a modelling approach in Chapter 4. The set-up and calibration of the sediment transport model of the Ems Estuary is described in chapter 5. The sediment transport model of the lower Ems River is described in Chapter 6. The main findings are summarised in Chapter 7.

2 Description of models

This chapter provides a brief description of the applied models. More details about each model (such as modelling assumptions, domains, time and resolution etc.) are described in the dedicated model reports to hydrodynamics and water quality (reports 4 and 6 in Table 1.1). This is report 5 (setup sediment transport models).

2.1 Introduction

The objective of this study is to determine why turbidity has changed, what the impact is on primary production, and if / how this can be mitigated. These questions can be addressed using a combination of field data and numerical models. The most important gaps in knowledge, as identified in report 1, have been translated into a list of hypotheses (see report 2). These hypotheses cover a range of research objectives related to hydrodynamics, sediment transport, and water quality. For research questions addressing hydrodynamic processes, a hydrodynamic model is used. Modelling turbidity requires the use of a sediment transport model in combination with the hydrodynamic model. Primary production is dependent on turbidity, and therefore primary production is modelled with a hydrodynamic-sediment transport- primary production model. This is known as an effect-chain model, which is described in more detail in section 2.2.

The hypotheses formulated in report 2 will be tested with the numerical models, on which is reported in report 7. The ability of the models to test these hypotheses is determined by the physical and/or ecological processes the models reproduce. The most important processes (see for details report 1) are:

a) Tidal propagation in the Ems Estuary and lower Ems River and changes therein as a result of deepening
b) Residual flows resulting from river discharge, wind and salinity, and changes therein as a result of deepening
c) Sediment transport mechanisms and typical sediment concentration levels as a result of tides, waves, and density-driven flows
d) Sediment trapping in ports and the long-term effect of subsequent dredging and dispersal on the suspended sediment concentration in the estuary.
e) Pelagic and benthic primary production under influence of light and nutrient availability

In each of the relevant reports, the applicability of the model to address the processes above will be addressed:
a) and b) in report 4 and 7;
c) and d) in this report and in report 7;
e) in report 6 and 7.

The starting point for the effect-chain model is the numerical model developed within the TO-KPP studies (see e.g. Van Kessel et al. (2013) for an overview). This model is originally based on a model developed by Alkyon (2008). This model is hereafter referred to as the WED model (Wadden Sea Ems Dollard). The original WED model was set up for the year 2005. In this project a large amount of monitoring data has been generated for the year 2012 and 2013. This includes the primary production and turbidity data, but also data of the continuous measurements near Eemshaven in the first half of 2012. Therefore, the model is recalibrated for the year 2012. Other aspects of the model that were improved are discussed in section 2.3.

The WED model is set up to simulate relatively long time periods and large spatial scales. Some of the research questions that need to be addressed cover smaller spatial scales and different process formulations. These questions require the use of more detailed models as the resolution of the WED model is insufficient to accurately model the dynamics in the lower Ems River and the exchange with the Ems Estuary. In order to better understand the changes in the lower Ems River (and exchange with the Ems Estuary), two models were set up: the Ems River Dollard (ERD) model and the Ems River (ER) model (see Figure 2.1). The ERD-model has a hydrodynamic model and the ER-model has both a hydrodynamic and a sediment-transport model (ER). See Table 2.1 for an overview of the modules for each model.

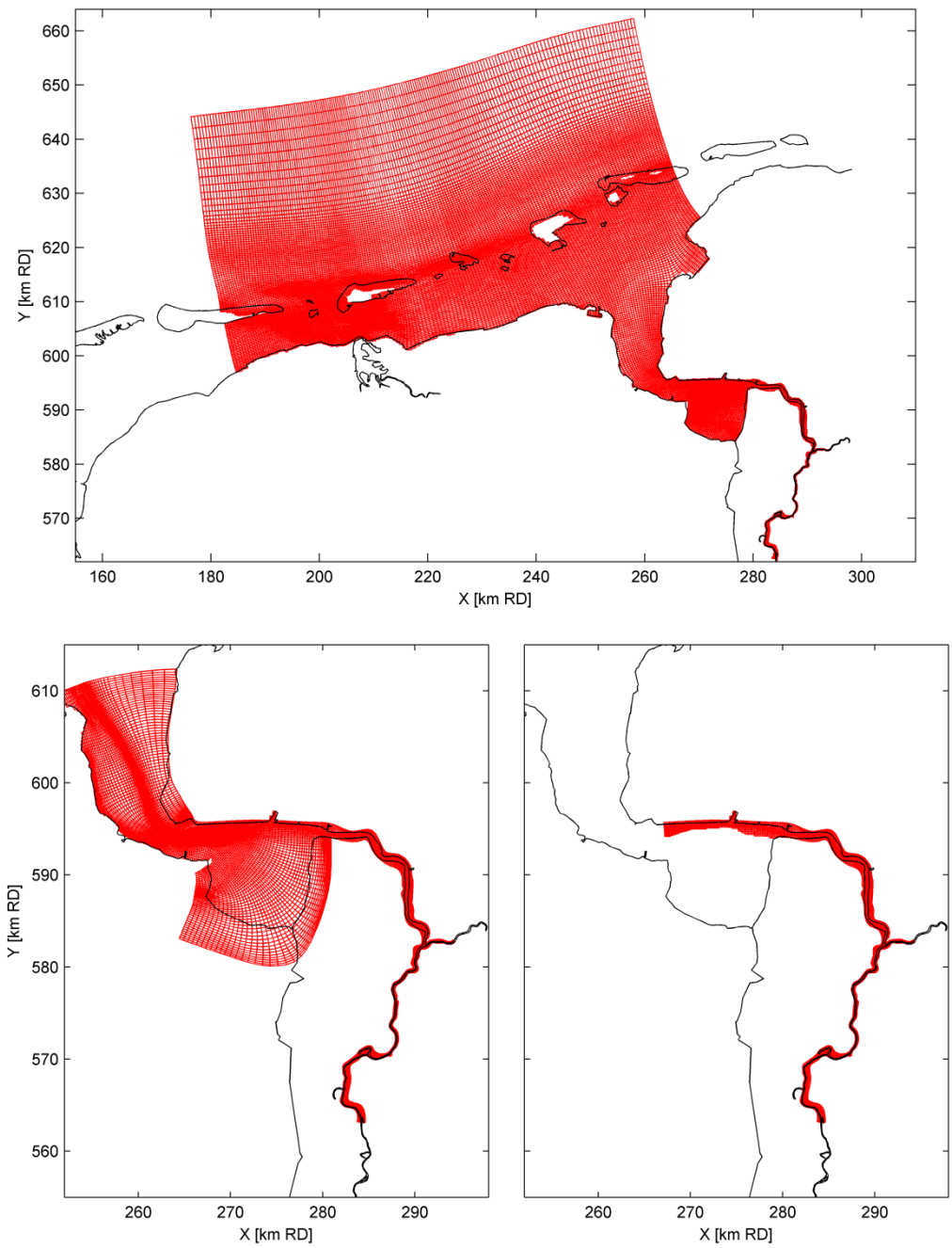

Figure 2.1 Computation grid of the WED model (top), the ERD model (lower left), and the ER model (lower right).

Table 2.1 Models adapted (WED) or developed (ER, ERD) within this project

Model	Hydro	Sediment transport	Waves	Water quality	Purpose
WED	yes	yes	yes	Yes	Set up of an effect chain model to simulate long-term hydrodynamic, sediment transport, and water quality changes
ERD	yes	no	no	no	Simulate tidal processes in parts of the Ems Estuary, the Dollard, and the lower Ems River.
ER	yes	yes	no	no	Quantify tidal and sediment transport processes within the lower Ems River and changes in sediment exchange between Ems river and Ems estuary

2.2 Effect chain models

An effect chain model is a set of models that describe jointly the effects of changes in the physical and morphological environment on chemical and biological variables. Each individual model describes a different set of processes within this chain of events. The basic idea of running different models is that each model component in itself can be optimally configured describing a limited set of processes. The alternative, one model describing all processes in one run, will have a higher computational demand and less flexibility, or a lower accuracy. Combining the results of the different models in a chain is necessary in order to take into account all relevant processes. In this study, the following three models were “chained” (Figure 2.2):

- A hydrodynamic model, producing time-dependent three-dimensional (3D) fields of salinity, temperature and other physical parameters such as bottom friction. This model is based on the open-source software Delft3D-Flow.
- A sediment model describing the transport and distribution of fine sediments, using the output of the hydrodynamic model as input. This model is based on the open-source software Delft3D-WAQ, configured for fine sediments.
- A water quality/primary production model describing cycling of nutrients, light distribution in the water, and primary production by phytoplankton and microphytobenthos. This model is based on the open-source software Delft3D- WAQ, configured for ecological processes. The water quality/primary production model component uses the output of both the hydrodynamic model and the sediment model as input.

For addressing the questions in this study, we follow an approach in which we assume that there is no significant feedback between hydrodynamics, sediment transport and water quality. This is elaborated in more detail in section 2.3. Therefore the coupling between the models is done off-line, meaning that each model is executed separately, using the output of the previous model in the chain as input. The hydrodynamic model exports files with hydrodynamic variables which are input for the sediment transport model. Subsequently, the sediment transport model generates files with sediment concentration fields that are (together with the hydrodynamic input files) used by the water quality model. This big advantage of this offline approach is that computational times remain manageable.

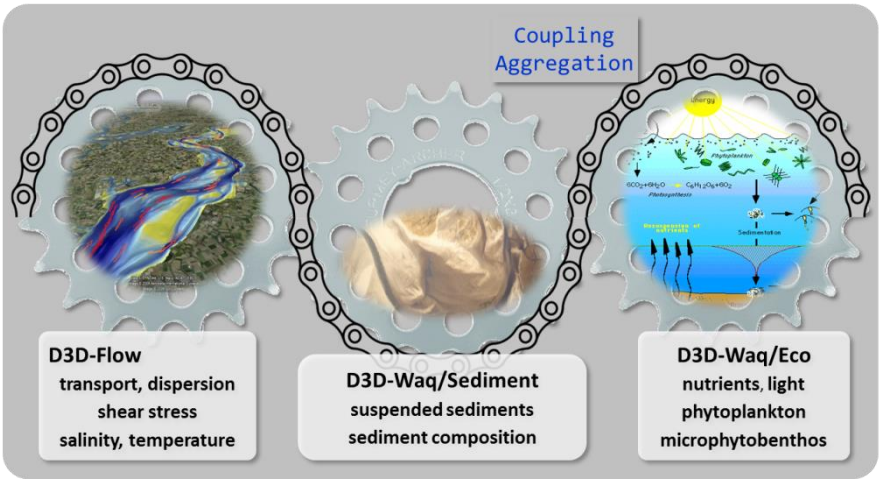

Figure 2.2 General set up of a linear effect-chain model.

2.3 The Waddensea Ems Dollard (WED) model

The combination of the hydrodynamic, sediment transport, and water quality models (the effect-chain model) will be used to explore the effects of natural variation and man-made changes in the nutrient loads and sediment dynamics of the estuarine waters on turbidity, primary production and phytoplankton biomass. This provides a tool which can be used to better understand the historic changes in the Ems Estuary (Report 7) but also to estimate the effect of proposed measures to improve the turbidity and primary production (Report 11). In order to adequately address the research questions formulated for this study (see section 1.1), the WED model developed in the TO-KPP studies needed to be improved on several aspects:

The computed salinity in the **hydrodynamic model** of the TO-KPP studies deviates considerably from the observed salinity. As salinity is a good approximation of computed dispersion and mixing, the salinity modelling needs to be improved for the current study. The mismatch of the model is probably the result of too strongly simplified boundary conditions. Therefore the freshwater sources are now implemented with more detail. In addition, the computed salinity is also verified with continuous measurements collected in the German part of the estuary and close to Eemshaven. These add to data collected at the Dutch MWTL stations). The second major improvement in the hydrodynamic model is the computation of wave-induced bed shear stresses with the SWAN wave model, instead of the less accurate fetch-length wave approach that was initially applied. The SWAN model generates a stronger along-estuary gradient in wave height and bed shear stress, which promotes up-estuary sediment transport.

The WED **sediment transport model** computes the transport of fine sediment (mud). One of the shortcomings of the TO-KPP sediment transport model was that the residual transport of sediment was directed down-estuary, whereas observations indicate that the Ems Estuary is importing. To achieve this, the wave model was improved, dredging and dumping was integrally modelled (sediment depositing in ports is regularly dredged and disposed on dumping locations through a dredging routine), and the sediment settings of the model were modified. Also, the original sediment transport model was only limitedly compared to observations. New observations were generated within the mud sampling programme (Report 8), the primary production measurements (Report 9), and the GSP measurements collected near Eemshaven to setup and validate the model. In addition to the turbidity measurements,

the model accuracy is determined by comparing modelled sediment fluxes with measured sediment fluxes (mainly using port siltation rates). Finally, the modelled sediment deposition is compared with observed sediment distribution patterns.

Within the Delft3D modelling suite, sediment can be modelled in Delft3D-FLOW sediment-online (with a full coupling between hydrodynamics, sediment transport and morphology) or in Delft3D-WAQ (which is coupled off-line, i.e. the sediment transport is computed after the hydrodynamic simulation. A coupling between hydrodynamics and morphology is needed when bed level changes significantly influence the hydrodynamics within the modelled timeframe, which is usually only required for sand and for decadal timescales. Morphological changes resulting from fine sediment erosion or deposition usually have limited impact on hydrodynamics. Fine sediment may influence the vertical mixing through suppression of turbulence at concentrations exceeding several 100 mg/l.

The WED sediment transport model is setup in Delft3D-WAQ, for 3 reasons. First, multi-year simulations are needed to develop a sediment transport model which is in dynamic equilibrium (where computed sediment concentrations are independent of initial conditions but determined by hydrodynamics, model settings, and boundary conditions), which is needed to compute the effect of perturbations to the system. Multi-year simulations are, however, problematic with a fully coupled model due to the associated computational times, as a fully coupled model is approximately 10 times slower than a non-coupled model. Secondly, in the majority of the Ems Estuary the concentrations are below several 100 mg/l and the bed level changes small. The sediment transport model therefore does not need to be fully coupled. And thirdly, in Delft3D-WAQ sediment transport processes are available (the buffering of fine sediment, using the model developed by van Kessel et al. (2011)) which are important for description of estuarine sediment dynamics.

The **water quality/primary production model** was further developed using a more detailed process description (Report 6), and using newly available monitoring data (Report 9). The implementation of a more detailed description of nutrient cycles including layered sediment with early diagenesis of organic material is needed to improve the calculation of phosphate compounds compared to the TO-KPP studies. The phosphate compounds show a strong sediment flux in summer in the inner parts of the estuary. Secondly, the monitoring programme carried out by IMARES (Report 9) provided a better approximation of phytoplankton growth process parameters, and validation data additional to the national monitoring programme.

2.4 The Ems River (ER) and Ems River Dollard (ERD) models

It is known that the lower Ems River became significantly more turbid in the last decades (e.g. de Jonge et al., 2014). At present the lower Ems River is a hyper-concentrated system with very limited ecological value. The exchange of sediment between the lower Ems River and the Ems Estuary may be important for the sediment dynamics in the Ems Estuary. This is also part of the hypotheses formulated in report 2. Also a more quantitative understanding of changes in the lower Ems River is needed to understand the current state of the Ems Estuary. The ecological state of the lower Ems River is not part of the current study.

The ERD model covers the Dollard and the Ems Estuary up-estuary of Eemshaven, whereas the ER model only covers the lower Ems River and the Emden navigation channel. The ERD model can, amongst others, be applied to model the effects of channel morphology and land reclamations in the lower Ems River, and investigate effects of changes in parts of the Ems Estuary (such as the Dollard) on the tidal dynamics.

The ER model only covers the lower Ems River and the Emden navigation channel, and is specifically set up to model the changes in tidal dynamics and sediment transport mechanisms that are caused by deepening of the Ems River. Section 2.3 explains that the sediment module of the WED model is executed in an off-line mode (without a dynamic feedback between hydrodynamics, sediment concentration, fluid density, and morphology). In the lower Ems River such a simplification is not valid, and therefore the hydrodynamics, morphology, and water density in the ER model are fully coupled.

3 Availability and interpretation of available data

3.1 Introduction

Field observation data is needed to (1) obtain insight in the relevant processes within a system, needed to setup numerical models, and (2) to calibrate the numerical models. Such observations include suspended sediment concentrations, morphological changes, grain size distribution patterns, and port siltation rates. This data is briefly analysed in Chapter 4, resulting in a conceptual model of the functioning of the Ems Estuary and lower Ems River which leads to a modelling approach described in the same chapter. The data is also used to calibrate the models (Chapters 5 and 6). A fairly large amount of data is available for the lower Ems River and the Ems Dollard estuary. However, there is also a large uncertainty associated with these observations, and some observations are conflicting. Therefore this chapter introduces and briefly analyses the available data in the lower Ems River (section 3.2) and the Ems Estuary (section 3.3).

3.2 The lower Ems River

The lower Ems River is characterized by the occurrence of thick layers with high sediment concentrations, extending from ~10 km from the mouth of the lower Ems River to the weir at Herbrum (Talke et al, 2009; see Figure 3.1). The sediment concentration in these layers are poorly known, but estimated to be several 10's to 100 g/l. Talke's measurements peak at values of 30 g/l (Figure 3.1), but continuous observations by NLWKN suggest maximum values exceeding 50 g/l (the maximum value registered by the instruments, see Figure 3.3). These layers are often referred to as fluid mud, but suspensions with sediment concentrations of 30 -50 g/l contain too much water, and are too dynamic, to be referred to as fluid mud. In fluid mud a measurable strength is build up, which is not yet the case at concentrations of 30 – 50 g/l. We therefore use the term HCBS (Highly Concentrated Benthic Suspensions). Measuring sediment concentrations at such high values is not straightforward: no instruments exist which can measure low sediment concentrations (< ~1 g/l) at high accuracy while at the same time measure high sediment concentrations. The sediment concentrations observed by NLWKN show a distinct concentration maximum at values of 20, 25, and 50 g/l (varying in time and per measurement station). This is probably caused by varying instrument settings: many turbidity sensors have an absolute maximum and a user-defined maximum sediment concentration.

This HCBS may migrate up- and downstream due to tidal currents (as observed by Talke et al., 2009) and possibly discharge. Talke presented the along-channel distributions of salt and sediment concentration during an ebb tide measured in August (Figure 3.1), during which NLWKN measurements of sediment concentration remain high deep into the estuary (see Figure 3.2 and Figure 3.3). However, there clearly is an inverse correlation between discharge and sediment concentration in the stations of Leerort and further up-estuary (Figure 3.3): with increasing discharge the sediment concentration decreases. At Knock and Pogum the opposite relation can be observed (although not as pronounced), with highest sediment concentration at large discharge (Figure 3.2). Apparently, during large discharge events sediment is pushed seaward from the area Leerort – Papenburg towards the area Pogum – Knock.

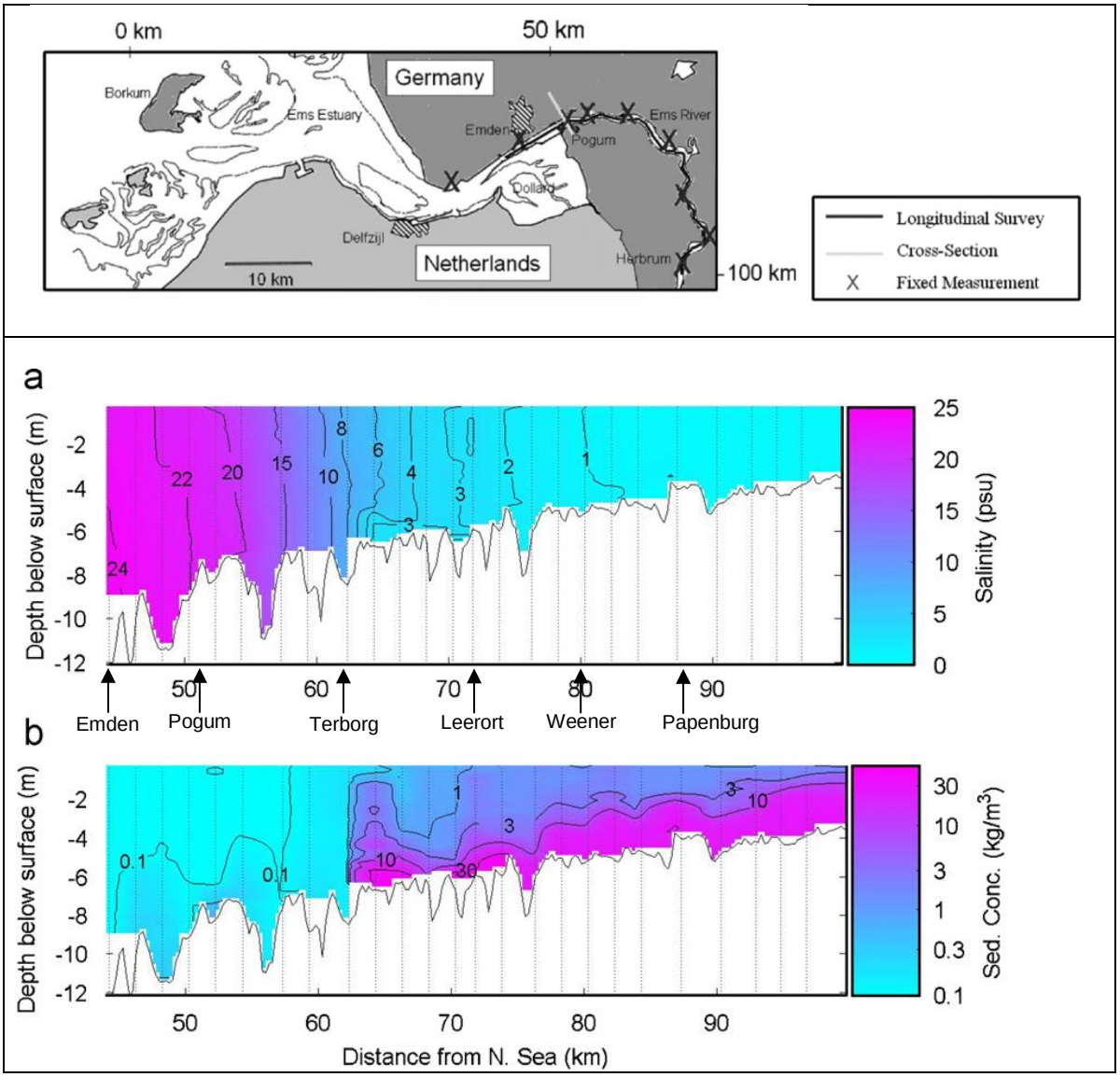

Figure 3.1 Longitudinal distribution of salinity (middle panel) and sediment concentration (lower panel) along the Lower Ems measured during ebb tide on August 2, 2006. The cruise began just downstream of Emden (km 45) app. 4h before LWS and ended in Herbrum (km 100) at LWS; see top panel for location. From Talke et al. (2009).

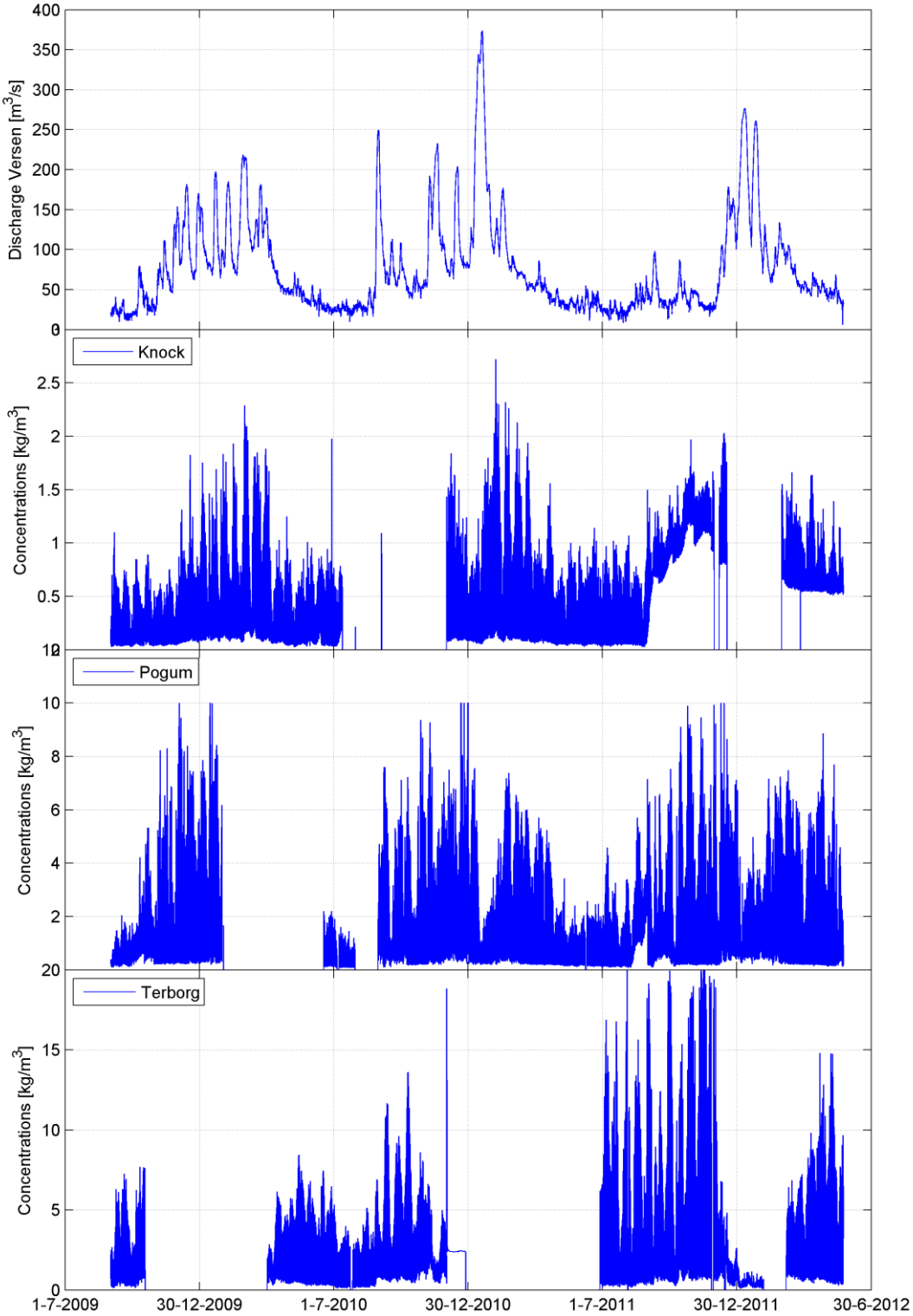

Figure 3.2 Discharge at Versen versus concentrations at Knock, Pogum and Terborg. See Figure 3.5 for the vertical position of the instruments. Blank sections are probably the result of instrument malfunctioning.

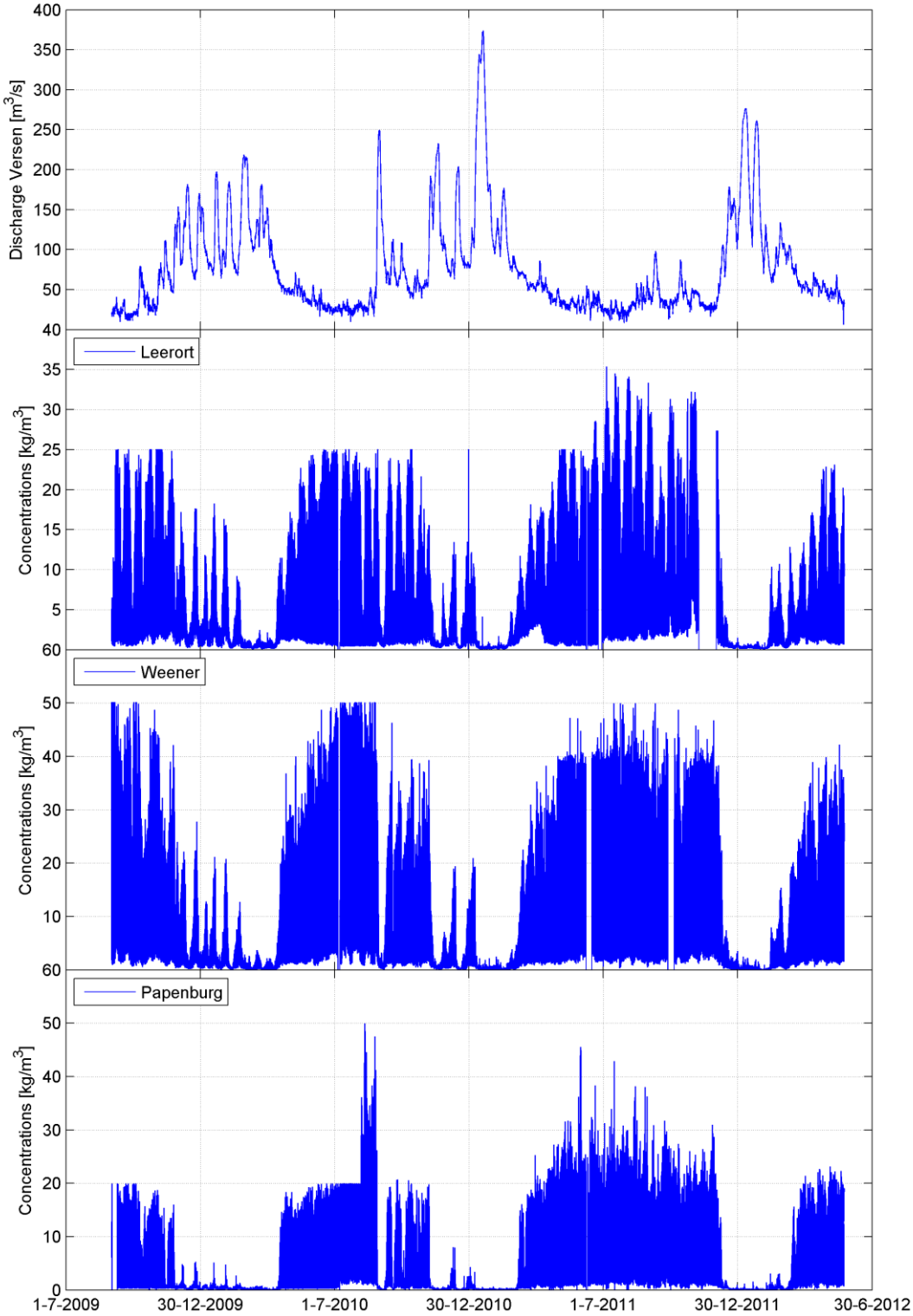

Figure 3.3 Discharge at Versen versus concentrations at Leerort, Weener and Papenburg. See Figure 3.5 for the vertical position of the instruments.

An important question for the turbidity in the Ems estuary is then how much of this sediment enters the estuary, and how much remains in the Emden fairway. The Emden fairway may be an effective sediment trap for sediments flowing out of the lower Ems River, because it is several meters deeper and likely trapping sediment because of estuarine circulation (a residual circulation pattern with up-estuary near-bed flows and down-estuary surface flows, generated by density differences resulting from freshwater sources). This will be examined in the analysis report (report 7). Larger trapping rates during high discharges are in line with the observation that more dredging is required. The peaks in the Emden fairway occur indeed during high discharge conditions (pers. Comm. Dr Weilbeer, BAW). Still some sediment should be discharged into the Ems estuary as well – to what degree this will dispersed throughout the estuary will also be evaluated in the analysis report (report 7). An important observation (Figure 3.2 and Figure 3.3) is that the high sediment concentrations rapidly return after high discharge events.

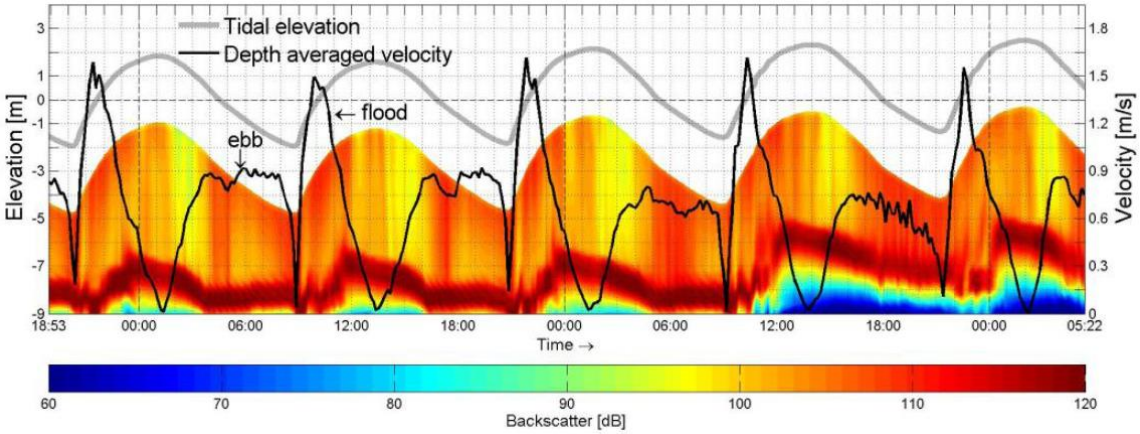

Figure 3.4 Flow velocity, water level and echo intensity observed between Terborg and Leerort in February 2009, between Terborg and Leerort (Wang, 2010). The HCBS can be approximated by an echo intensity < 90 (blue / green), in which simultaneous OBS measurements recorded concentrations of ~ 40 g/l (Wang, 2010).

This rapid return of high sediment concentrations was observed in more detail by Wang (2010), who measured rapid up-estuary propagation of fluid mud layers after a flushing event (Figure 3.4, measured shortly after a flushing event). The rapid return of sediment suggest that a substantial amount of the sediment that is flushed seaward during high discharges is not dispersed within the Ems estuary (down-estuary of Knock), but remains in the Emden fairway (from which it can rapidly be transported back into the lower Ems River). An alternative explanation is that during some periods all locally available mud is below the sensor location (see Figure 3.5). This can be the result of (1) a lower availability of mud, resulting in thinner fluid mud deposits (i.e. some sediment is flushed seaward), but also of (2) less vertical mixing, resulting in more consolidated (and therefore thinner) fluid mud deposits.

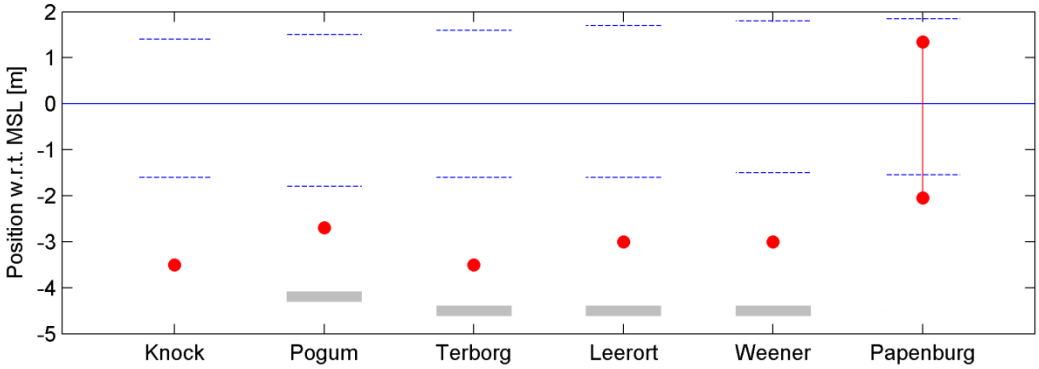

Figure 3.5 Position of the instruments (red dots) relative to MHW (dashed line), MSL (solid line), MLW (dashed line) and the bed (thick grey line).

3.3 The Ems Estuary

Sediment concentration measurements are used to calibrate the sediment transport model. Three main sources of data are used: the MWTL measurements, Imares measurements, and GSP measurements. However, as will be shown later in this section, some inconsistencies exist within and between the different datasets. This limits their applicability for model calibration. Therefore in this section the available data is introduced and analysed briefly for consistency.

3.3.1 Data sources

Since the 1970's suspended sediment concentration measurements are carried out by Rijkswaterstaat at regular time intervals at a number of fixed locations as part of the MWTL monitoring. The number of locations is gradually decreasing in time, and only three stations have remained operational by 2012 (Figure 3.6). Water samples are collected 1.5 m below the water surface at fixed locations within the tide every 2 weeks, and analysed in the laboratory for suspended sediment concentration. The three stations are sampled during measurement cruises that start 5 hours before LW at Huibertat, and finish around LW at station Groote Gat. Since the suspended sediment concentration varies throughout the tidal cycle, the observations do not need to be representative for tidally averaged conditions. However, since they are consistently sampled on the same phase of the tidal cycle, they do allow analysis of long-term trends (as in report 3) and assessment of the representativeness of the 2012 observations.

Imares carried out measurements following the same sampling methodology and analysis methods as the MWTL measurements (report 9), i.e. no measurements during storms. The cruises start at Imares station 1, which is the same location as Huibertgat, at the same phase of the tidal cycle as the MWTL measurements (5 hours before LW). The cruises are faster than the MWTL cruises, and therefore the station Imares 6 (same location as Groote Gat) is reached before LW.

Groningen Seaports and Rijkswaterstaat jointly carried out continuous measurements in the first 6 months of 2012 at locations GSP2 and GSP5, at two positions in the vertical (4 metres below the water surface (instrument attached to chain) and several metres above the bed (attached to tripod)).

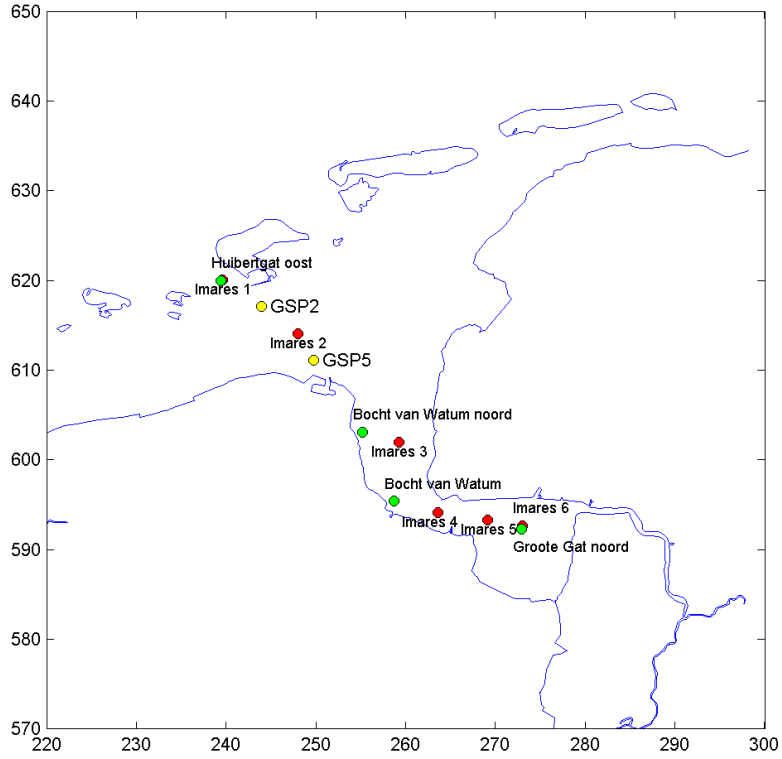

Figure 3.6 Location of suspended sediment observation points in the Ems Estuary: MWTL stations (green), Imares stations (red), and Groningen Seaports moorings (yellow). The MWTL station Bocht van Watum Noord was abandoned in 2010.

3.3.2 Data analysis

The MWTL observations at Groote Gat (Figure 3.7) show a fairly constant sediment concentration throughout the year in both 2012 and 2013, hovering around 100 mg/l. The Imares measurements from the second half of the year (both 2012 and 2013) show usually a similar pattern, but half of the measurements taken in January-June strongly differ from the MWTL measurements, with concentrations of several 100 mg/l. This is more pronounced in 2012 than in 2013. An important difference between the MWTL observations and the Imares observations is that the MWTL samples were always taken at local low water, when typically the near-surface suspended sediment concentrations are low. The sampling period of Imares measurements is slightly more variable within the tidal cycle.

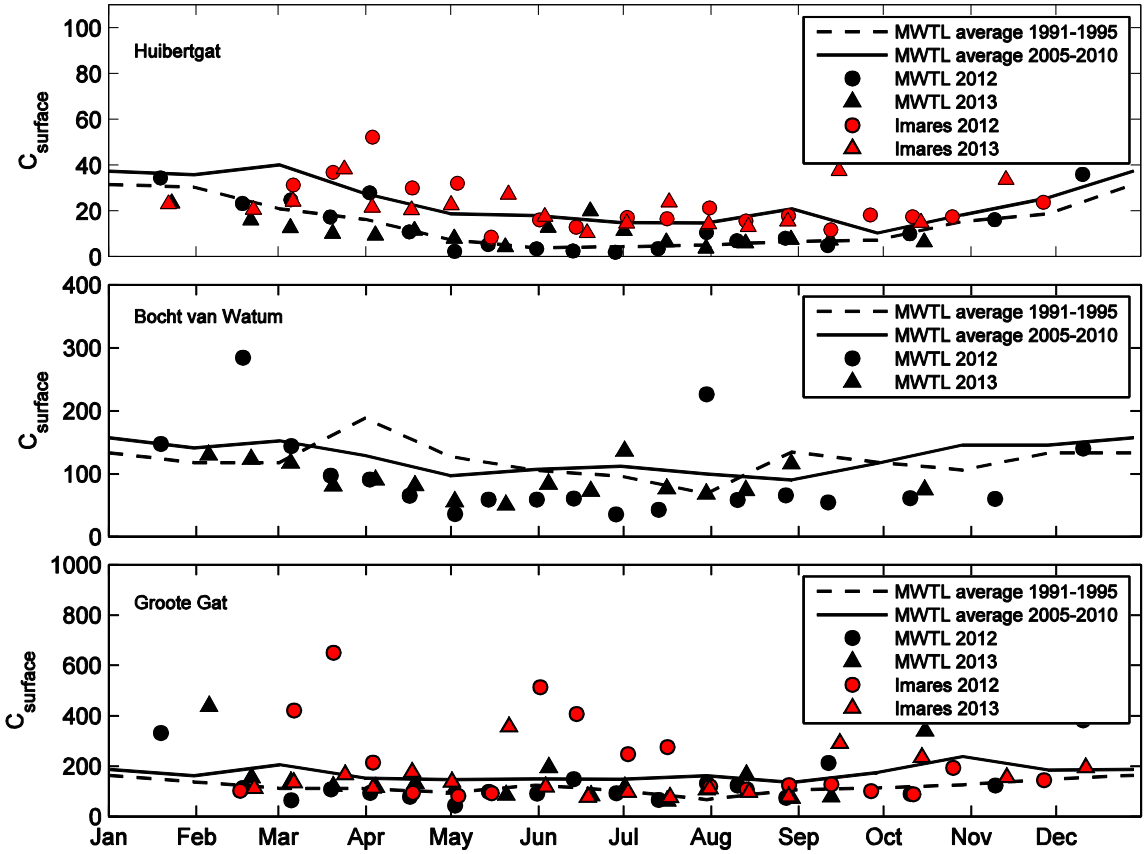

Figure 3.7 Sediment concentration measured by Imares (red) at station Imares 1 (top panel) and Imares 6 (lower panel), and MWTL observations (black) at Huibertgat (top panel), Bocht van Watum (middle panel) and Groote Gat (lower panel), for 2012 (circles) and 2013 (triangles). The dashed line is the average concentration of MWTL observations over the period 1991-1995, the solid line is the average concentration over the period 2005-2010.

The difference between the Imares and MWTL measurements can therefore be explained by the intratidal variability in suspended sediment concentration. Some of the sediment carried in suspension as large flocs has a fairly large settling velocity (1 to several mm/s), while some sediment has a much lower settling velocity. Sediment with a large settling velocity shows a pronounced intra-tidal variation as a result of erosion and deposition processes, whereas the finer fraction remains suspended, resulting in a sediment concentration more constant in time. Around slack time, the larger particles have probably settled on the bed and only the fines remain suspended. During other phases of the tide, the suspended sediment concentration may be much larger. This is supported by long-term observations in 1997 presented by Ridderinkhof et al. (2000): there is a pronounced spring-neap and intratidal variation, and the level of maximal concentrations is 1-2 g/l (Figure 3.8). It seems likely that the Imares measurements are occasionally not done during slack tide conditions (as the MWTL measurements), during which the suspended sediment concentrations are (much) larger (several 100 mg/l).

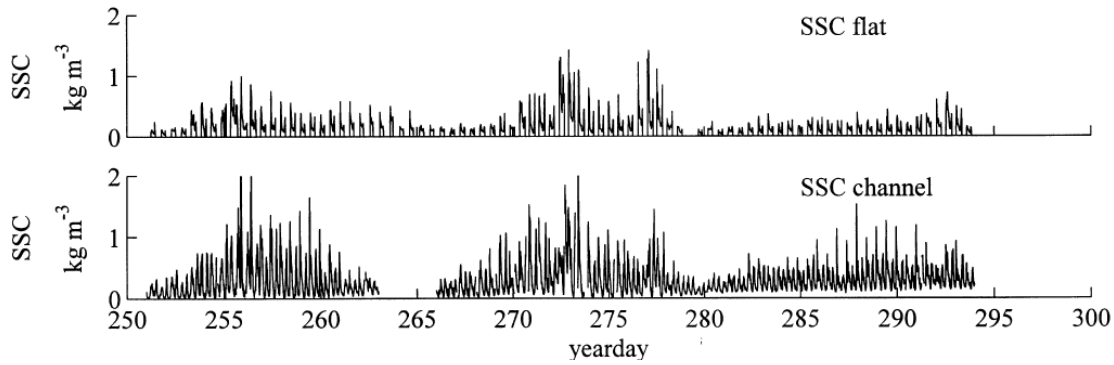

Figure 3.8 Observed near-bed sediment concentration on a tidal flat in the Dollard (top) and in a tidal channel (bottom). From Ridderinkhof et al., 2000

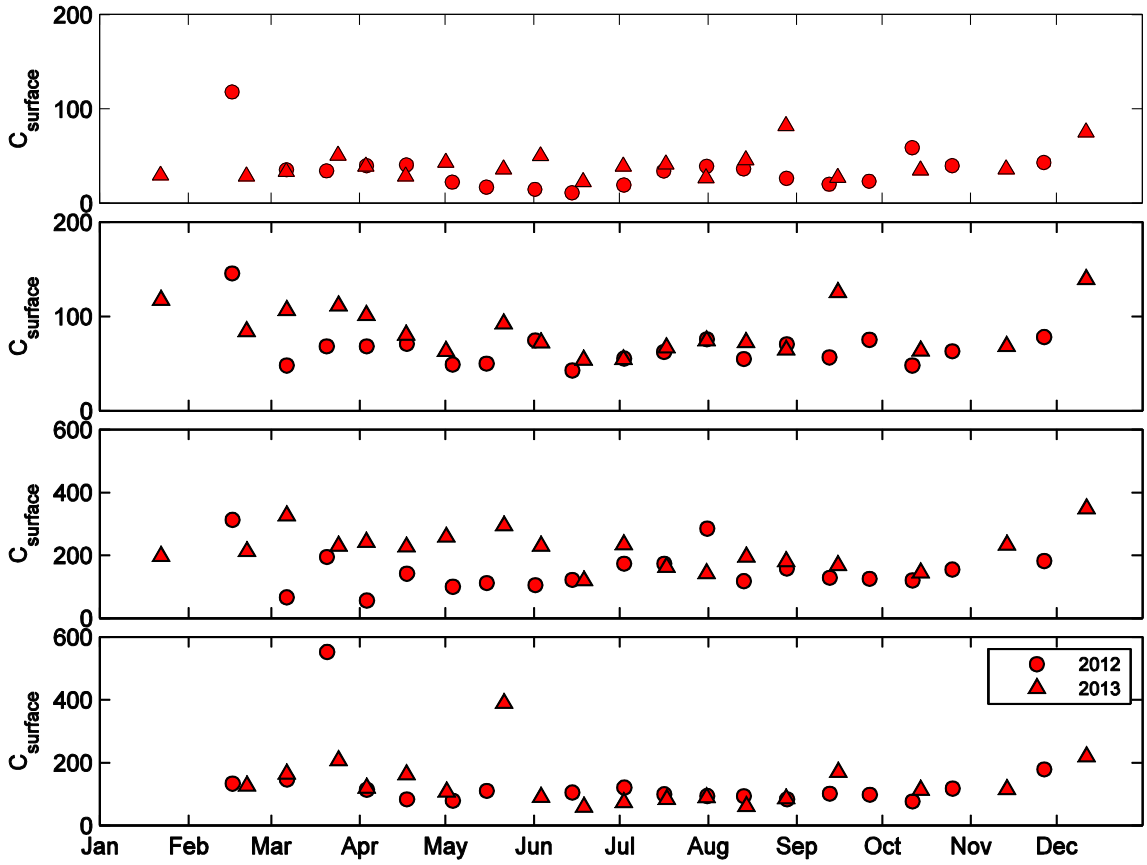

Figure 3.9 Sediment concentration measured at location Imares 2 (top panel), Imares 3 (second panel), Imares 4 (third panel), and Imares 5 (fourth panel), for 2012 (circles) and 2013 (triangles)

At Huibertgat (Figure 3.7), there is a pronounced difference between Imares data and MWTL data. The MWTL sediment concentration levels are low, less than 10 mg/l in summer (in both 2012 and 2013). In both years, the suspended sediment concentration measured by Imares is two times larger, with typical values of 20 mg/l. This difference is surprising, since these stations are at the same location, sampled at the same tidal phase, and processed following the same methodology. At present, we cannot explain this difference, although the persistent difference suggests a methodological origin. Comparing the 2012-2013 MWTL measurements with the average of 2005-2010, the 2012 sediment concentrations are

typically 10-20 mg/l lower in 2012 and 2013 (similar to the average measured from 1991 to 1995). Also this cannot be explained. It is remarkable, however, that the Imares measurements at Huibertgat (in 2012 and 2013) are comparable to the MWTL average of 2005-2010. This inconsistency leads to uncertainty in the sediment concentration at Huibertgat, and therefore also to an uncertainty in the transport model (using this data for calibration purposes); see also section 3.5.

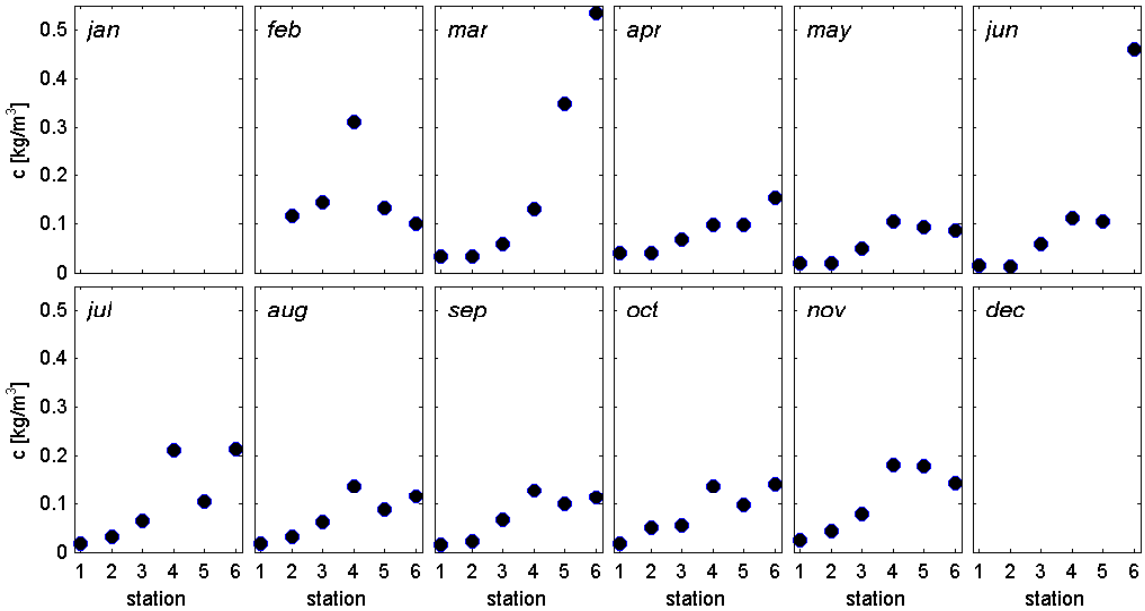

Figure 3.10 Sediment concentration per month as a function of Imares station number, measurements 2012-2013.

The Imares measurements reveal that the sediment concentration is gradually increasing landward (Figure 3.9, but especially Figure 3.10). At Imares station 2 the sediment concentration is typically several 10's to 50 mg/l. The GSP 2 station located in-between Imares 1 (Huibertgat) and Imares 2 frequently observed concentrations of several 100 mg/l (Figure 3.11). However, the MWTL and Imares measurements are typically conducted ~4 hours before LW, during which the sediment concentration at GSP2 and GSP5 are at their lowest. This suggests that the MWTL measurements at Huibertgat and Imares station 1 and 2 provide a lower bound of sediment concentrations.

The differences between the different datasets can be summarised as follows:

- The sediment concentrations measured as part of MWTL in 2012 are lower than the Imares observations.
- At Huibertgat, the MWTL and Imares measurements should be equal, and why they differ by almost a factor two is not understood.
- The nearby GSP continuous observations show much larger concentrations then both MWTL and Imares, but this may be explained by the tidal phase of MWTL / Imares measurements and the vertical position (MWTL measures 1.5 meter below the water surface, GSP 4 meter). As a result, the GSP sensors probably measure a considerable sand fraction as well.
- Differences between MWTL and Imares measurements at Groote Gat can probably be attributed to intra-tidal variations.

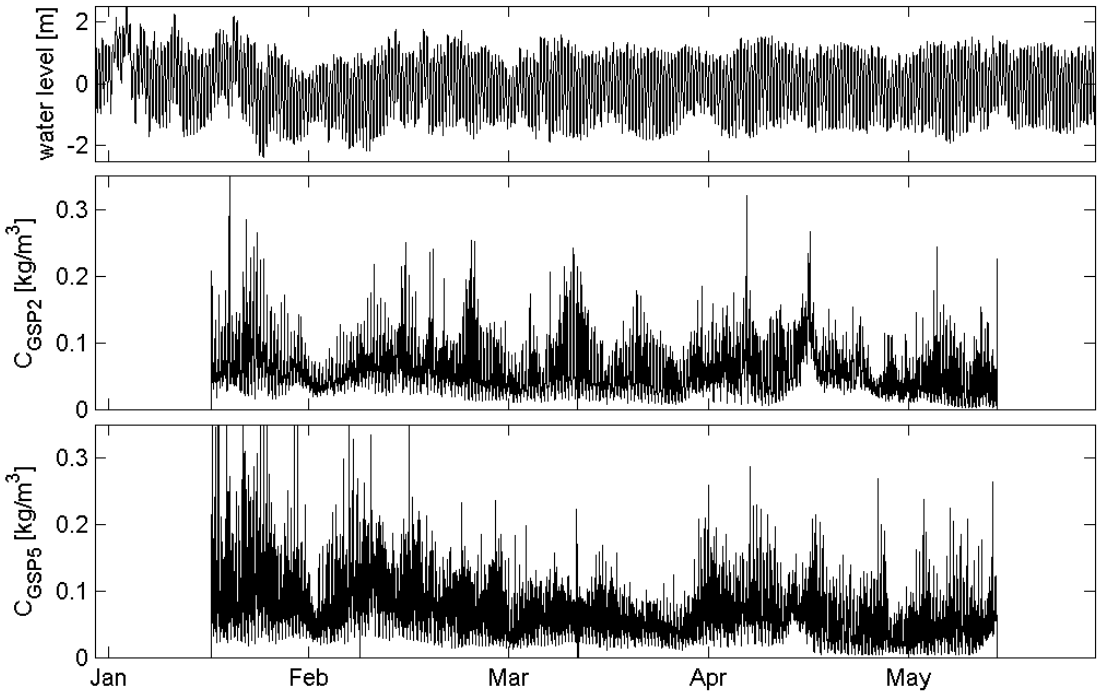

Figure 3.11 Water level near the GSP stations (top panel), and surface sediment concentration measured at GSP 2 (middle panel) and GSP 5 (lower panel).

3.4 Dredging, bathymetric changes and mud distribution

An approximation of sediment fluxes into the ports can be obtained from dredging volumes (Figure 3.12, see report 3 for more details), assuming that over longer timescales the sediment concentration (and fluid mud mass) remains constant. Dredging from (and therefore fluxes into) the Eemshaven and port of Delfzijl are 1.1 and 1.6 million m^3 between 2006 and 2010 (Mulder, 2013). The density of the dredged material from the Emden fairway is 500 kg/m^3 (Mulder, 2013). Assuming this density represents sediment in the ports of Eemshaven and Delfzijl as well, these volumes are equivalent to 0.5 and 0.8 ton/year. The net long-term sediment flux into the Ems River can be estimated with net extraction rates, presently averaging 1.5 million m^3/year (see Figure 3.12). Dredging from the Emden fairway was 3 million m^3/year from 2006 to 2010, approximately 1.5 million ton/year.

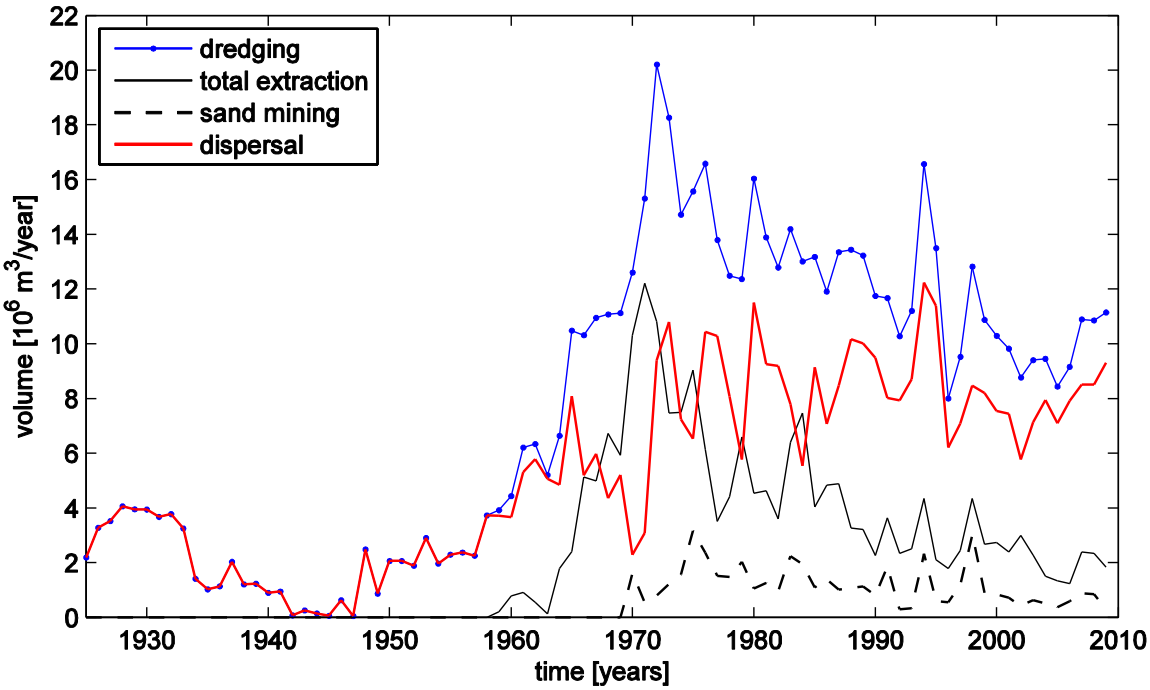

Figure 3.12 Dredging volumes since 1925. Dredging volumes before 1960 is from de Jonge (1983) and is excluding sand mining. Dredging volumes after 1960 as from Mulder (2013) for the Ems-Dollard estuary (including sand mining) and from Krebs (2006) in the lower Ems River (until 2006; after 2006 a constant value of 1.5 million m^3 is used). Total extraction includes sand mining and dredge spill. Before 1994, this sediment was mainly from the port of Emden and approach channel (Mulder, 2013), averaging 5 million m^3/year. After 1994, mostly sediment dredged in the lower Ems River is brought on land (~1.5 million m^3; Weilbeer and Uliczka, 2012). Sediment dispersal is the difference between dredging and total extraction.

A second sediment sink (in addition to sediment extraction described above) is sediment accumulation in low-energy environments. From 1985 to 2005, 20.4 million m^3 of sediment accumulated in the Bocht van Watum, a degenerated tidal channel west of Hond-Paap island (based on the bedlevel changes from 1985 to 2005 in Figure 3.13). These deposits are predominantly muddy (Figure 3.14), with a typical dry density of 600 - 1000 kg/m^3. From 1985 to 2005, 0.6 - 1 million tons of fine sediment annually accumulated here. Net bed level changes in the Dollard area are much smaller (Figure 3.13) but since the areal extent is much larger than the Bocht van Watum, small differences in bed level may also lead to large deposition volumes of fine sediment. However, such small differences also become very inaccurate due to measurement errors, and therefore no accurate sediment budget can be computed for the Dollard area. In deeper (sandy) parts of the estuary bed level changes are mainly caused by migrating channels (resulting in alternating patterns of erosion and deposition), with minor net accumulation or erosion of fine sediments.

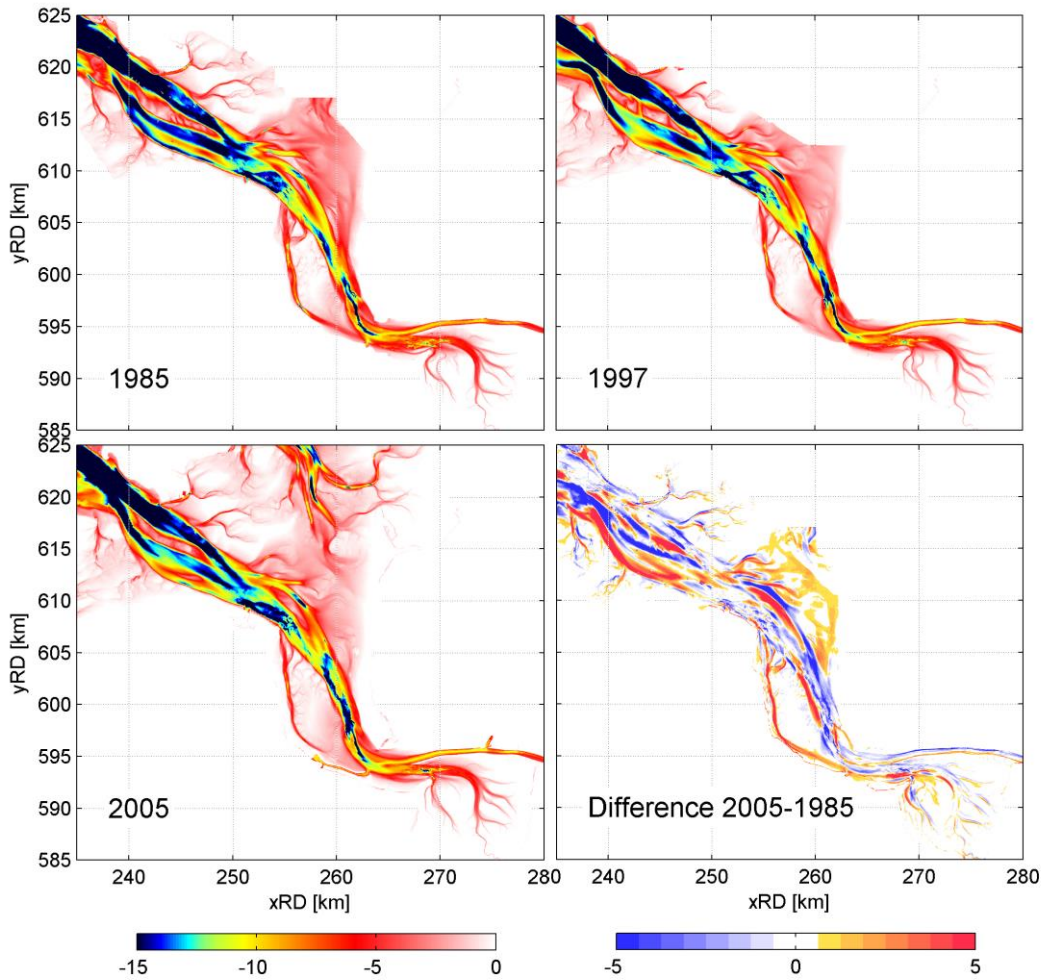

Figure 3.13 Bathymetry in 1985, 1997, 2005 (depth relative to NAP, in meters), and the difference between 2005 and 1985 (in meters, red: accumulation, blue: erosion)

Comparison of the mud content (The fraction of sediment with a diameter *d*<63 µm) in 1991 (Figure 3.14) with 2013 (Figure 3.15), reveals that the the tidal channels (especially the Groote Gat – see Figure 1.1 for location) have probably become more fine-grained, whereas the tidal flats have apparently become less fine-grained since 1991. Also the mud content in the Ems River has increased (Figure 3.15, see also Krebs and Weilbeer, 2008).

The main tidal channel in the Dollard (the Groote Gat) is generally very fine-grained, even more than the surrounding tidal flats. The tidal flats show a seasonal variation in mud content, and are typically more fine-grained during tide-dominated summer conditions compared to wave-dominated winter conditions. Still, the large mud content in the main tidal channel in the Dollard is in contrast with tidal flat-channel systems in the Wadden Sea and Scheldt, where the flats are more fine-grained compared to the channels. Probably, accumulation on the tidal flats of the Dollard is limited because of remobilization by waves. Over longer timescales (suggested by the small bathymetric changes in Figure 3.13), sediment that is transported towards the Dollard can, apparently, not accumulate on the flats, but remains suspended in the tidal channels or on the bed of the tidal channels.

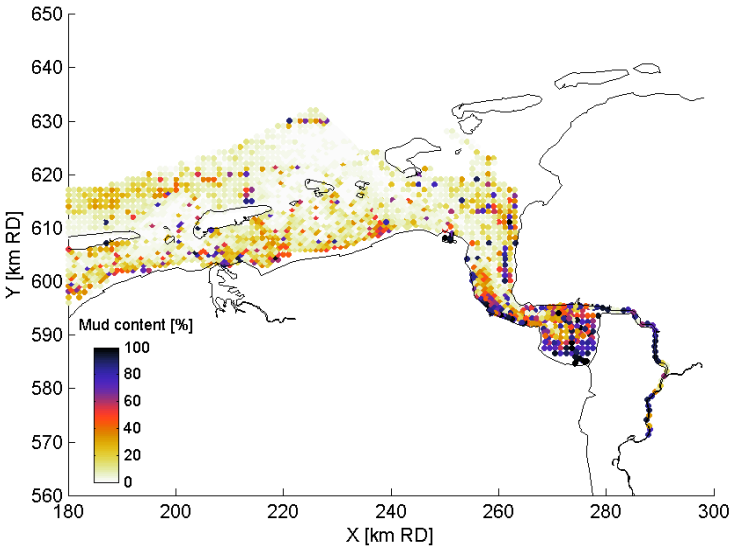

Figure 3.14 Observed mud content (fraction < 63 µm) in the Ems Estuary. Data from the Sedimentatlas, based on samples collected in 1989 and 1991.

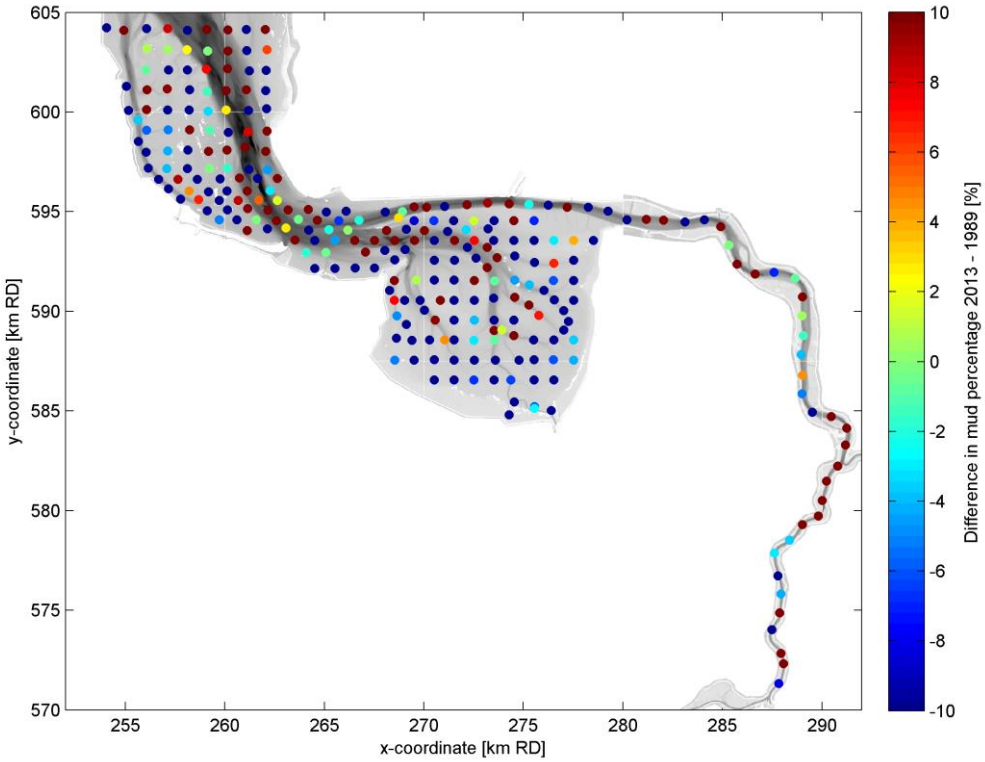

Figure 3.15 Increase in mud content (fraction < 63 µm) in the Ems Estuary using data from Sedimentatlas (1991) and the mud sampling programme (2013).

3.5 Synthesis

Measurements of suspended sediment concentration collected at various stations in the lower Ems River are continuous. Their absolute value should be interpreted with care since the high concentration levels typical for this part of the system are difficult to measure and are partly influenced by user-defined settings of the instruments.

In the Ems Estuary, most sediment concentration observations are composed of near-surface snapshot measurements collected during MWTL and Imares measurements. When the snapshot measurements are compared (Figure 3.7, Figure 3.9) with nearby continuous observations (Figure 3.11) it is shown that the snapshot measurements:

(1) introduce themselves a substantial uncertainty. Such uncertainty in the quality of the calibration data introduces an uncertainty in the model (in addition to any uncertainty arising from the difference between model results and data).

(2) represent the lower bound of the sediment concentration levels (the continuously measured sediment concentration at the GSP stations ranges from 30 to 300 mg/l, whereas the sediment concentration measured at nearby Imares stations 1, 2, and Huibertgat is typically below 30 mg/l). During the calibration, the modelled suspended sediment concentration is therefore allowed to exceed the sediment concentration observed at Huibertgat.

(3) cover only a limited part of the tidal cycle, whereas the intra-tidal variation is large, as demonstrated by the GSP measurements (Figure 3.11). This introduces a systematic deviation of snapshot measurements compared to average sediment concentrations. Furthermore, the tidal phase of the observations varies spatially (ranging from high water at the seaward end of the estuary to low water in the Dollard). Therefore this systematic deviation varies spatially.

4 Physical processes in the Ems Estuary and lower Ems River

4.1 Introduction

Sediment transport in the Ems Estuary and in the lower Ems River is determined by a range of processes, which operate on various time and spatial scales. Setting up the sediment transport model therefore requires understanding of the relevancy of processes on each timescale. There is a fundamental difference in transport processes within the Ems Estuary (and the exchange between the Ems River and the Ems Estuary), and the transport processes within the Ems River. Therefore separate models are set up for both these domains (the ER model for the lower Ems River, and the WED model for the Ems Estuary). The sediment transport processes in the lower Ems River and the Ems Estuary are discussed in section 4.2 and 4.3 (respectively), resulting in a modelling approach explained in section 4.4.

4.2 The lower Ems River

The lower Ems River is presently characterised by thick HCBS layers (e.g. Talke *et al*., 2009) which are transported and re-distributed by a combination of tidal asymmetry, internal asymmetry, flocculation asymmetry (Winterwerp, 2011), sediment-induced density-driven flows (Talke *et al*., 2009) and settling lag effects (Chernetsky *et al.,* 2009). These processes (described hereafter) can be represented by numerical models with a variable degree of accuracy. This up-estuary directed transport is balanced by tide-induced mixing of the longitudinal concentration gradient (generating transport from high to low sediment concentration), and flushing during large discharge events. The sediment transport processes relevant for the exchange between the Ems River and the Ems Estuary will be discussed qualitatively below. Note that these processes are highly complex and are still poorly understood, and that such a combination of processes cannot be simulated by existing models yet.

Up-estuary of Pogum, the tide becomes progressively more asymmetric with larger maximum flood flow velocities than and ebb flow velocities. The duration of flood is shorter than the duration of ebb. When sufficient sediment is available, sediment transport rates are proportional to the cubed flow velocity. The amount of sediment in the lower Ems River is abundant, and therefore more sediment is transported up-estuary during the flood than can be transported seaward during the following ebb (despite a longer duration). The net up-estuary transport by tidal asymmetry depends on the degree of tidal asymmetry and amount of available sediment, but also on the sediment properties (see van Maren and Winterwerp, 2013). In order to model this residual transport, the hydrodynamic asymmetries need to be resolved by the model, and modelled sediment properties need to be realistic.

Net transport by internal asymmetry results from intratidal asymmetries in vertical mixing of sediment. When sediment is vertically mixed, relatively more sediment is transported by the near-surface flows, where the flow velocity is larger. When sediment is not vertically mixed, most sediment is confined near the bed, where the flow velocity is smaller. Therefore the net depth-integrated transport rate of vertically mixed sediment is larger. Such an asymmetry may arise from flow velocity asymmetry, strengthening net transport by tidal asymmetry, especially due to the feedback mechanism between hydrodynamics and sediment concentration (the density coupling). These processes are included in the Delft3D sediment-online software, in which the settling and vertical mixing of sediment is accurately reproduced through the

interaction between turbulence and sediment-affected density within the *k*-ε turbulence model.

Flocculation of sediment is the aggregation of smaller particles into a larger floc with a larger settling velocity than the individual particles. Flocculation rates depend on the hydrodynamics (shear rate), and increases with the sediment concentration. Typically, there is a shear rate at which flocculation is maximal: at lower shear rates flocculation rates become too low compared to the residence time in the water column, and at larger shear rates the flocs are destroyed. Therefore an intra-tidal variation in flow velocity leads to an intra-tidal variation in settling velocity and thereby vertical concentration gradient. This, in turn, gives rise to net transport by mixing asymmetry (as described above).

Density-driven flows may be generated by horizontal gradients in salinity or sediment (temperature-induced flows are not considered important in the Ems River). Horizontal salinity gradients generate a near-bed flow in the direction of the freshwater source (compensated by surface flow in the opposite direction), and with a non-uniform sediment distribution this generates a landward sediment flux.

Of specific importance for modelling the lower Ems River are the HCBS layers. HCBS forms when the rate of sediment settling from suspension exceeds the rate at which the deposit can form a rigid bed or fluid mud. This transition is dominated by hindered settling and consolidation processes. The consolidation rate is determined by properties of the sediment, and scales with the square of the thickness of the deposit. In the Ems River, the HCBS layer seems to be resuspended (or entrained) every tidal cycle (especially during the flood), preventing the formation of a rigid bed (Li Wang, 2010). The concentration of the HCBS typically is several 10's of g/l (Talke *et al.,* 2009; report 3).

The processes described above transport sediment up-estuary. This landward transport is balanced by seaward transport resulting from tide-induced horizontal mixing of an up-estuary increasing sediment concentration gradient, and by river discharge (flushing). The sediment concentration in the Estuarine Turbidity Maximum (ETM) is up to several 10's of g/l, generating pronounced horizontal concentration gradients. Since tide-induced mixing transports sediments from high to low sediment concentration, tidal mixing leads to down-estuary sediment transport. Based on sediment extraction rates from the lower Ems River, the net transport into the Ems Estuary is around 0.75 million ton/year (section 3.4). Probably the sediment concentration in the lower Ems River is still gradually increasing (in response to historic deepening), introducing an additional (but unknown) net import term, but compared to dredging amounts this amount is low. Through-tide measurements during low-discharge conditions by Weilbeer and Uliczka (2012) reveal sediment fluxes which, when extrapolated to annual fluxes, amount to upstream sediment transport of 5 million tons/year. The discrepancy between short-term observations and long-term sediment accumulation rates suggest that the sediment in the Ems Estuary is occasionally flushed seaward during high-discharge events. It is during these conditions that the Ems Estuary is strongly influenced by the Ems River.

4.3 The Ems Estuary

The most important processes determining sediment transport in most estuaries are landward transport by tides and estuarine circulation (driven by salinity gradients), balanced by seaward transport resulting from wave-induced resuspension and by residual flow. In the Ems estuary, these dynamics are further influenced by dredging and disposal.

Tidal currents generate transport through a number of processes, usually in the up-estuary direction. Residual sediment transport is generated by time-asymmetries and by horizontal asymmetries (gradients) in the tides. Time asymmetries range from a difference in the duration of high and low water (slack tide asymmetry) to the difference in maximum flood and ebb flow velocity (maximum flood velocity asymmetry). In case of slack tide high water (HW) asymmetry, the period with low flow velocities is much longer during HW than during LW. Particles can therefore settle at HW whereas they remain in suspension during LW, resulting in a landward transport of sediment. Maximum flow asymmetry is characterised by a short period of large flow velocities in one direction, followed by a longer period with lower flow velocities in opposite direction. Most common are estuaries with large flood flow velocities than ebb flow velocities. Sediment transport responds non-linearly to flow velocity (typically scaling with u^3), resulting in larger transports during the tidal phase with larger flow velocities. In addition to these time-asymmetries, horizontal gradient in tidal velocities generate residual sediment transport in combination with settling and or scour lags. The classic example is a particle moving landward from a high-energy-environment (where sediment is resuspended at the beginning of the flood) to a low-energy environment (where the same particle remains on the bed for a finite period of time, before travelling in the seaward direction). Therefore a landward decreasing flow velocity generates a landward residual transport component. The effectiveness of flow asymmetries on residual transport strongly depends on the sediment properties (see van Maren and Winterwerp, 2013). Tides transport sediment in the landward direction at the scale of the estuary, but also at a smaller scale, leading to net transport of fine sediment (mud) from the tidal channels to the flats.

A substantial amount of fresh water coming from the Ems River (and smaller tributaries) creates a horizontal salinity gradient and thereby estuarine circulation. Combined with a non-uniform sediment distribution, estuarine circulation drives an up-estuary directed net sediment transport.

In natural conditions, the main process balancing up-estuary transport by tides and salinity-induced density-driven flows is wind and wave-induced sediment resuspension. Waves and wind-driven currents stir up sediment from tidal flats, leading to a horizontal gradient in sediment concentrations. Tidal mixing of the concentration gradient then often leads to net down-estuary transport. In the past decades, sediment is dredged from the estuary and disposed further offshore, additionally resulting in a net down-estuary transport component.

Other relevant processes, even though considered to be of secondary importance, are

(i) Sediment-induced density effects are important for settling of sediment in the Ems River (Winterwerp, 2011), but probably not in the larger part of the Ems Estuary because here the concentrations are lower. They may influence sediment deposition on the flats of the Dollard (van der Ham and Winterwerp, 2001).

(ii) Sediment on the flats consolidates, leading to strengthening of the sediment (and therefore resistance to erosion) in time.

(iii) Seasonal variation in sediment properties due to temperature (viscosity of the water) and especially biologic effects. Sediment that accumulates on the flats is strongly influenced by biostabilisation (strengthening the deposits, especially algal mats) and bio-destabilisation (destruction of the algal mats by grazing; Staats (2001a, 2001b), Kornman and de Deckere (1998), and de Deckere *et al.* (2002)).

4.4 Modelling approach

Within the Delft3D modelling suite, 2 basic model types are available to simulate sediment transport: Delft3D sediment-online and Delft3D WAQ. The WED sediment transport model will be setup in WAQ, the ER sediment transport model in sediment-online. Both these models simulate transport resulting from tides, waves, and estuarine circulation. The reasons for setting up both model applications (WED and ER) in different model types will be explained in more detail below (see Table 4.1 for a summary).

Table 4.1 Model domain, type and summary of strengths

Model domain	Sediment model type	Strengths
ER	Delft3D sediment-online	- Sediment-induced density coupling - Dynamic morphological feedback (bed level changes)
WED	Delft3D WAQ	- Long timescales - Mud buffer model - Wave-induced resuspension

4.4.1 The WED model

For the outer estuary (for which the WED model was designed), long timescales are important (it takes multiple years to reach dynamic equilibrium of the suspended sediment transport in, for instance, the Dollard). The sediment transport model therefore needs to be computationally efficient. In Delft3D WAQ, the sediment transport is computed with existing output from a hydrodynamic model. Since the hydrodynamics do not need to be re-computed, the model is much faster, allowing simulation of multiple years and a relatively wide range of sediment transport model settings. The WAQ model does not achieve full morphological equilibrium, but a spatially varying equilibrium in suspended sediment mass in the water column, in the upper sediment layer and in a deeper sediment layer (see the next chapter for details).

Secondly, sediment exchange between the flats and the channels are important. To accurately model this exchange, the so-called buffer model was developed by van Kessel et al. (2011) and implemented in WAQ.

Thirdly, the sediment concentration and morphological changes in the majority of the Ems Estuary are probably sufficiently low to model the sediment dynamics without full coupling between hydrodynamics, sediment transport and morphologic changes. This may not be a valid assumption for sediment dynamics in the lower Ems River and the Emden navigation channel (because of the high sediment concentration and resulting sediment-induced density effects), as it does not include sediment-induced density effects. With the focus on the Ems Estuary, the computational efficiency and process formulations in WAQ are more important than this shortcoming.

4.4.2 The ER model

Because of the high sediment concentrations occurring in the lower Ems River, the ER model needs to account for the interactions between turbulence, sediment concentration, and flow. Both interactions are implemented in Delft3D sediment-online, and therefore the sediment transport module of the lower Ems River is set-up in Delft3D sediment-online. A disadvantage of this approach is that for each sediment transport simulation (needed for calibration, sensitivity analyses, or scenarios), the hydrodynamics have to be re-computed. Since simulation of the hydrodynamics is most time-consuming, sediment-online models are relatively slow. It should be realised that the sediment transport processes in the lower Ems River are very complex and not all processes are included in standard Delft3D sediment-online (such as flocculation and consolidation). This leads to some parameterizations which will be explained in more detail in Chapter 6.

4.5 Summary

Sediment transport in the lower Ems River and Ems Estuary is determined by three transport processes:

- Tide-induced residual (up-estuary) transport, which is determined by tidal asymmetries and sediment properties
- Residual (up-estuary) transport by estuarine circulation
- Down-estuary sediment transport by residual flow

A fourth mechanism, only relevant in the Ems Estuary, is down-estuary sediment transport resulting from wave-induced resuspension combined with tidal mixing. A fifth mechanism, mainly relevant In the Ems River, is the interaction of hydrodynamics, sediment transport, and bed level changes (sediment-induced density effects and rapid morphological changes).

The ER transport model will be setup using Delft3D sediment online because of the dynamic coupling between hydrodynamics, sediment concentration and morphology. The WED model will be setup using Delft3D WAQ because of available process formulations (allowing an accurate description of exchange between tidal flats and channels) and because WAQ is faster.

5 Calibration of the WED model

5.1 Introduction

The WED sediment transport model is setup to (1) relate changes in the estuary (channel deepening, dredging strategies) to the suspended sediment dynamics in the Ems estuary , and (2) to provide turbidity fields for the water quality modelling (report 6). This chapter describes the set up (section 5.2), calibration (section 5.3), sensitivity (section 5.4) and validation (section 5.5) of the sediment transport module of the WED model. Based on the calibration, sensitivity, and validation, a semi-quantitative assessment of model accuracy is made in section 5.6, followed by recommendations (section 5.7) and a synthesis (section 5.8).

The TO-KPP sediment transport model of the Ems estuary (van Kessel *et al*, 2013) reasonably reproduces the sediment concentrations (as observed at the MWTL stations) and spatial distribution of mud on the bed. This model is improved in the following aspects:

- The model is run for the year 2012 (for recalibration) and 2013 (for validation); see report 4 for the hydrodynamic model set-up.
- Waves are more realistically modelled (see also report 4)
- Dredging and disposal is an integral part of model recalibration (section 5.2.4)
- More concentration observation stations are used in the recalibration (section 5.3)
- Sedimentation in the ports is included (section 5.3.4)

It is difficult to evaluate the improvement of the model after changing a single process or parameter, because these are all mutually related. Changing the wave climate, for instance, requires an adaptation of sediment parameter settings to achieve equally good model performance. Similarly, increasing the settling velocity (thereby changing model behaviour) requires an increase in the erosion parameter to maintain the same sediment concentration levels. Due to this complexity the following recalibration procedure was followed.

The parameter settings were varied within a large amount of model runs, within realistic limits. The results were compared with available data. The model set-up was obtained with the combination of parameters that best reproduced the available data. This model run will hereafter be referred to as the *reference run* and is presented in section 5.3. We refrain from presenting the results of all runs with variable parameter settings. Insight in the sensitivity of the model is given by the results of variation of a number of key variables related to settling, deposition, and buffering of sediments (section 5.4). Some aspects which influence the model calibration are also part of the historic analysis (such as changes in dredging and disposal, bathymetry, effect of the Wadden Sea and North Sea). These effects will be evaluated in the analysis study (report 7), and not in this section.

5.2 Model set up

5.2.1 Model domain

The domain of the WED model extends (see report 4) from Herbrum to the ~30 km seaward of the Wadden Sea islands (Figure 5.1). The offshore boundary conditions are nested in a large-scale tidal and wind-driven hydrodynamic model. The river inflow (Ems, Leda, Nieuw Statenzijl, Delfzijl, Knock) is prescribed as density-varying point discharges. Wind-driven

currents are computed with a uniform but time-varying wind field, whereas waves are computed with SWAN (see the hydrodynamic model set up in report 4).

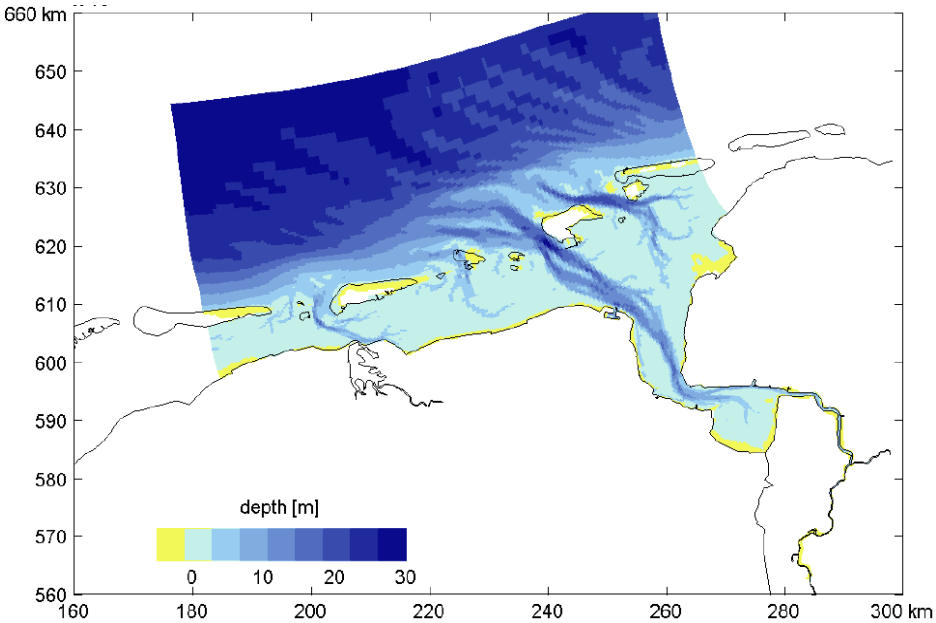

Figure 5.1 Initial bed level of the model, based on 2005 soundings.

5.2.2 Model formulations and settings

Sediment transport in the WED model is simulated with the mud buffer model (van Kessel et al., 2011, implemented in Delft3D-Delwaq), in which fine sediment is stored in a sandy matrix within the seabed. This model was also used in the KPP Eems-Dollard model (van Kessel et al., 2013).

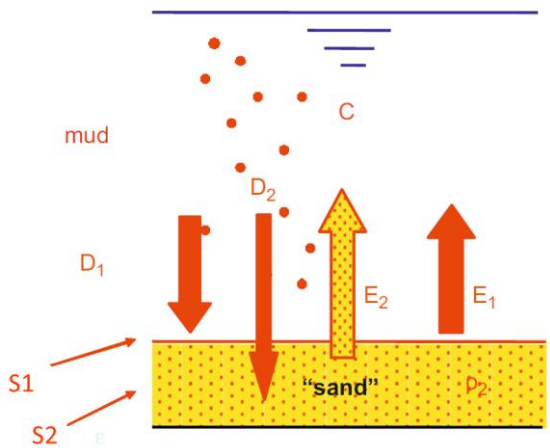

Figure 5.2 Schematic representation of the buffer model. Layer 1 (S1) is the thin fluff layer overlying layer 2 (S2), with default erosion and deposition fluxes: sediment settles from suspension directly to S1 and S2 (with the relative deposition flux determined by the factor α (see text).

This model distinguishes two bed layers: an upper layer (S_1) which rapidly accumulates and erodes, and a deeper layer (S_2) in which only gradually sediment accumulates but which is only eroded during energetic conditions. Most fine sediment is stored (buffered) in the pores

of the sand in S_2, S_1 represent the typically thin fluff layer on top of the solid bed. The amount of fine sediment that can be stored in S_2 depends on the density ρ_s, porosity n, and thickness of the S_2 layer Z_{s2} and is given by $\rho_s(1-n)/Z_{S2}$. With n = 0.4 (typical values for sand beds), ρ_s = 2650 kg/m^3, and Z_{s2} = 10 cm, the maximum mud content in S_2 is 156 kg/m^2. The erosion rate of S_1 depends linearly on the amount of available sediment below a user-defined threshold M_0/ M_1:

$$E_1 = mM_1\left(\frac{\tau}{\tau_{cr,1}} - 1\right) \qquad m < \frac{M_0}{M_1}$$

$$E_1 = M_0\left(\frac{\tau}{\tau_{cr,1}} - 1\right) \qquad m > \frac{M_0}{M_1}$$

Here m is the mass of sediment in layer 1 (in kg/m^2). This has the important consequence that also in dynamic environments the equilibrium sediment mass on the bed is non-zero, contrary to standard Krone-Partheniades (KP) models. Typically, this results in smoother and more realistic model behaviour in mixed sand-mud environments ($m < M_0/M_1$). For completely muddy areas ($m > M_0/M_1$), the buffer model switches to standard KP formulations for erosion of bed layer S1. Hence, M_0 is the standard zero-order erosion parameter (kg/m^2/s) whereas M_1 (1/s) is the erosion parameter for limited sediment availability.

The erosion E_2 of S_2 scales with the excess shear stress to the power 1.5, in line with empirical sand transport pick-up functions:

$$E_2 = p_2 M_2\left(\frac{\tau}{\tau_{cr,2}} - 1\right)^{1.5}$$

Here, p_2 is the fines fraction in S_2 (computed by the model) and M_2 is the resuspension parameter for S_2 (kg/m^2/s). The deposition flux D is the settling velocity w_s times the sediment concentration C:

$$D = w_s C$$

The amount of sediment transport towards layer S_1 and S_2 is determined with a user-specified parameter α:

$$D_1 = (1-\alpha) w_s C$$

$$D_2 = \alpha w_s C$$

The values for α are based on expert judgement, and is typically 0.05 to 0.2. The effect of α will be explored in the sensitivity analysis.

In many estuaries in the world, sediment flocs occur as macroflocs (large but fragile, with a settling velocity of several mm/s) and smaller microflocs (which are more compact and

therefore stronger, with a settling velocity typically several 0.1 mm/s). The microflocs are the building blocks of the macroflocs. The larger the sediment concentration, the larger the ratio of macro to microflocs $F_{ma/mi}$ is, and thereby the relative equilibrium concentration of the macroflocs ($C_{ma,eq}$).

Based on data from a large number of European estuaries, Manning and Dyer (2007) related $F_{ma/mi}$ to the sediment concentration as:

$$F_{ma/mi} = \frac{C_{ma,eq}}{C_{mi,eq}} = 0.815 + 3.18\times10^{-3}C - 1.4\times10^{-7}C^2$$

The suspended sediment concentration C (in mg/l) varies with time (and space) in the system, so does the macro to micro flocs equilibrium ratio (Figure 5.3). Because the system adaptation to a new equilibrium is not immediate, an aggregation and break up rate is defined with a first order kinetic relation as:

$$\frac{dC_{ma}}{dt} = k_f (C_{ma,eq} - C_{ma})$$

k_f is a user-defined, empirical parameter for the aggregation and break-up rate. The total suspended sediment concentration C is the sum of the micro and macro flocs:

$$C = C_{mi} + C_{ma}$$

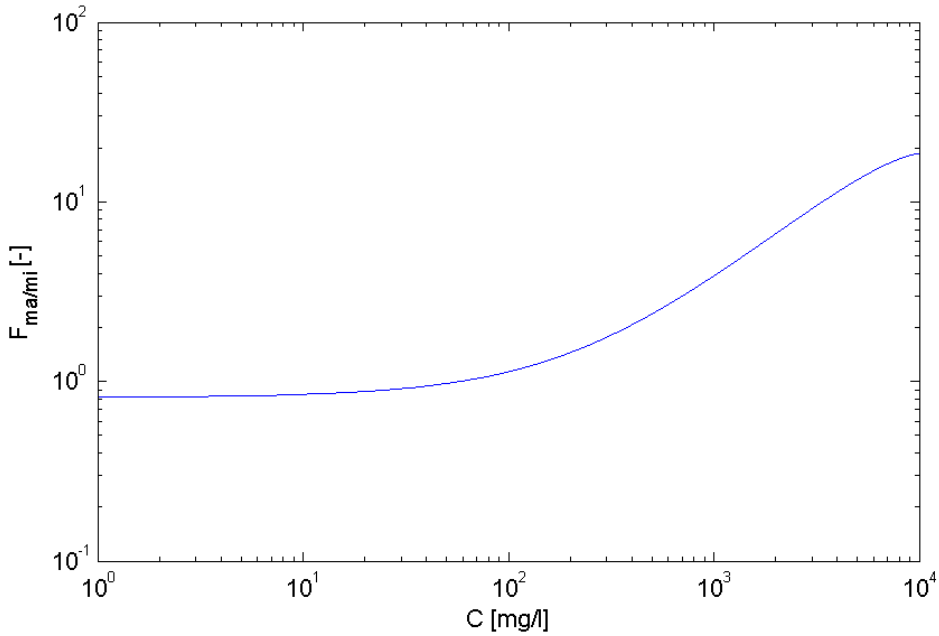

Figure 5.3 Macro to micro flocs equilibrium ratio as a function of suspended sediment concentration.

Numerically, at any computational timestep the model first computes the sediment mass per computational cell of each of the individual fractions. Depending on the resulting ratio of the

micro and macro flocs (and the aggregation and break up rate), the mass of one sediment fraction (within that computational cell) may be transferred to the other fraction.

5.2.3 Model settings, initial conditions, and boundary conditions

We use two sediment fractions, IM1 for macro flocs with a large (1.2 mm/s) settling velocity and IM2 for micro flocs with a small (0.25 mm/s) settling velocity (see Table 5.1). The settling velocity of IM1, representing fairly large and rapidly settling flocs, is based on the analysis of the soil samples collected in 2013 (1.2 mm/s on average, see report 8). Probably, the settling velocity varies throughout the tidal cycle, between values of several 0.1 mm/s to 4 mm/s (van Leussen and Cornelisse, 1996, see Figure 5.4). The reference settling velocity of the flocs are slightly larger compared to the settling velocity of flocs used in the ER model (1 and 0.2 mm/s), in line with observations by van Leussen and Cornelisse (1996).

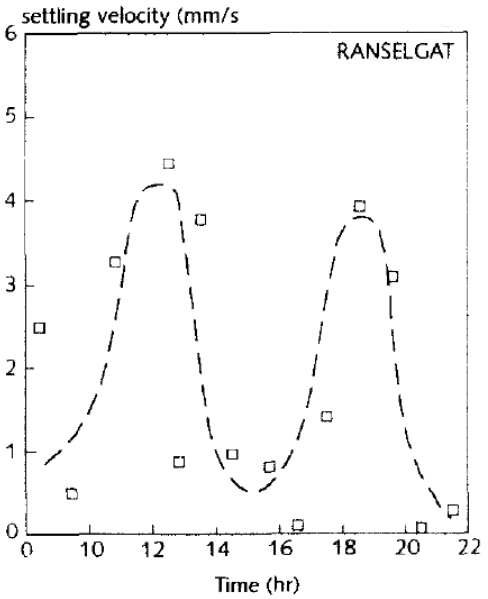

Figure 5.4 Settling velocity of mud flocs measured at Ranselgat (van Leussen and Cornelisse, 1996).

Sediment which does not or only marginally consolidates, has a critical shear stress for erosion $\tau_{cr,1}$ of several 0.01 to ~0.1 Pa (e.g. Widdows, 2007). Therefore the critical shear stress for the fluff layer is very low (0.05 Pa), implying that sediment in the top layer is easily resuspended. Sediment in S2 is assumed to erode during more energetic conditions only, when a substantial amount of sand is brought in suspension and the mud trapped in the sand layer is released. This occurs at larger shear stresses than the initiation of motion of sand particles. Earlier studies (van Kessel et al., 2011; 2013) suggest a value around 1 Pa. The mud sampling programme (report 8) suggests values in-between 1 and 2 Pa. Sensitivity analyses (not shown here) suggested $\tau_{cr,2}$ should be 0.9 Pa. The effect of this parameter will be reported in more detail in section 5.4.2. The values for M_0, M_1, and M_2 are based on previous modelling studies, complemented with a sensitivity analyses not reported here. The zero order erosion rate M_0 is much larger than the first order erosion rate M_1, implying that erosion is mostly first order (and therefore depending on the available mass of sediment). The thickness of the sand bed (layer S_2) is set to 10 cm. This represents the zone where active mixing by biological activity and bedform-related sediment transport takes place.

The sediment concentration from the rivers is set to 10 mg/l (distributed close to equilibrium ratio over IM1 and IM2 as shown in Figure 5.3). The majority of the sediment enters the model domain through the seaward boundaries, with larger sediment concentrations at the Wadden Sea than the North Sea. The Wadden Sea sediment concentration is set to constant values of 100 mg/l (see the station Dantziggat, located close to the model boundary, in Figure 5.5), and the North Sea to 20 mg/l. Seasonal variation in suspended sediment concentration (as in Figure 5.5) is not prescribed at the model boundaries, but will be resolved by the model itself through seasonal variation in wave height (with larger waves resulting in higher sediment concentrations) and river discharge.

The model is initialised without fine sediment in / on the bed or in suspension. This model is run for several years with cyclic forcing (i.e. repeating the model with the same hydrodynamic year-forcing). This period required for model spin-up increases with the thickness of S_2, and starting with an empty S_2 bed with a realistic thickness (10 cm) would require a very long spin-up time. Therefore the model is first run with a thickness of layer S_1 of 1 cm, with which the model reaches equilibrium within several years. Subsequently the thickness is extended to 10 cm, while maintaining the relative mud content (i.e. the amount of mud is multiplied with a factor 10). The resulting sediment distribution provides the basis for all model runs, which are subsequently run for another 5 years to reach dynamic equilibrium corresponding to their settings. Dynamic equilibrium is attained when the sediment dynamics during subsequent year cycles remains constant. For most settings, this occurs after 3-4 years (see e.g. Figure 5.8); a period of 5 years is therefore sufficient. The sensitivity of the model to the parameters in Table 5.1 will be verified in section 5.4. Exception is the aggregation / breakup rate (for which the value is based on a larger number of observations, presented by Manning and Dyer (2007)),

Table 5.1 Sediment transport model settings for the WED model

Parameter	Description	IM1 macro	IM2 micro
$w_{s,0}$ [mm/s]	Settling velocity	1.2	0.25
M_0 [kg/m^2/s]	Erosion parameter	2.5 10^{-3}	2.5 10^{-3}
M_1 [/s]	Erosion parameter	1.2 10^{-4}	1.2 10^{-4}
M_2 [kg/m^2/s]	Erosion parameter	1.2 10^{-3}	1.2 10^{-3}
$\tau_{cr,1}$ [Pa]	Critical bed shear stress	0.05	0.05
$\tau_{cr,2}$ [Pa]	Critical bed shear stress	0.9	0.9
α [-]	Burial rate	0.1	0.1
K_f [1/s]	Aggregation / break-up rate	2.7 10^{-5}	
Thickness S_2 [m]	Thickness of sand bed	0.1	

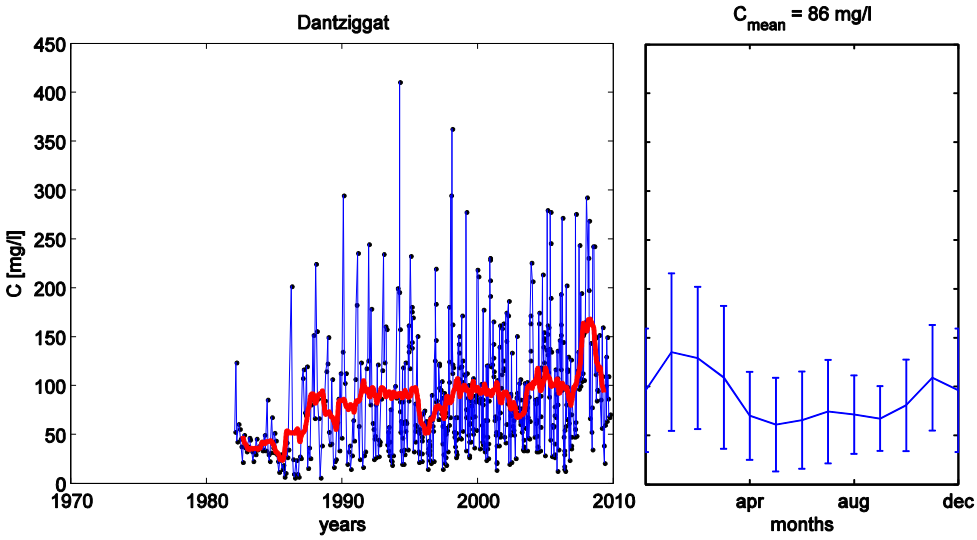

Figure 5.5 measured sediment concentration at Dantziggat as timeseries (left) and averaged per month (right).

5.2.4 Dredging and Disposal Module

The dredging module extracts sediment from the bed of prescribed areas (dredging areas) at prescribed periods, and releases this into the water column at a specific depth, location, time and rate.

Nine dredging areas were prescribed to the model (Figure 5.6) and activated depending on different model scenarios (report 7). Dredging areas include the Ports of Eemshaven, Delfzijl and Emden, the Emden fairway, the Eems River and a small portion of the Dollard (as reported in detail in Table 5.2). For the model calibration, all sediment deposited in the ports and channels is released at their actual disposal site (Table 5.3). Hence, the amount of dredged and disposed sediment is not imposed by the user, but determined by modelled sediment dynamics. It also implies that no extra sediment is added during dredging and disposal scenarios. In each dredging area, when active, the sediment is dredged from layer S_2 (where most of the sediment mass is stored).

Table 5.2 Dredging Area corresponding to the numbering in Figure 5.6

Dredging Area Code	Dredging Area
1	Eemshaven
2	Port of Delfzijl
3	Emden fairway W1
4	Emden fairway W2
5	Emden fairway E2
6	Emden fairway E1
7	Port of Emden
8	Dollard
9	Eems River

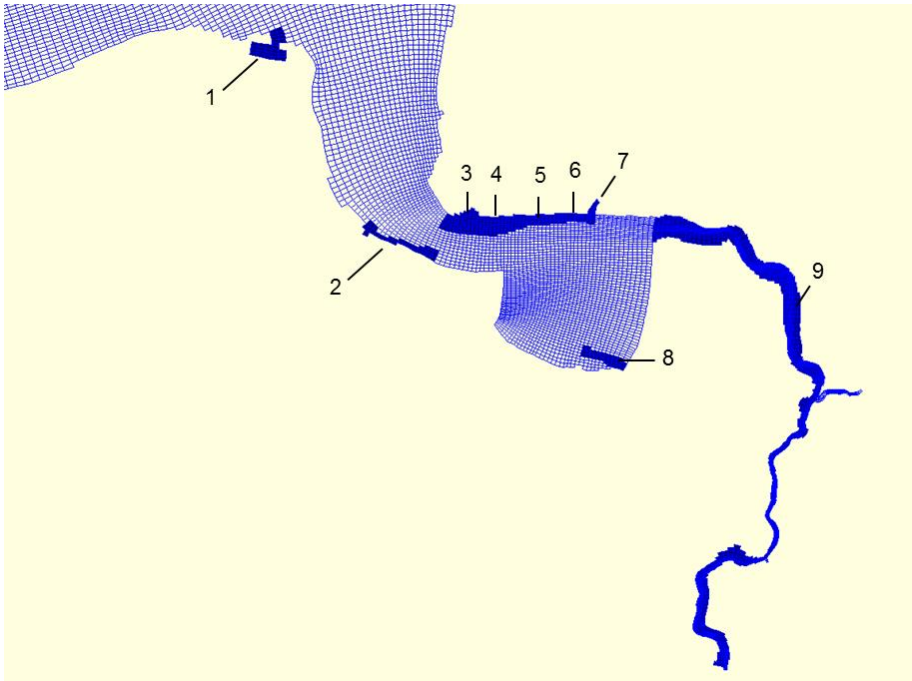

Figure 5.6 Dredging areas set up in the model

In the model, dredging occurs weekly. In reality, the frequency will be different, but limited information is available on such detail of real dredging frequencies. Whether dredging occurs weekly or monthly has, however, little impact on the model outcome. All harbours and fairways are dredged weekly, in fixed sequence, spread over the week with three days interval. This means that dredging in Area 2 will occur 3 days after dredging in Area 1, etc. During each dredging event the sediment of an entire dredging area is removed instantaneously. This schematization is chosen as a best compromise between reality, simplicity in model set up, and to guarantee a general continuity of dredging (and disposal) activities throughout the simulation to avoid unrealistic concentration peaks. The amount of sediment dredged and dumped depends on the siltation rates: the larger the siltation rates, the larger dredging and disposal volumes.

Disposal of dredged sediment occurs in four prescribed disposal areas in the Ems Estuary and Dollard (Figure 5.7). Each disposal site is associated to one or more specific dredging areas (Table 5.3). In reality, sediment dredged from the Port of Emden is not disposed, but is regularly re-aerated to prevent consolidation. A model shortcoming (see section 5.3.4) is that sedimentation in the Emden fairway is underestimated. In order to model the effect of disposal on turbidity in the Ems Estuary as realistic as possible, sediment deposited in the Port of Emden is dredged and disposed in the model in the same way as for the fairway.

Table 5.3 Disposal areas corresponding to the numbering in Figure 5.7

Disposal Code	Dredging Area Code	Dredging Area
D1	1	Eemshaven
D2-8	2 – 8	Port of Delfzijl and Dollard
D3-5	3 – 5	Emden fairway W1 and E2
D4-6-7	4 – 6 – 7	Emden fairway W2, E1 and Port of Emden

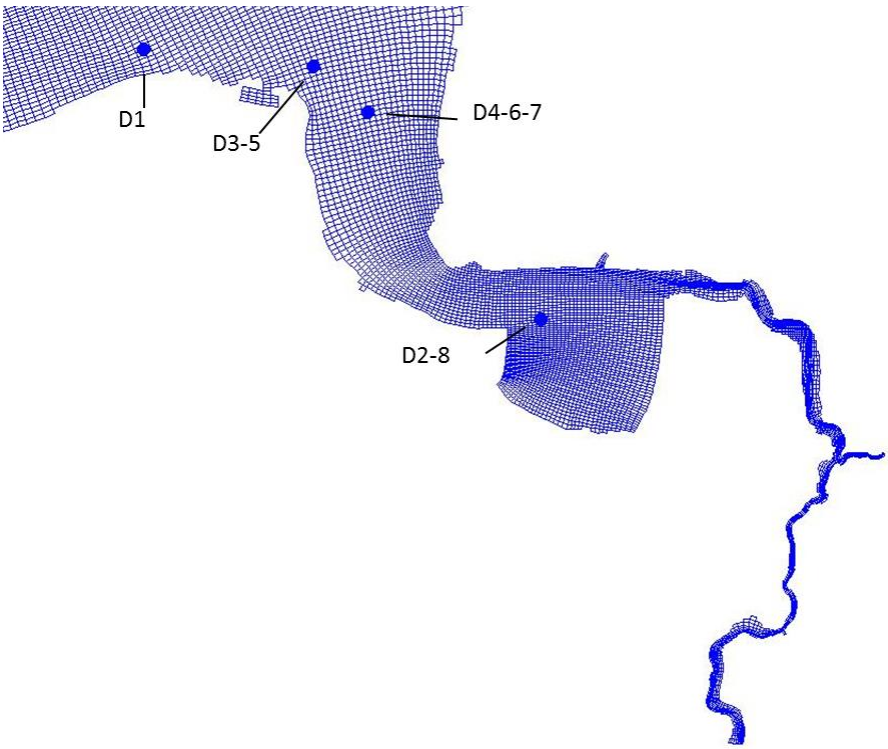

Figure 5.7 Disposal areas as set up in the model

Disposal of dredge disposal is a very complex process, where the majority of the sediment released from the hopper during disposal settles on the bed as a (sediment-induced) density current. Some sediment will be entrained by the water columns (typically several 1's to 10's % of the total deposited mass). The deposited layer is initially very mobile, but gradually settles permanently or mixes with available bed sediment. This process is poorly understood, and modelling this in detail requires large computational effort. As a compromise, all sediment is dumped in the lower hydrodynamic layer. This allows some of the sediment to diffuse upward in the water column (representing the entrainment of the dredging plume). The majority of the sediment will rapidly settle on the bed. Depending on the available amount of mud in the seabed, this sediment will be easily deposited on the bed (low mud availability in the seabed near the dump site) or transported elsewhere (large mud availability). Disposal of sediment dredged at a specific location is spread out over 3 days, avoiding unrealistic concentration peaks in the proximity of the disposal location.

In case of sediment extraction (such as the current practice in the lower Ems River, and historically in the Emden fairway and the port of Emden), sediment is dredged from the system but not disposed.

5.3 Model recalibration

5.3.1 Introduction

The TO-KPP sediment transport model developed and reported by van Kessel et al. (2013) reasonably reproduced the sediment concentration observed at the Dutch MWTL stations in the Ems-Dollard. Also the distribution of sediment in the bed reasonably agrees with observations (the Wadden Sea Sedimentatlas). In this study, a wider range of data has been used to:

- Determine values for input parameters (settling velocity and critical bed shear stress, using the soil sampling analysis (report 8);
- Calibrate the suspended sediment concentration (using MWTL, Imares and GSP measurements described in chapter 4)
- Validate port siltation rates (using dredging quantities)

Changes in the model itself (relative to the TO-KPP model) mainly include the dredging and disposal model, and the use of the SWAN wave model instead of the fetch length model.

The largest effect of using SWAN (compared to the fetch length model) is that the wave-generated bed shear stresses in the North Sea and the Wadden Sea increase significantly. The bed shear stresses deeper in the Ems estuary, notably in the Dollard, are much smaller. This has several important consequences.

(1) The energy gradient from sea to land increases. Since transport of fine sediment is larger with higher gradient, the application of the SWAN wave model should lead to (more) import of fine sediment into the estuary compared to the fetch length model
(2) Sediment is no longer deposited in large quantities on the North Sea bed (shortcoming of the previous model).

The following sections describe the results of the reference run. In section 5.4, important parameters are systematically varied and compared with observations, in order to (1) determine the sensitivity of the model to unknown input parameters, and (2) improve system understanding.

5.3.2 Suspended sediment concentration

The model is initialized by a certain initial amount of sediment (based on a previous model run). All model runs (used for the sensitivity analysis in sections 5.4.1 to 5.4.4 but also the model scenarios reported in report 7) are inter-compared when they are in dynamic equilibrium. This dynamic equilibrium is characterised by sediment concentrations with regularly re-occurring sediment concentration levels. The model attains equilibrium after about 3 years (see Figure 5.8). The yearly averaged suspended sediment concentration near the surface, computed by the model in dynamic equilibrium, is provided in Figure 5.9. Hereafter, the reference model run is compared with available suspended sediment concentration observations.

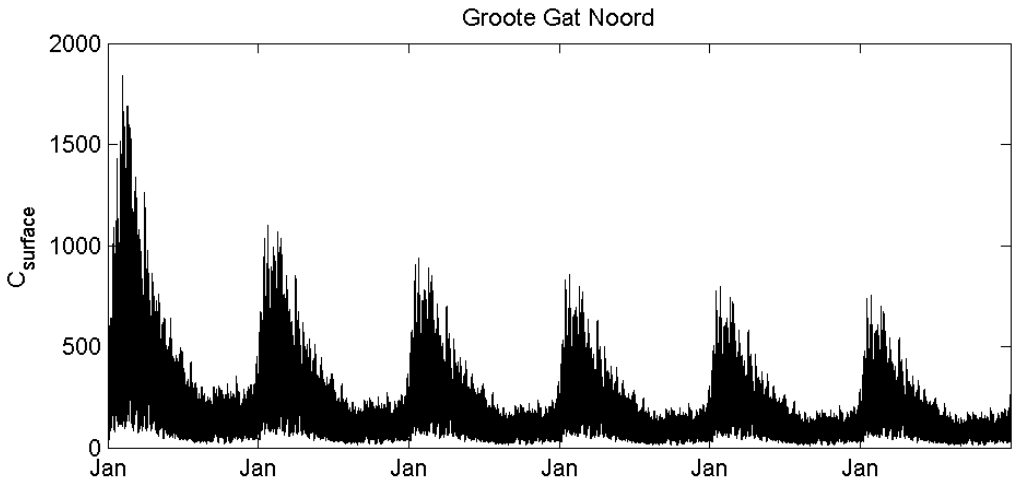

Figure 5.8 Sediment concentration over a 6-year period, computed with the reference settings, at Groote Gat Noord (in mg/l).

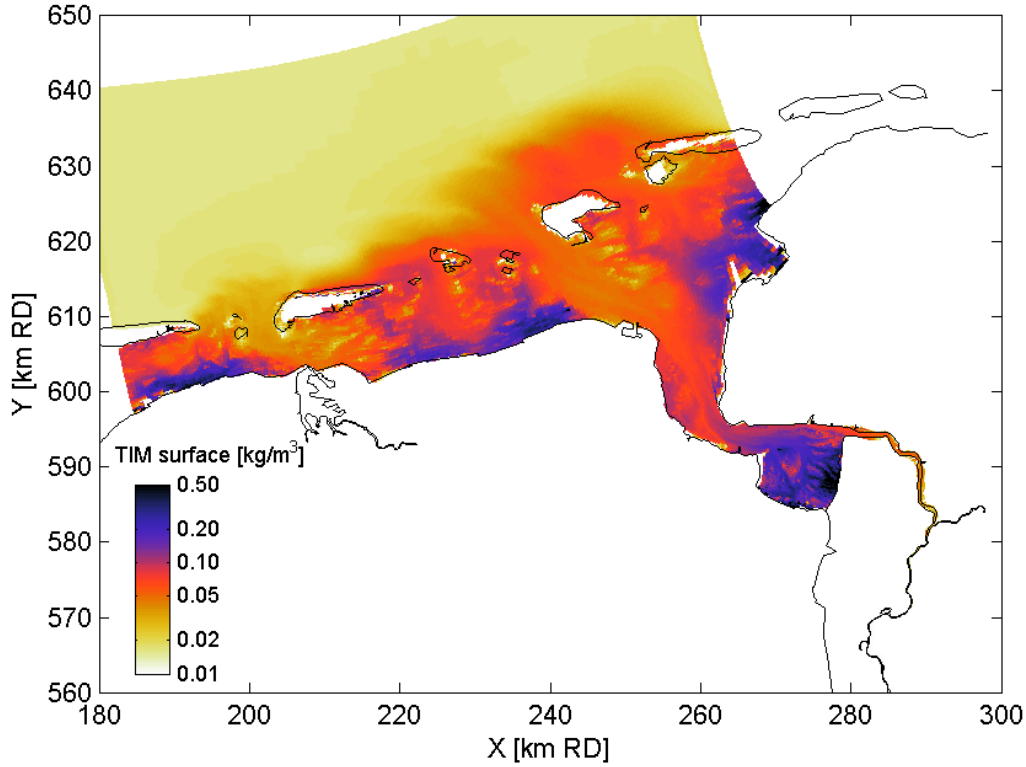

Figure 5.9 Yearly averaged surface suspended sediment concentration in the WED model domain (in kg/m^3), computed with the reference settings.

Suspended sediment concentration observations are available as 2-weekly surface sample observations (measured as part of the Dutch MWTL measurements, and by Imares), Long-term observations in the first half of 2012 by Groningen Seaports and Rijkswaterstaat. See Figure 5.10 for the location of observation stations, and Chapter 3 for a more detailed description of the data.

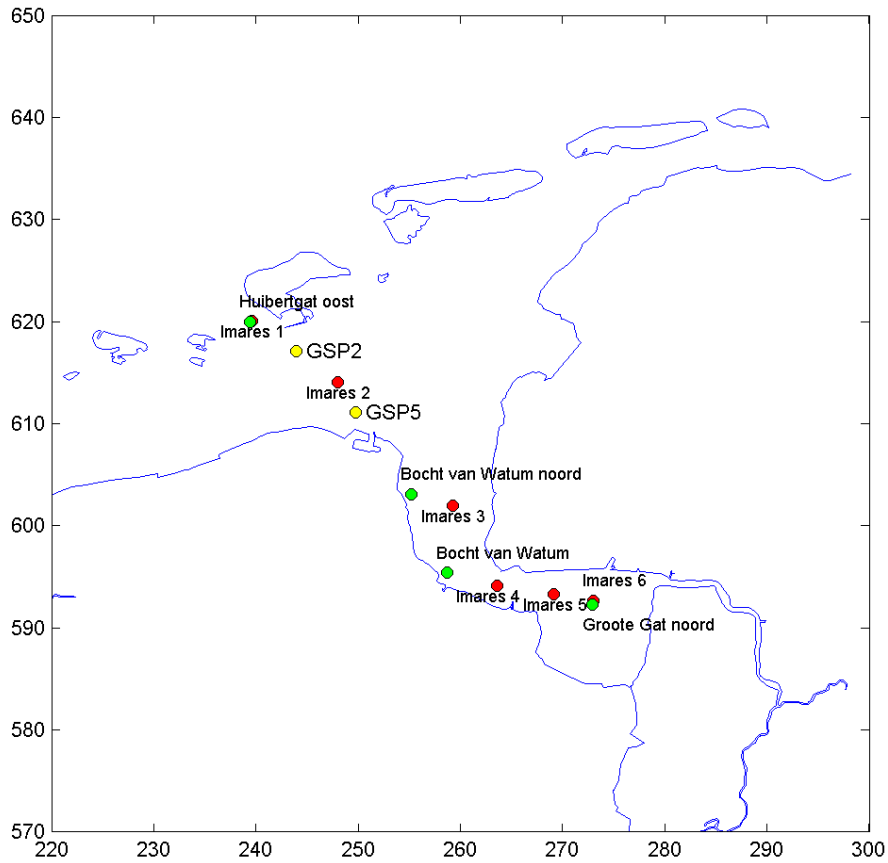

Figure 5.10 Location of suspended sediment observation points used for model calibration: MWTL stations (green), Imares stations (red), and Groningen Seaports moorings (yellow).

As mentioned in chapter 3, the observations from MWTL show higher sediment concentrations than Imares measurements at Groote Gat station. As hypothesized in that chapter, this difference may be related to a different sampling period over the tide: MWTL was measured close to low water whereas the Imares measurements were taken earlier. The computed sediment concentrations at low water (green line in Figure 5.11) match the MWTL observations in the first half of the year, but are slightly too low in the second half. The suspended sediment concentrations are larger during non-slack water conditions, with computed values exceeding 0.5 g/l in the first half of the year (more closely resembling Imares observations).

Both the model and the Imares measurements suggest that the sediment concentration is larger in the first half of the year than in the second half. This suggests that the model is realistic with respect to the calculated high concentrations and the seasonality. The reason for the seasonal variation will be elaborated in section 5.4.4. In the second half of the year, the observed sediment concentrations correspond to the higher values computed at Groote Gat. At station Bocht van Watum (in the degenerated tidal channel west of Paap Island) the observed surface sediment concentrations correspond to the average of the computed sediment concentrations (Figure 5.12). It is not understood why the 2012 observations deviate substantially from the previous 5-year average (see also chapter 3).

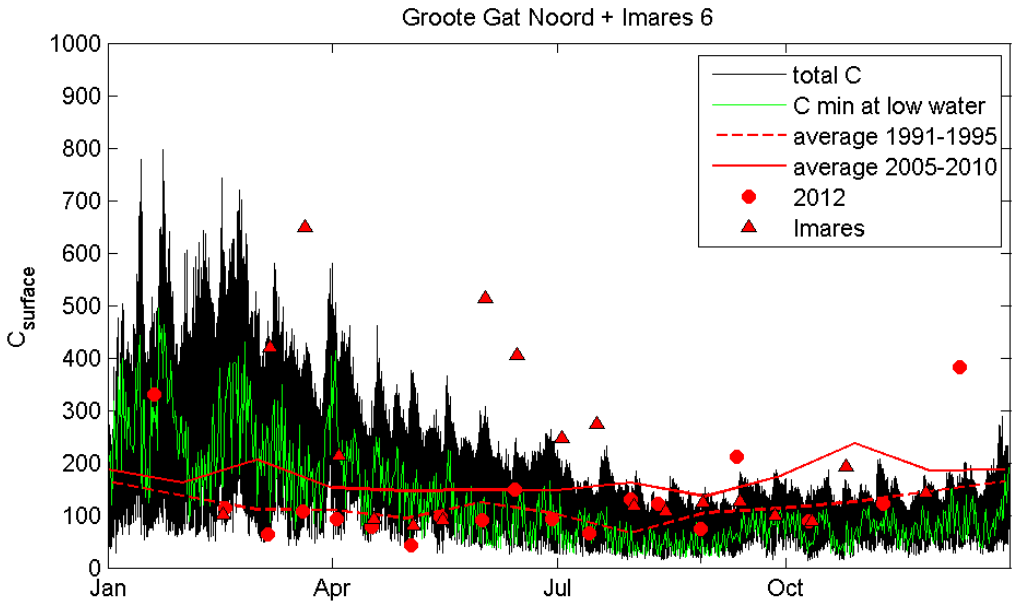

Figure 5.11 Observed and computed surface suspended sediment concentration in 2012 at station Groote Gat Noord / Imares 6 (in mg/l). The MWTL observations are red dots, with red lines representing 5-year average values of MWTL data in the period 1991-1995 (dashed) and 2005-2010 (solid). The Imares observations are red triangles. Model results (reference settings) are denoted with the black line, with the green line representing the sediment concentration at low water (corresponding to the period the MWTL measurements were taken).

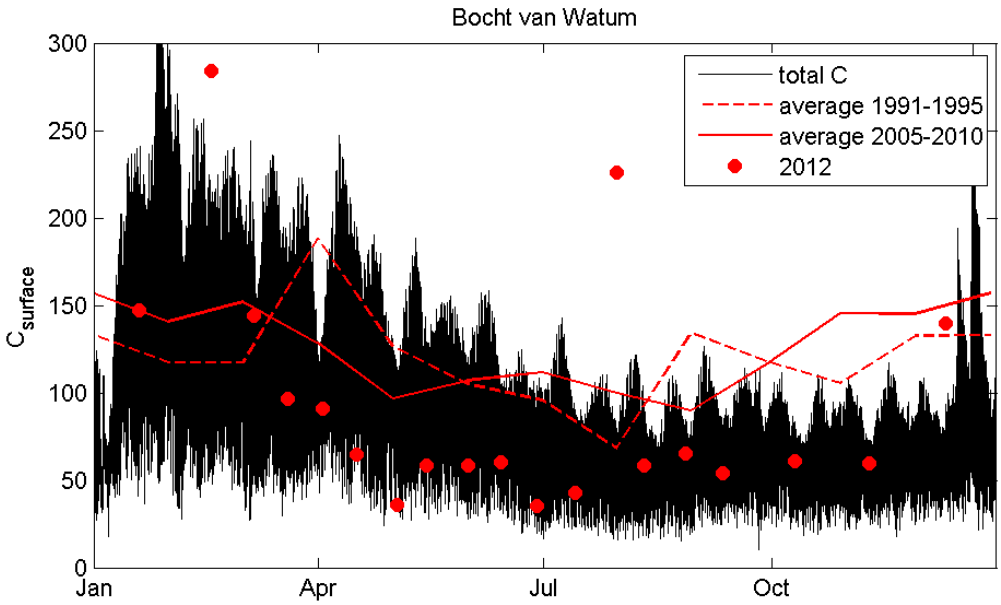

Figure 5.12 Computed (reference settings) and observed surface sediment concentration in 2012 at MWTL station Bocht van Watum (in mg/l). The 2012 observations are red dots, with red lines representing 5-year average values of MWTL data in the period 1991-1995 (dashed) and 2005-2010 (solid).

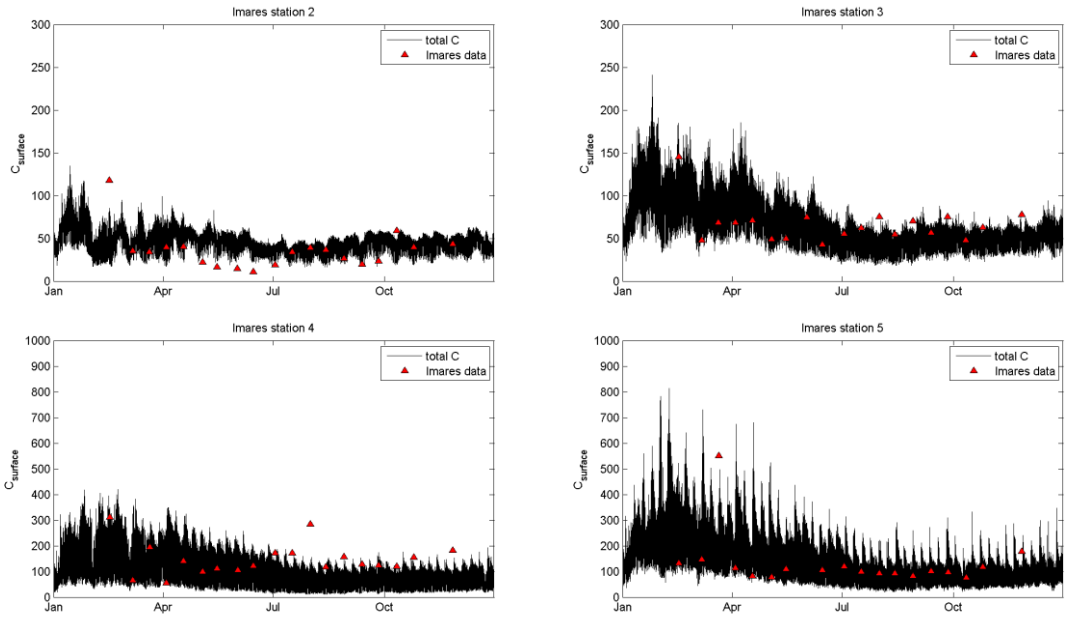

Figure 5.13 Computed (reference settings) and observed surface sediment concentration in 2012 at Imares stations 2-5 (in mg/l).

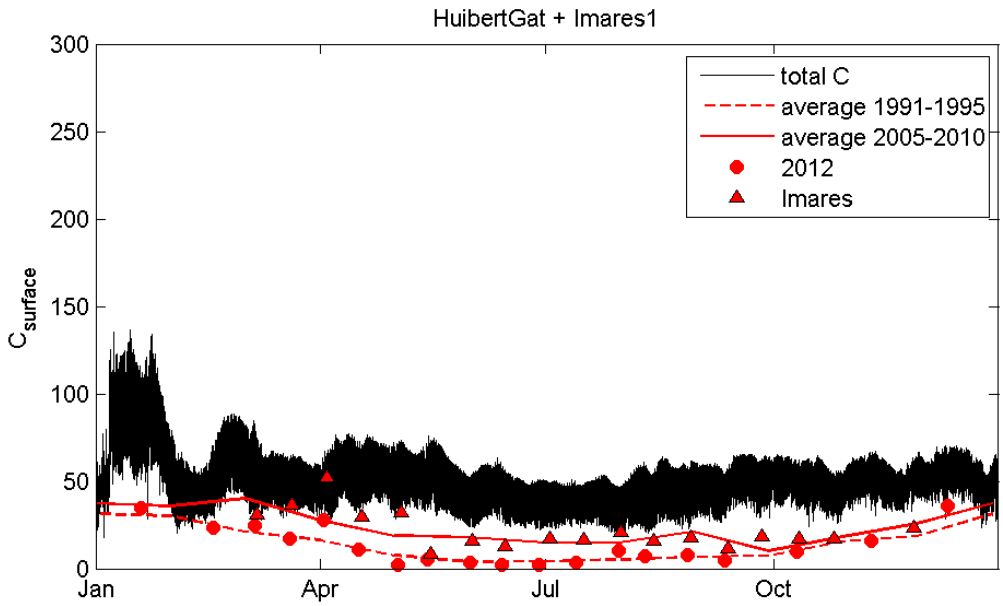

Figure 5.14 Observed and computed (reference settings) surface suspended sediment concentration in 2012 at station Huibertgat / Imares 1 (in mg/l). The MWTL observations are red dots, with red lines representing 5-year average values of MWTL data in the period 1991-1995 (dashed) and 2005-2010 (solid). The Imares observations are red triangles.

From the Dollard (Figure 5.11) towards the outer estuary (Figure 5.13 and Figure 5.14), the sediment concentrations decrease (in line with observations, see Figure 5.15). Also the timing of the computed sediment concentration peak shifts in time (end of January / beginning of February in Groote Gat; early January in Huibertgat); the observed sediment concentration is measured too infrequent to validate this pattern. The computed sediment concentration reasonably corresponds with observations, but the seasonal variation in SSC computed at

Imares 3, 4, and 5 is larger than any observed seasonal variation. At station Bocht van Watum, however, the data does suggest seasonality, in line with the model. The sediment concentration is too low in the second half of the year in some stations, in particular at Imares station 4.

At Huibertgat (Figure 5.14), there is a pronounced difference between Imares data, MWTL data, and model results. The MWTL observations are lowest, below 10 mg/l in summer. The Imares measurements are two times larger, with typical values of 20 mg/l. The modelled concentration however, is closer to 50 mg/l, suggesting that the model overestimates the sediment concentration. In contrast, comparing the model with data collected approximately 5 km landward (GSP2) suggests that the model underestimates the sediment concentration (Figure 5.16). The sediment concentration at GSP5 (10 km up-estuary from GSP2, see location in Figure 5.10) is underestimated in a similar manner (Figure 5.17). A detail of GSP5 during a spring neap cycle in March (same cycle as evaluated for the hydrodynamic calibration) reveals that the spring-neap variation as well as the intra-tidal phasing is well reproduced (Figure 5.18). The observed sediment concentration close to the bed is approximately double that of the near-surface observations (compare Figure 5.18 with Figure 5.19, note the different y-scale in both figures). This near-bed increase in suspended sediment concentration is also computed by the model, suggesting that the settling velocity used in the model is reasonable. A smaller settling velocity would generate a more vertically uniform sediment concentration profile (and vice versa for a larger settling velocity).

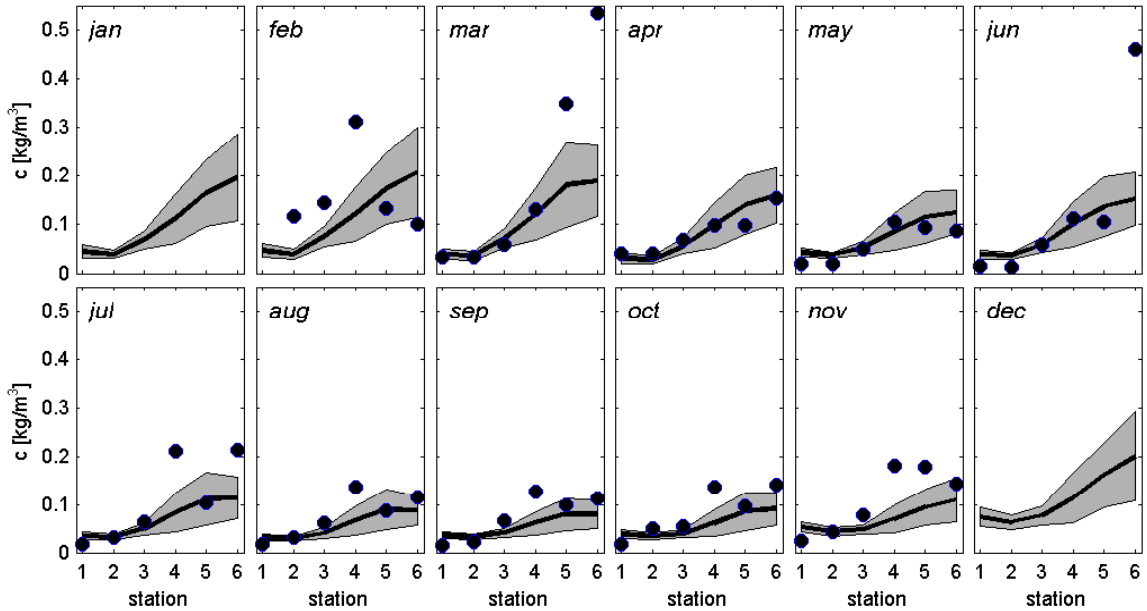

Figure 5.15 Monthly averaged computed surface sediment concentration (black line, with gray shading indicating the standard deviation, computed from hourly modeloutput) and observed surface sediment concentration (black dots, February through November) in 2012 at stations Imares 1 to Imares 6 (in kg/m^3). See Figure 5.10 for the location of stations.

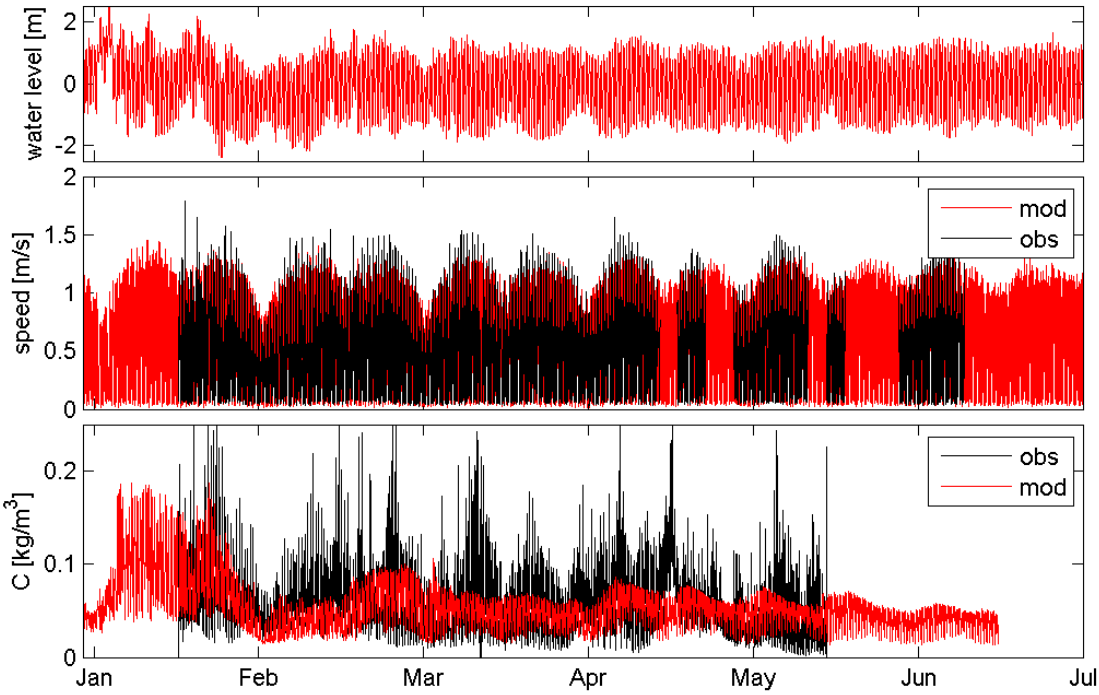

Figure 5.16 Water level (top panel) and observed (black) and computed (red) depth-averaged flow velocity (middle panel) and near-surface sediment concentration (chain, third panel)) at location GSP2

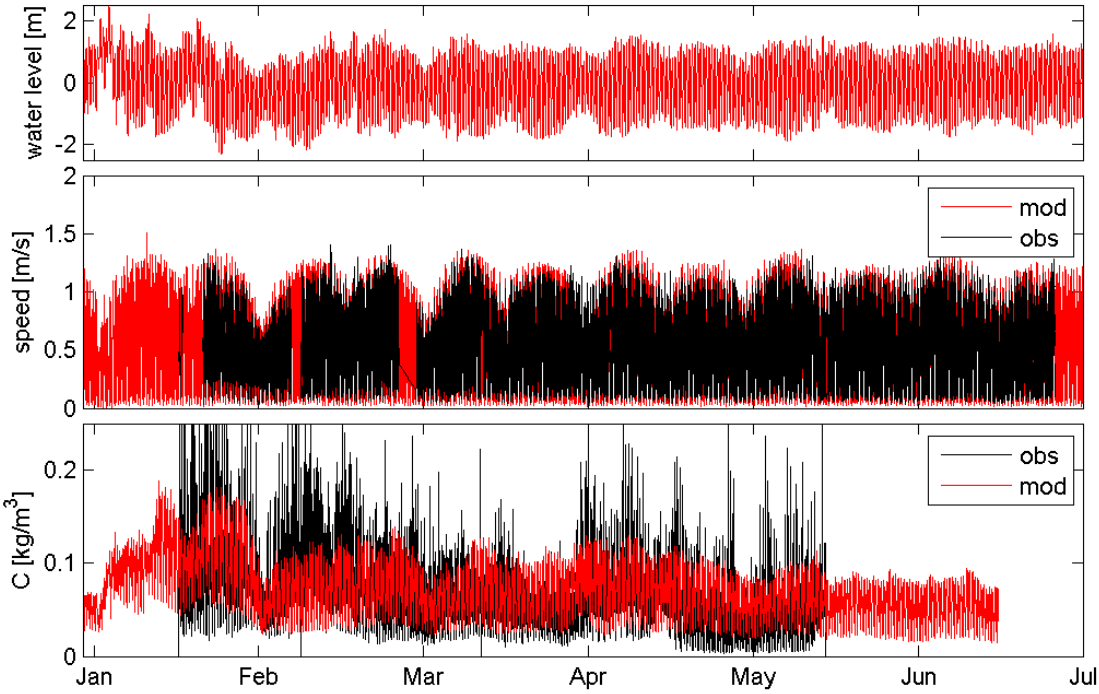

Figure 5.17 Water level (top panel) and observed (black) and computed (red) depth-averaged flow velocity (middle panel) and near-surface sediment concentration (chain, third panel)) at location GSP5

It is unclear why the model overestimates the sediment concentrations at Imares 1 / Huibertgat and Imares 2, but underestimates the sediment concentration at nearby stations GSP2 (especially) and GSP5. The large intra-tidal variation and the strong apparent correlation with spring-neap variation in the flow velocity (Figure 5.16) is indicative for resuspension of fine sand. The concentration of suspended fine sand in tidal currents of 1.5 m/s and a water depth of 12 m is typically 100-200 mg/l. Sand is not modelled in this study, since deeper into the estuary the flow velocity is too low to generate significant sand transport. However, it is likely that the computed sediment concentration is too low because sand transport is not accounted for. This may also provide an explanation for the large difference between Huibertgat and the GSP stations. The concentration at Huibertgat is measured closer to the water surface, and sand has a strong vertical concentration gradient. Also the water depth at Huibertgat is larger, leading to lower sand concentrations.

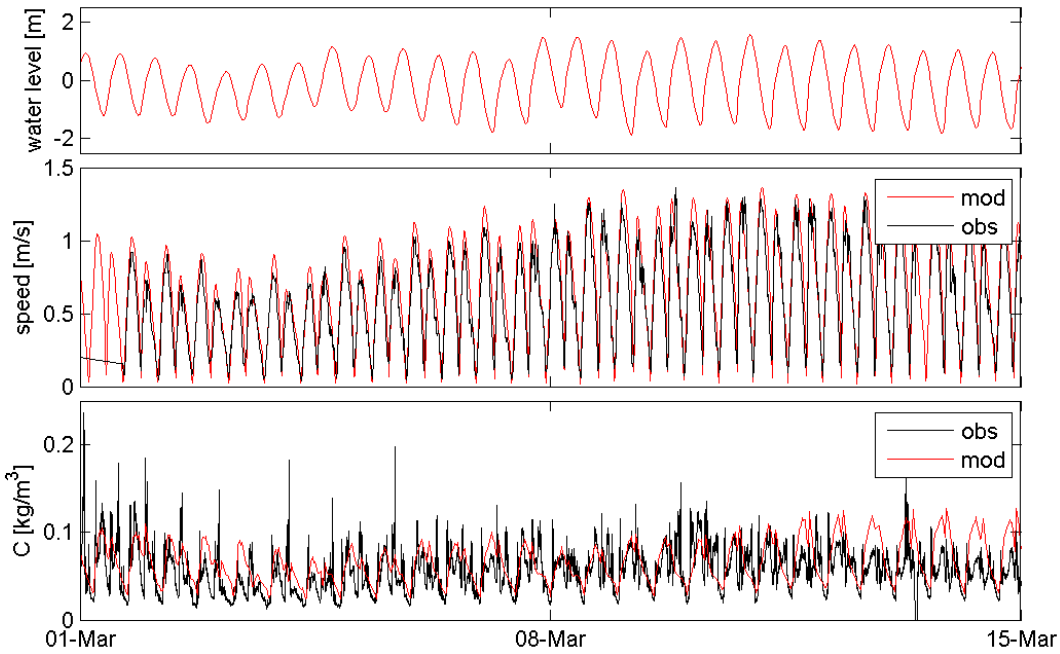

Figure 5.18 Water level (top panel) and observed (black) and computed (red) depth-averaged flow velocity (middle panel) and near-surface sediment concentration (chain, third panel)) at location GSP5, from 1 to 15 March.

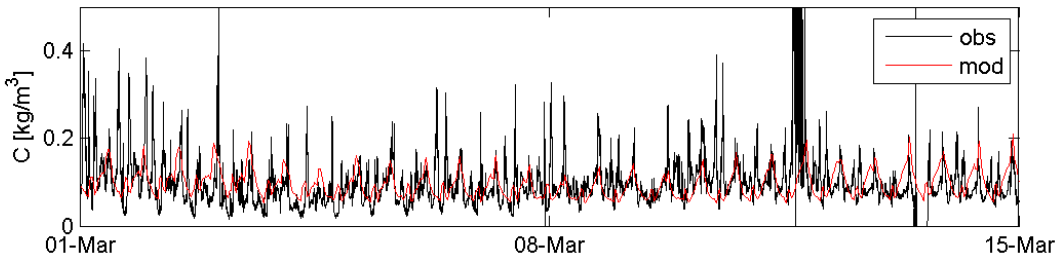

Figure 5.19 Observed (black) and computed (red) near-bed sediment concentration (bottom panel) at location GSP5.

5.3.3 Summary sediment concentration calibration

In the first half of the year, the model seems to underestimate the measured suspended sediment concentration at GSP2 and GSP5, but overestimate the sediment concentration measured at the nearby station Imares 1. Station GSP2 is located in-between Imares 1 and 2 whereas GSP5 is located in-between Imares 2 and 3 (Figure 5.10). As already discussed in Chapter 3, the available data seems contradictory. It is well possible that the measured sediment concentration at Imares 1 is too low (especially the MWTL observations), or that the sediment concentration at GSP2 and GSP5 is too high. Because of inconsistencies in the data, the model is calibrated in such a way that the sediment concentration at Imares 1 is overestimated but the sediment concentration at GSP2 and GSP5 is slightly underestimated.

The model approximates the observed intratidal variation in suspended sediment concentration at the entrance of the estuary, and the along-estuary gradient in suspended sediment concentration, and the seasonal variation in suspended sediment concentration, providing confidence in the model to reproduce the estuarine sediment dynamics. As a next step, the computed sediment fluxes are compared with observations.

5.3.4 Sediment fluxes

Sediment fluxes in Delft3D-WAQ are defined as the exchange between (user-defined) observation areas. The observation areas in the Ems estuary are graphically provided in Figure 5.20 (details in Figure 5.21), and tabulated in Table 5.4.

Table 5.4 Areas definitions: used for flux computations

ObsArea1	Eems River Upstream
ObsArea2	Eems River Center
ObsArea3	Eems River Downstream
ObsArea4	Emden fairway East
ObsArea5	Emden Port
ObsArea6	Emden fairway Center
ObsArea7	Dollard
ObsArea8	Emden fairway West
ObsArea9	DelfZijl Port
ObsArea10	Eems Estuary
ObsArea11	Eems Port
ObsArea12	Wadden Sea
ObsArea13	North Sea

Sediment with a large settling velocity (IM1, 1.2 mm/s) can be transported landward by a number of mechanisms. The sediment is non-uniformly distributed through the water column, with sediment concentrations increasing towards the bed. In case of a salinity-driven residual flow velocity (estuarine circulation), which is landward-directed near the bed (and seaward-directed near surface), larger near-bed concentrations lead to landward transport of sediment. Additionally, when sediment settles during slack tide, it may be transported landward by settling / scour lags in combination with Eulerian or Lagrangean tidal asymmetries (see Friedrichs, 2012 or van Maren and Winterwerp, 2013).

Table 5.5 Estimated fluxes (based on net sinks or dredging volumes) and computed fluxes

Port / area	Estimated flux (million ton/year)	Computed flux (million ton/year)
Ems Estuary	1.5	-0.12
Eemshaven	0.5	0.44
Delfzijl	0.8	0.76
Emden port and fairway	1.5	0.55
Lower Ems River	0.75	0.08

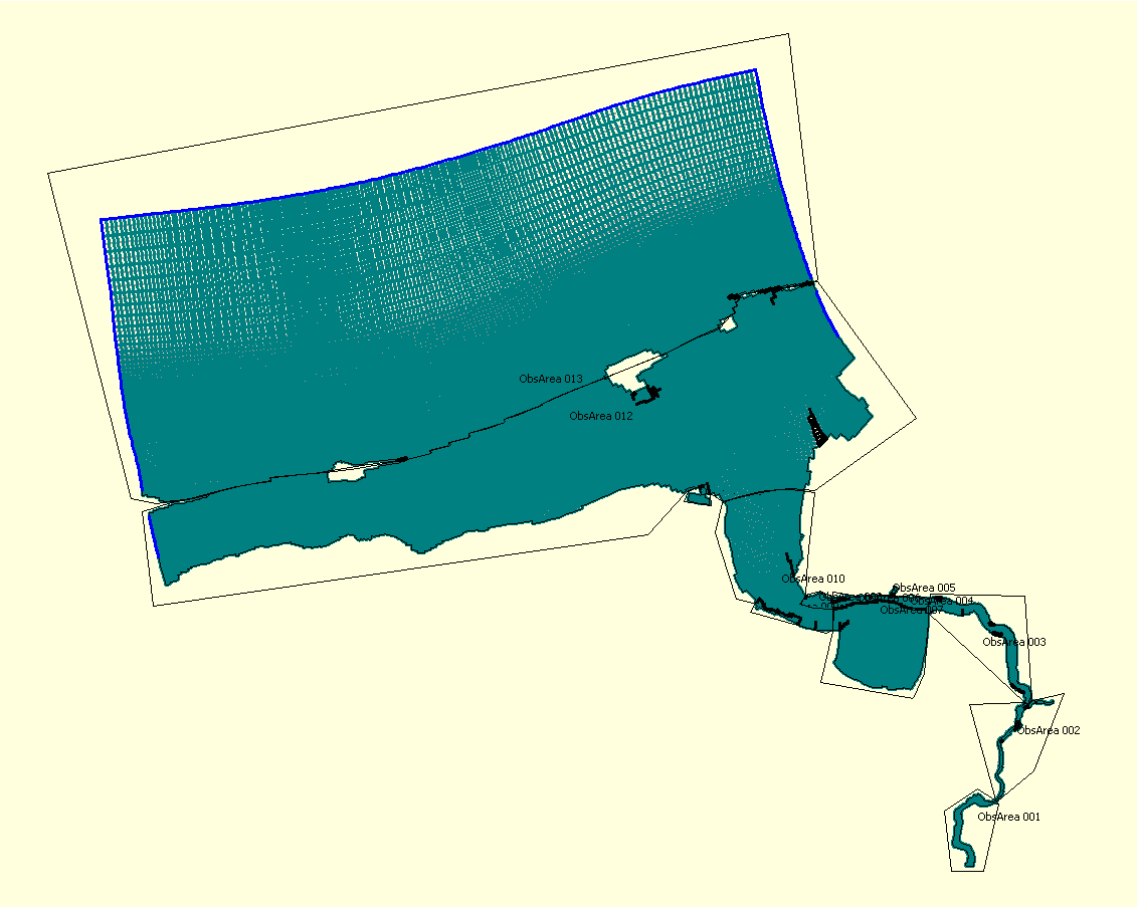

Figure 5.20 Area definition used for computation of sediment fluxes

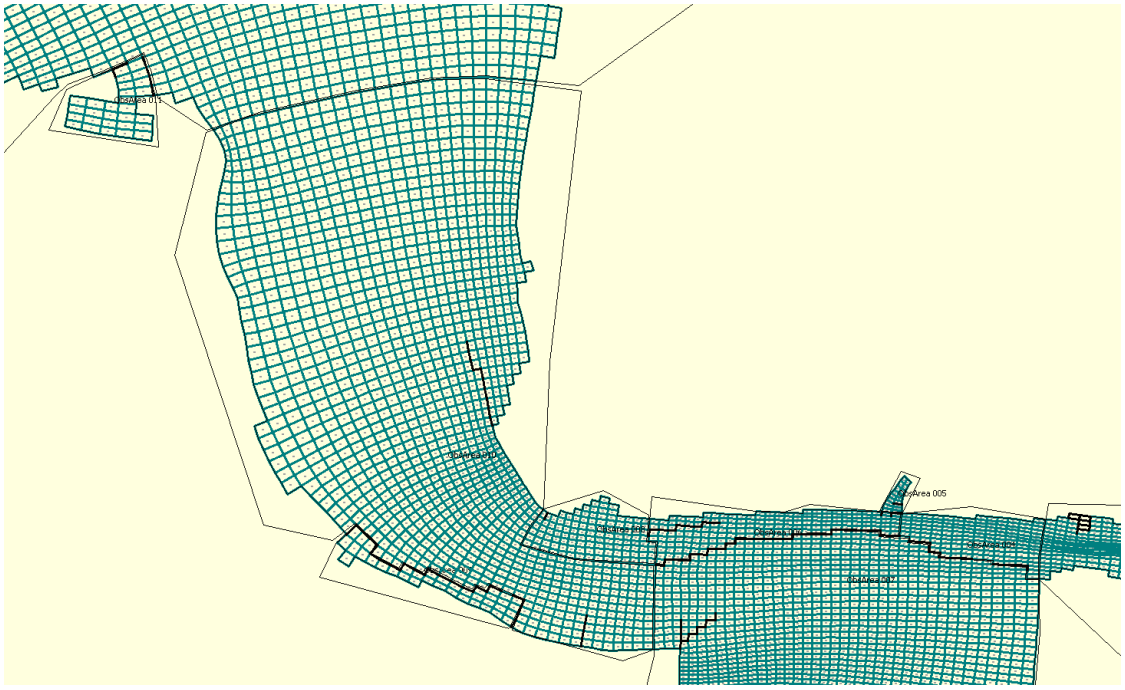

Figure 5.21 Area definition used for computation of sediment fluxes, detail of the middle reaches.

Through-tide ADCP observations (Extrapolation of Weilbeer and Uliczka (2012)) yields ~5 million ton/year (see Table 5.5) import of sediment into the Ems estuary. Nevertheless, annual residual transports should be equal to net sediment sinks in the estuary, which are probably in the order of 1.5 million ton/year (0.75 million ton / year extracted from the lower Ems River and 0.75 million ton/year into the Bocht van Watum – see Chapter 3). 1.5 Million ton is therefore probably a more realistic estimate for the net transport into the estuary. The model does not compute sediment transport in up-estuary direction. It even computes export of 0.15 million ton of sediment (0.3 million ton export of IM2, partly compensated by 0.15 million ton import by IM1): see the flux from Wadden Sea to Ems Estuary in Figure 5.22 (transect located just south of Eemshaven, see Figure 5.20). The model does not reproduce import because

(1) The Delft3D-WAQ buffer model for the Ems Estuary is an equilibrium model of which the settings are such that the erosion rate of the S1 fluff layer increases with the amount of sediment in the S1 layer. As long as the bed shear stress at a certain location exceeds the critical bed shear stress for a finite period, accretion in the S1 layer balances deposition rates at a critical amount of sediment (depending on local hydrodynamics and model settings), and sediment no longer accumulates. For each setting, the model is run for consecutive cyclic years, until inter-annual differences in sediment dynamics are negligible (dynamic equilibrium, where residual fluxes are low or absent). This implies that throughout the model domain the erosion and deposition fluxes are in long-term equilibrium. Net siltation, such as is occurring in the Bocht van Watum, is then not reproduced when using a very low critical bed shear stress for erosion. This would require a constant transfer of mass from the S1 layer to a more dynamic S2 layer (the deeper layer which is less erodible), representing consolidation processes.
(2) In a depositional area such as the Bocht van Watum, the flow velocities and resulting bed shear stress decrease in time as the channel degenerates. Hence, the erosion rate

decreases in time. In the WED model, there is no coupling between hydrodynamics and sedimentation, and the decrease in erosion rate is not accounted for.

(3) As described previously, the hydrodynamics and sediment dynamics in the lower Ems River are not realistically simulated (requiring full coupling between hydrodynamics, sediment dynamics, and bed evolution). Therefore the Ems River is not a net sink of sediment, as it is in reality.

Sediment sinks as a result of sediment extraction within the Ems Estuary, or siltation in the ports, can be reproduced with the model. This is important for computation of scenarios explaining the historic development of the estuary (report 7) and mitigating measures (report 11). However, the residual flux resulting from the above-mentioned three processes are underestimated by the model. The long-term dispersion of dredged material is influenced to a certain extent by the underestimation of residual fluxes. In reality some of the disposed dredge spoil will be transported towards a net sediment sink and therefore not contribute to turbidity. Therefore the absence of sinks leads to an **overestimate** of the effect of dredging/disposal. However, the fluxes into and out of the ports are larger (~8 million m^3/year, see Figure 3.12) than net deposition rates (~0.8 million m^3/year and extraction from the lower Ems River (each (1.5 million m^3/year), and therefore this effect will probably be limited. Additionally, the amount of material dredged from the ports and disposed in the estuary was **underestimated** by the model (Table 5.5). Therefore the absence of sinks may (partly) compensate the underestimation of the effect of dredging resulting underestimated siltation in the port and approach channel of Emden.

With 0.1 million ton/year transported into the lower Ems River (Figure 5.22), the model predicts 0.55 million ton of annual deposition in the Emden navigation channel and port (Table 5.5). Between 2006 and 2010, 3.1 million m^3 was annually dredged from the Emden fairway, equivalent to 1.5 million ton (assuming a dry density of 500 kg/m^3 as reported by Mulder, 2013). The net extraction rates from the lower Ems river is 1.5 million m^3/year (equivalent to 0.75 million ton/year with a dry density of 500 kg/m^3). Deposition in the navigation channel is therefore underestimated with 1 million ton / year, and residual transport into the lower Ems River is underestimated with 0.6 million ton/year by the model. This may be the result of

(1) An underestimation of the sediment concentration
(2) The absence of a coupling between sediment and water density. The sediment-induced density coupling increases settling from suspension through suppression of turbulence by vertical concentration gradients, and may lead to fluid mud formation (see Winterwerp, 2001).
(3) Neglecting consolidation and flocculation processes. Sediment settles around slack tide as mobile particles with a critical bed shear stress for erosion. Within hours, the strength of the bed increases substantially due to consolidation, and during the subsequent ebb or flood, the sediment is not easily resuspended anymore. In the model, this process is not accounted for, and therefore the erosion is overestimated. This shortcoming is mainly visible for the Emden Fairway because here net sedimentation occurs (due to the large water depth and concentration) despite strong currents.
(4) Inaccurate simulation of tidal deformation in the lower Ems River (see report 4).

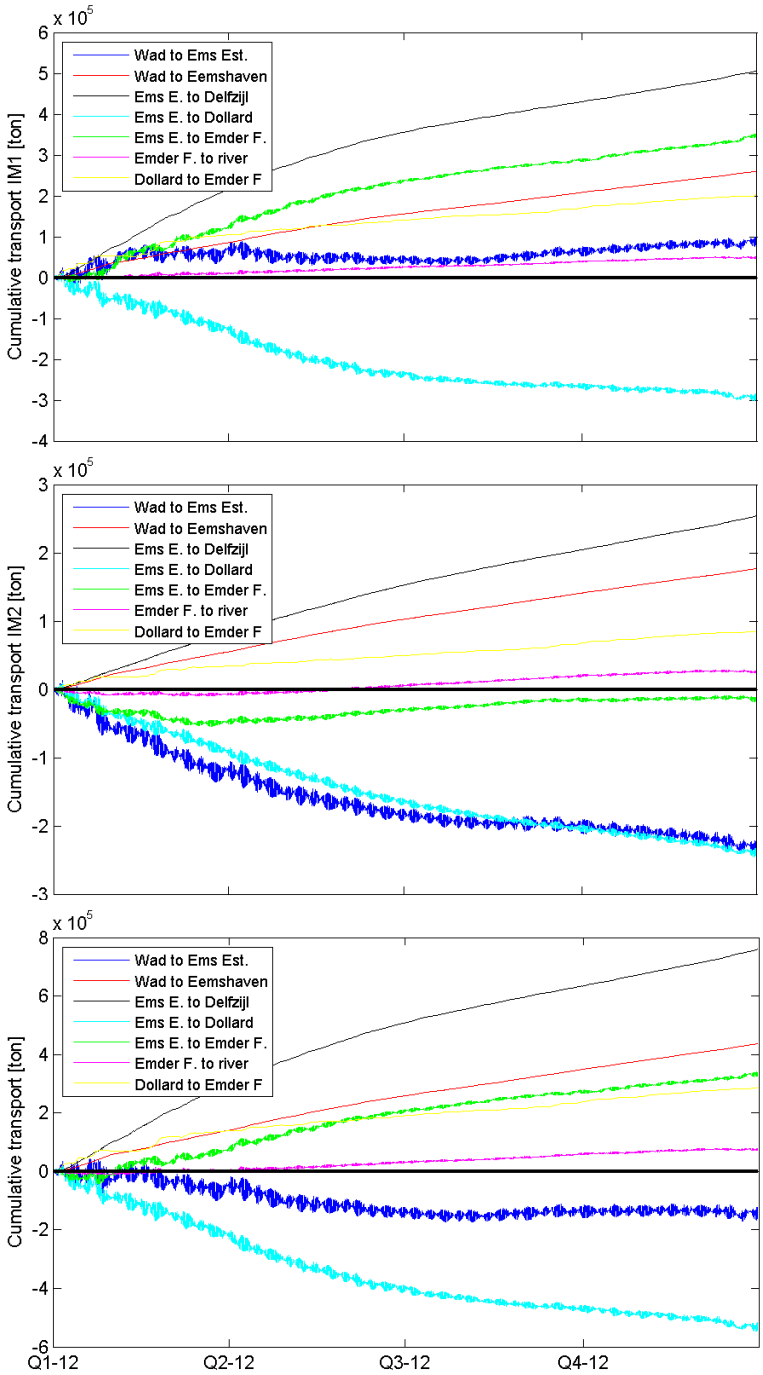

Figure 5.22 Sediment fluxes (up-estuary transport positive) computed for the reference run for IM1 (w_s = 1.2 mm/s, top panel), IM2 (w_s = 0.25 mm/s, second panel) and combined (third panel), in 2012. See Figure 5.20 for definition of the fluxes.

5.3.5 Bed sediment distribution

The observed mud content (defined as the fraction of sediment with a grain size below 63 µm) is largest in the tidal flats of the Dollard bay, with values of 50-100%. Also the main tidal channel in the Dollard (Groote Gat) is mostly fine-grained. The degenerating Bocht van Watum (left of Hond-Paap shoal) and Hond-Paap shoal itself are also fine-grained, with a

mud content of typically 50%. The intertidal zones of the North Coast of Groningen are also relatively fine-grained, although less than the Dollard bay and the Hond-Paap area.

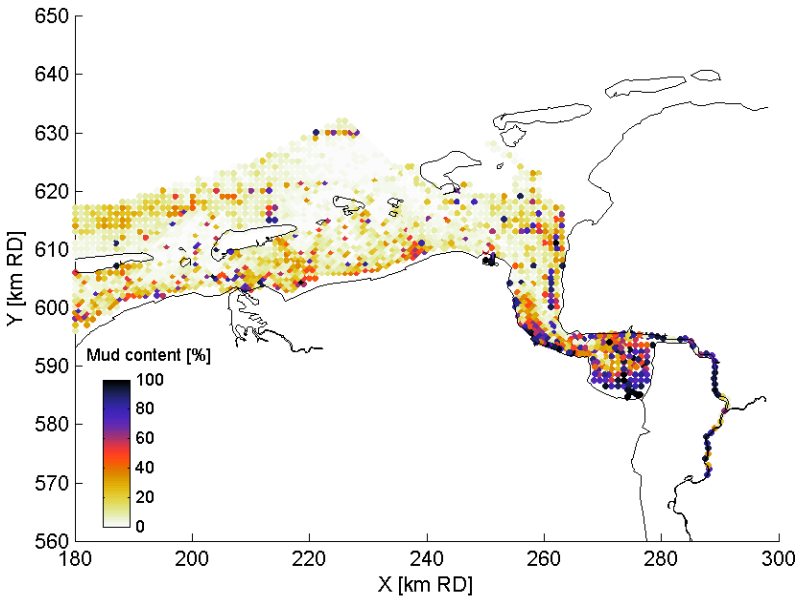

Figure 5.23 Observed mud content (fraction < 63 µm) in the Ems Estuary. Data from the Sediment Atlas, based on samples collected in 1989 and 1991.

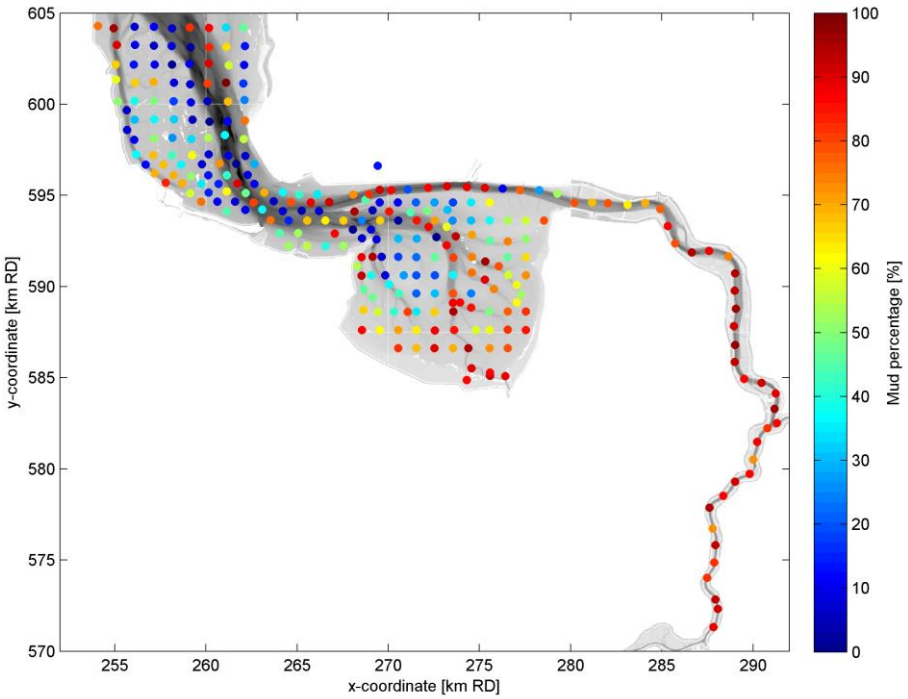

Figure 5.24 Mud content, defined as the percentage of material with a d < 63 µm, as derived with the Malvern from the samples collected in summer 2013.

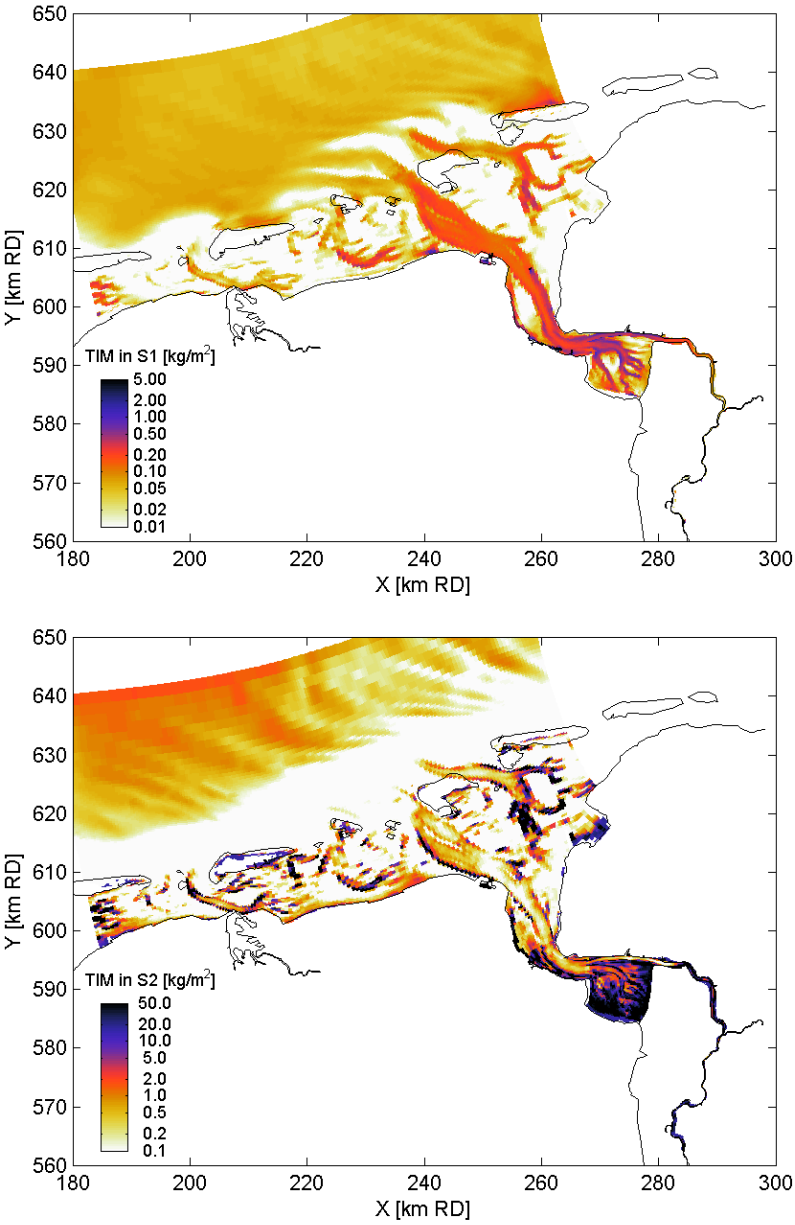

Figure 5.25 Computed mud distribution (kg/m^2) in layer S1 (top) and S2 (bottom), using the reference model settings

The computed mud content is given in Figure 5.25. Mud in layer S_1 represents mud that is easily resuspended, typically within a tidal cycle, and is therefore several kg/m^2. The mud content in Figure 5.23 or Figure 5.24 can be best compared to the mud content in layer S_2. The model reproduces the areas with large mud content in the Dollard and the Hond-Paap area (compare Figure 5.23 with Figure 5.25). The large mud content in the bocht van Watum (Figure 5.25) is caused by rapid infilling of the degenerated tidal channel, in line with observations of mud content (Figure 5.23) and net deposition rates (Figure 3.13). The larger mud content on the intertidal areas of the Groningen coast is qualitatively reproduced, but in absolute terms too low (up to 5 kg/m^2 or 50 kg/m^3. This low mud content probably results from the large bed shear stress computed with the SWAN model, which will be evaluated in more detail in section 5.4.4. Also the apparent increase in mud content observed in deeper waters of the North Sea (Figure 5.23) is reproduced by the model.

The observed high mud content on the bed of the Groote Gat tidal channel relative to the surrounding tidal flats (Figure 5.24) was attributed to the mature state of the tidal flat deposition (sediment deposited on the flats is eroded by waves) balancing constant supply (Chapter 3). The flow velocity within the channel is large and therefore sediment does not accumulate in S_2 but temporarily in the dynamic layer S_1 (Figure 5.25). This is in line with the interpretation if the observed mud distribution in section 3.4.

5.3.6 Dredging mass

Figure 5.26 shows the mass (in ton/year) of dredged material for the reference scenario. Most sediment is dredged from the ports, especially in Delfzijl and Emden (> 0.5 million ton/year in the model). A low amount of sediment is dredged from the Emden fairway (see section 5.3.4). In order to obtain more realistic dredging volumes, sediment from the port of Emden is dredged and dispersed together with sediment from the Emden fairway. The dredging operations will be analysed in more detail in report 7.

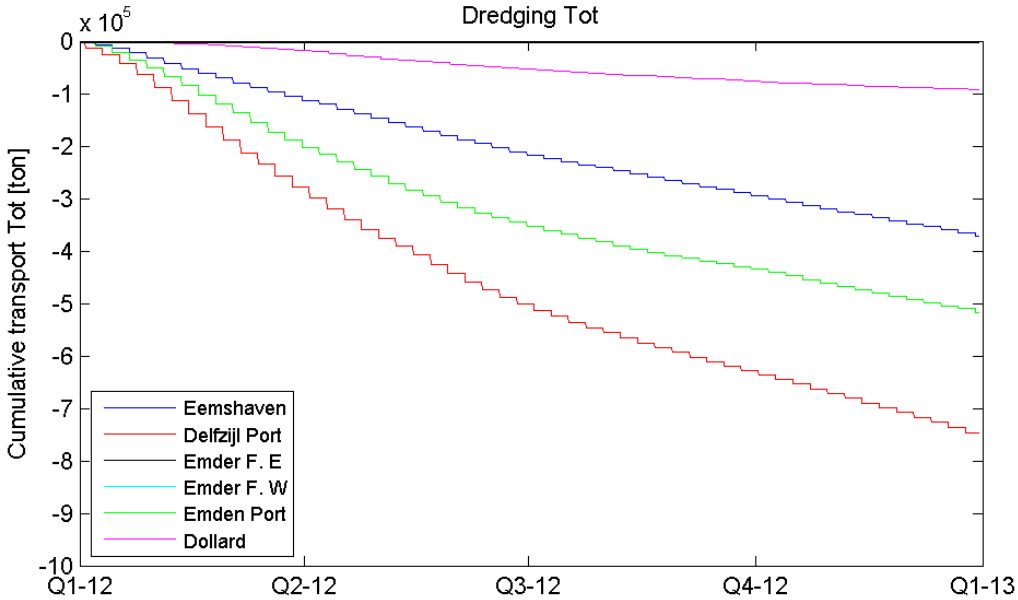

Figure 5.26 Dredged sediment mass (in ton) for the different dredging areas (see Figure 5.6) for the reference scenario (Scenario 1) for the year 2012.

5.3.7 Role of waves and river discharge

The computed relations between waves, river discharge, and high concentrations are qualitatively agreeing with observations. In the Ems Estuary, little or no attention has so far been given to the role of estuarine circulation to residual sediment transport. A reason for this may be that detailed and long-term measurements of the vertical distribution of flow velocity and suspended sediment concentration are needed to quantify its contribution, and these are not available. Previous model studies did not analyse the effect of salinity, and therefore it is not possible to compare our predicted effect with earlier studies.

The increased suspended sediment concentration in the estuary during storm conditions, including export from the Dollard basin, is in line with earlier studies and therefore the modelled wave-induced resuspension is sufficiently well represented. During fair weather

conditions sediment is transported towards the tidal flats while sediment is transported towards the channels during stronger wave action (De Haas and Eisma, 1993; De Jonge and van Beusekom, 1995; Ridderinkhof, 2000). De Haas and Eisma (1993) further distinguish an intermediate stage with increased wave height without storm set up, during which residual transports are negligible. The January storms, which mostly impacted the computed suspended sediment levels, are examples of storms with significant storm set-up. Literature disagrees on the critical wind speeds after which resuspension on the flats becomes large, varying from 6 m/s (de Jonge and van Beusekom, (1995), 10 m/s (only for winds from the West to North quadrant; van de Kreeke 1993), to 12 m/s (Ridderinkhof et al., 2000). Comparing these limits with observed wind speeds close to the Dollard (Figure 5.27) suggests that only in January, February, and July significant wave-induced resuspension is expected (using van de Kreeke, 1993 and Ridderinkhof, 2000); based on de Jonge and van Beusekom (1995) significant wave-induced transport is expected throughout the year. Although the model results qualitatively agree with van de Kreeke (1993) and Ridderinkhof (2000)'s criteria, more data is needed to further validate wave-induced resuspension in detail.

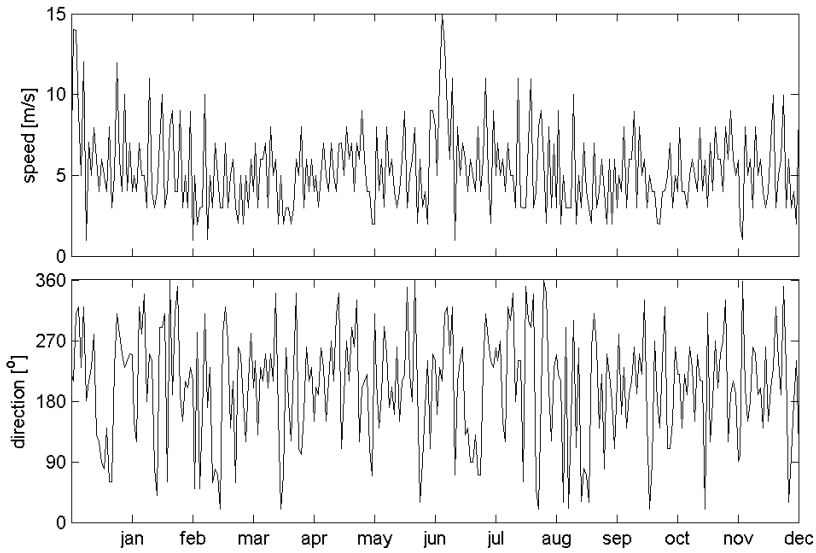

Figure 5.27 Hourly wind speed and direction measured in 2012 at KNMI station Nieuw Beertha (meteorological station closest to the Dollard).

5.3.8 Summary

A comparison of the WED sediment transport model (using the reference settings) with available data reveals that

- The computed suspended sediment concentration matches the observed suspended sediment concentration within a factor 1.5 – 2, but more importantly the along-estuary gradient in suspended sediment concentration is in line with observations (Figure 5.15). The model computes a seasonal variation in suspended sediment concentration which is in agreement with data in some stations (Groote Gat Noord, Bocht van Watum) but seems too pronounced in some other stations (especially towards the outer reaches of the estuary). In these outer reaches, continuous observations are available in the first half of 2012, revealing that the computed intra tidal variation in SSC corresponds to observations.
- The sediment fluxes into the ports of Delfzijl and Eemshaven each differ 25% from dredging requirements (with Eemshaven underestimated and Delfzijl overestimated), but

their combined dredging requirement is the same amount as the computed combined deposition (1.2 million ton/year). Siltation in the Emden navigation channel is underestimated. In order to still reproduce the effect of dredging on the sediment dynamics in the Ems Estuary, sediment is also dredged from the port of Emden, instead of regular re-aeration. Still, this results in 0.6 instead of the observed 1.6 million ton / year in the Emden navigation channel.

- The model does not compute up-estuary residual sediment transport whereas in reality the net up-estuary sediment transport is probably 1.5 million ton/year. This is probably because the model is in dynamic equilibrium, without consolidation of morphological feedback. It leads to an overestimation of the effect of dredged material dispersal on suspended sediment concentration. This overestimation is (partly) compensated by underestimation of disposal quantities (described above). Residual transport resulting from net extraction (such as ports, as part of future scenario studies) is not affected.
- The computed mud distribution is qualitatively in agreement with observations, with a large mud content in the Dollard bay, the degenerate Bocht van Watum, and the Groningen coast. The dynamic bed layer of the model has a higher mud content in the Groote Gat tidal channel compared to adjacent tidal flats, in line with observations.
- The model is in equilibrium, and therefore there are no sediment sinks and residual up-estuary transport. Net sediment sinks and residual sediment transport (import into the estuary) can only be realised by extracting sediment from the estuary.

5.4 Sensitivity analysis

The sediment concentration computed with the numerical model is sensitive to input parameters. These input parameters have an uncertainty range themselves. Some of the input parameters are based on well-known parameters with a clear physical meaning (settling velocity, critical erosion rate) and consequently also the uncertainity ranges of these values are reasonably known. Others, such as the erosion rate or transfer from layer S1 to S2 are poorly known. In this section, the model input values are systematically varied to identify the response of the model to variations. Since the uncertainty range of some of these input parameters is poorly known, also the absolute values of the model variation have limited physical meaning. The purpose of the sensitivity analysis is to identify the trend in the model response (when and where does the sediment concentration increase / decrease) as a function of input parameter variation.

5.4.1 Settling velocity

The soil sampling programme (report 8) suggest that the settling velocity w_s is 1.2 mm/s. Older observations by van Leussen and Cornelisse (1996) reveal a value in-between 0.5 and 4 mm/s (varying over the tidal cycle). Although the time variation is partly the result of flocculation processes, this tidal variation is also strongly influenced by settling of the coarser particles (at low current velocities only slow-settling particles remain in the water column). Therefore the input settling velocities can be constants. In order to verify model response to variations in the settling velocity, w_s has been varied from 0.5 to 2 mm/s (Table 5.6).

Table 5.6 Scenarios for the effect of the settling velocity

Alternative	W_{s1} [mm/s]	W_{s2} [mm/s]
Reference	1.2	0.25
1	1	0.25
2	1.5	0.25
3	2	0.25
4	0.5	0.25
5	1.2	0.1

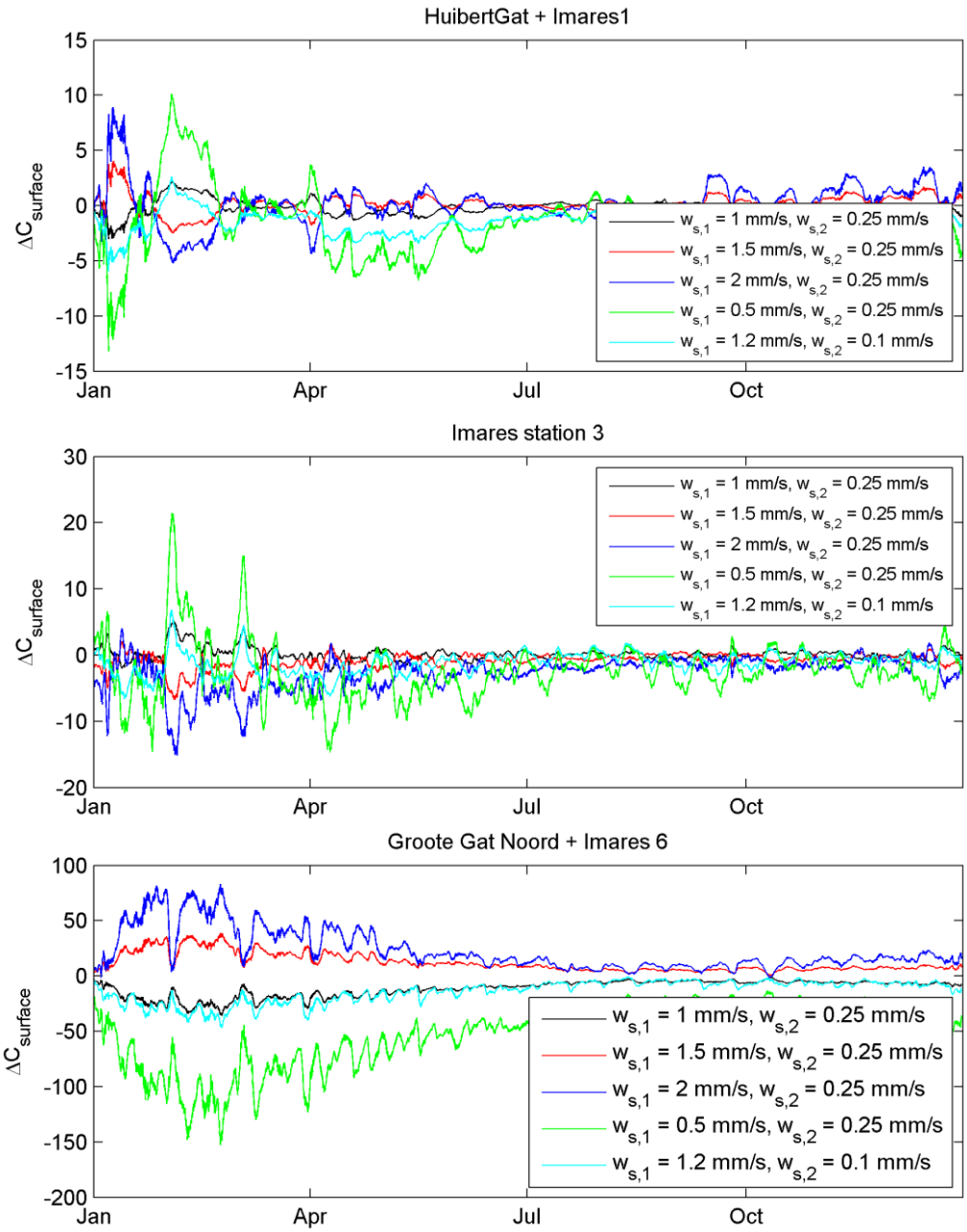

Figure 5.28 Increase in sediment concentration ΔC (relative to the reference simulation, in mg/l) for simulations with variable settling velocities. The sediment concentration is smoothed with a 24-hour running mean

With increasing settling velocity, the sediment concentration in the Dollard becomes substantially larger (Figure 5.28). This is the result of (i) increased sediment trapping by settling lag effects (section 4.3, see also van Maren and Winterwerp, 2013) and (ii) because the intra-tidal variation of sediment with a larger settling velocity is larger than that of particles with a smaller settling velocity (and therefore the peak sediment concentrations are much larger for particles with a large settling velocity). The stations located more seaward (Huibertgat, Imares 3) are much less influenced. Examining the spatially distribution of the yearly averaged suspended sediment concentration (Figure 5.29) reveals that a larger settling velocity especially leads to higher suspended sediment concentrations in shallow areas. Comparing the computed sediment concentrations for alternative 3 (with w_{s1} = 2 mm/s, lower panel in Figure 5.30) with data, reveals that this may provide an equally good or better setting. A low settling velocity (e.g. w_{s1} = 0.5 mm/s, upper panel in Figure 5.30) results in underestimated sediment concentrations (see also Figure 5.11 for comparison). With increasing settling velocity, the up-estuary sediment transport increases slightly (Figure 5.31). Also the sediment transport into the ports increases with settling velocity (see Figure 5.31 and Table 5.7). For the port of Emden, this means an improvement but siltation rates in the port of Delfzijl become too large. Another effect of increasing w_s is that the seasonal variation in sediment concentration, especially in the Dollard, increases. Despite uncertainties in the seasonal variation in SSC in the Dollard (with contrasting observations from the MWTL and the Imares surveys), the seasonal variation using w_{s1} = 2 mm/s seems very high. Therefore w_{s1} = 1.2 mm/s is maintained as a reference value.

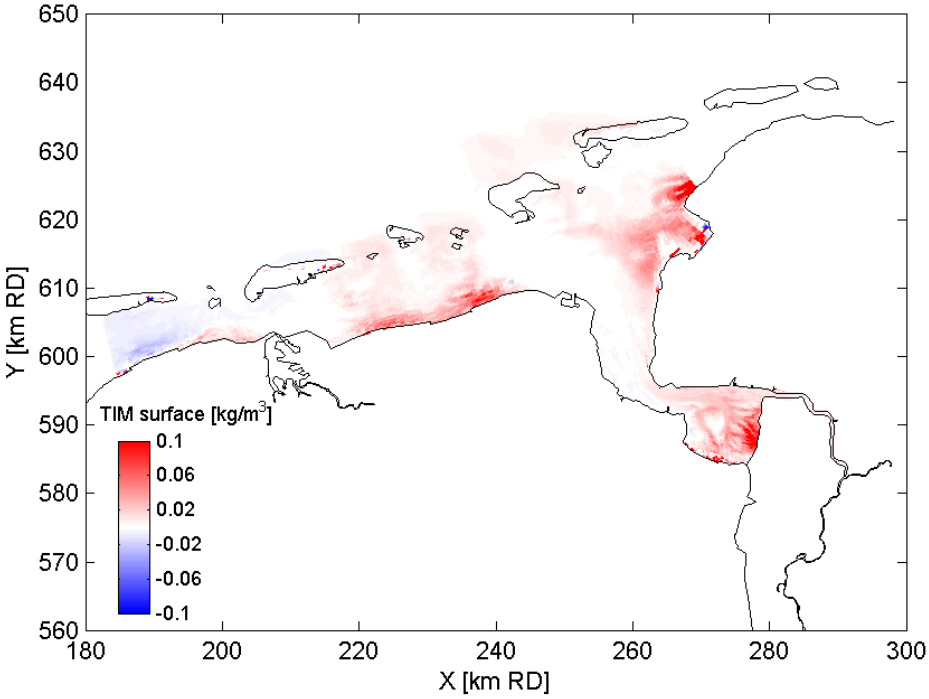

Figure 5.29 Increase in yearly-averaged suspended sediment concentration (in kg/m^3) by increasing the settling velocity for IM1 from 1.2 to 2 mm/s.

Table 5.7 Estimated fluxes (based on net sinks or dredging volumes) and computed fluxes (both in million ton/year); effect of settling velocity

Port / area	Estimated flux	reference	Alt. 1	Alt. 2	Alt. 3	Alt. 4	Alt. 5
Ems Estuary	1.5	-0.12	-0.17	-0.05	0.08	-0.28	-0.20
Eemshaven	0.5	0.44	0.42	0.45	0.46	0.34	0.39
Delfzijl	0.8	0.76	0.71	0.81	0.85	0.49	0.64
Emden port and fairway	1.5	0.55	0.47	0.66	0.83	0.25	0.45
Lower Ems River	0.75	0.08	0.06	0.10	0.13	0.02	0.05

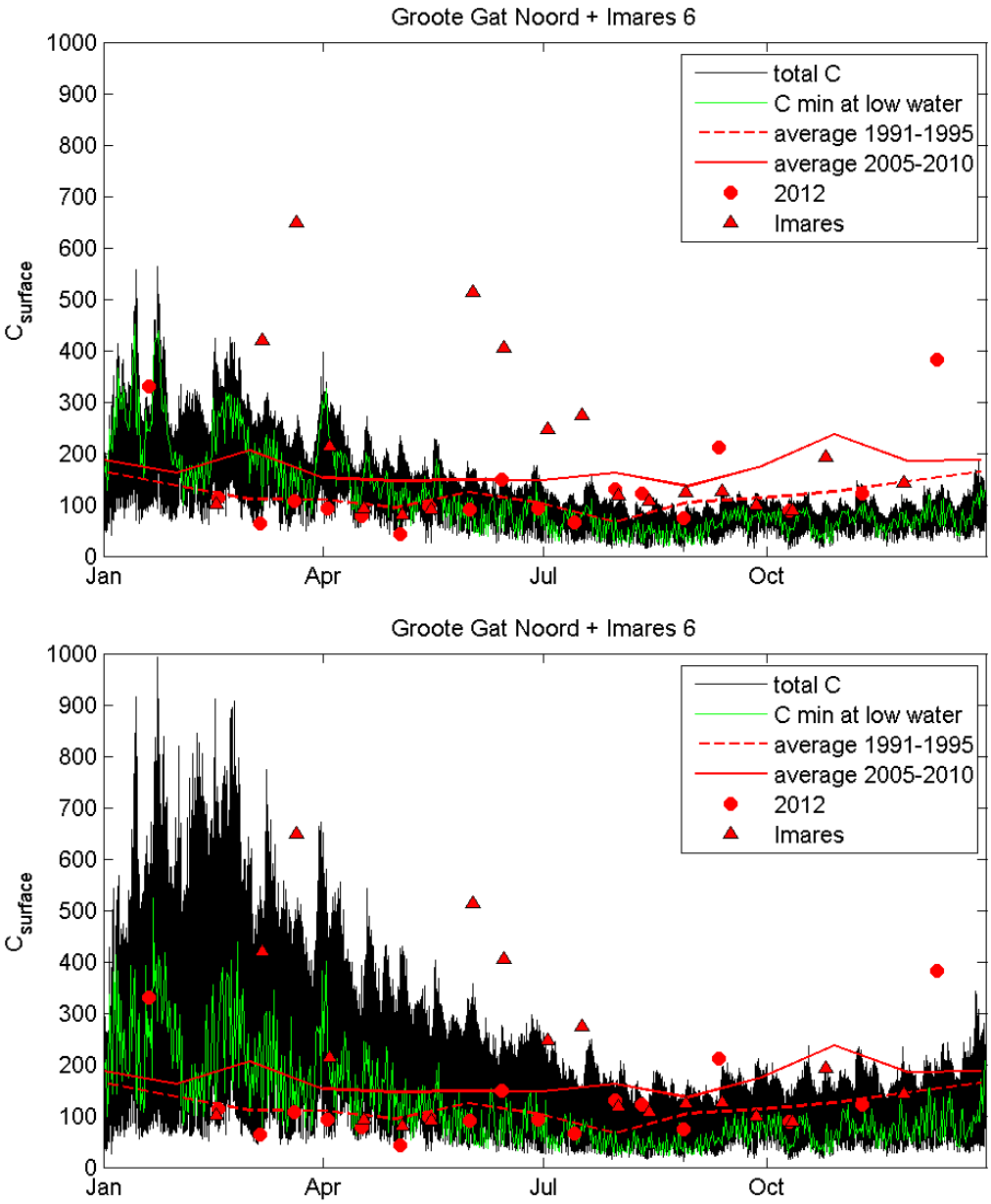

Figure 5.30 Observed and computed suspended sediment concentration (in mg/l) at Groote Gat Noord / Imares 6 for settling velocity alternative 4 (w_{s1} = 0.5 mm/s instead of 1.2 mm/s, top panel) and alternative 3 (w_{s1} = 2mm/s instead of 1.2 mm/s). See also Figure 5.11 for comparison.

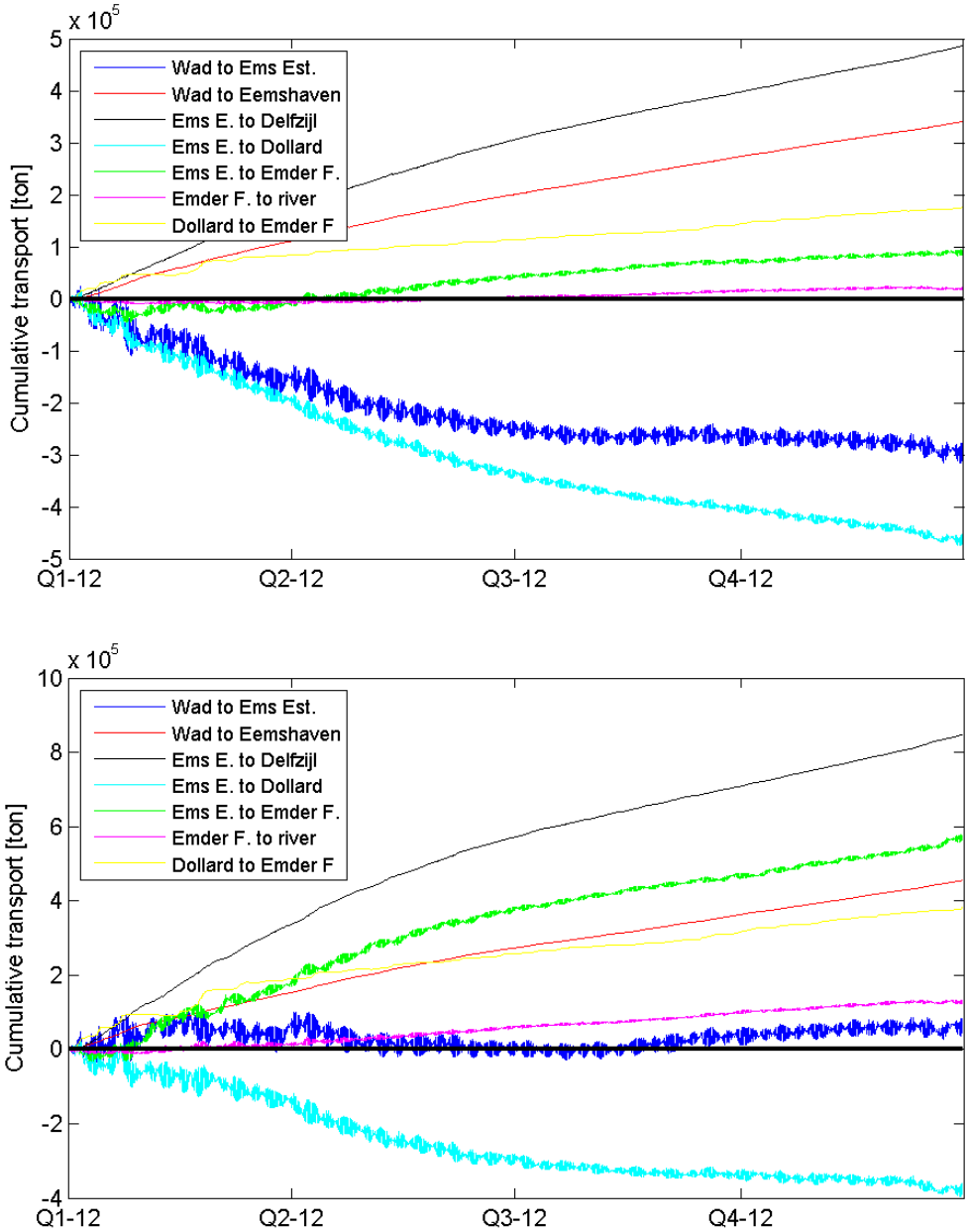

Figure 5.31 Sediment fluxes (up-estuary transport positive) for settling velocity alternative 4 (lower settling velocity IM1, top panel) and alternative 3 (larger settling velocity IM1, lower panel). See also Figure 5.22 for comparison.

5.4.2 Erosion flux

5.4.2.1 Layer S1 erosion

Erosion of the top layer can be modelled as zero-order, defined by erosion as a function of the dimensionless excess bed shear stress and the erosion parameter M_0. Erosion of the top layer can also be computed as first order, where erosion is determined by M_1 and the available amount of sediment, see section 5.2.2. The effect of varying M_0 and M_1 on the sediment dynamics is tested by varying both with a factor 2 (higher or lower, see Table 5.8).

M_0 does not influence the suspended sediment concentration (Figure 5.32), implying that throughout the model the erosion is first order (as expected, see section 5.2.3). Increasing (decreasing) M_1 with a factor 2 typically leads to several 10 to 20 mg/l higher (lower) sediment concentration within the estuary, especially in summer. During storm conditions M_1 has an opposite effect (especially near the estuary mouth at Huibertgat): a larger M_1 leads to lower sediment concentrations. This is caused by depletion of the sediment bed of the Wadden Sea and North Sea bed during low-energy conditions, resulting in a smaller sediment availability in layer S1 and in layer S2 during storm conditions (Compare the available amount of sediment in S2 for the reference conditions in Figure 5.25 with the smaller mud content in Figure 5.35 computed with a larger M_1). A larger M_1 further reduces the mud availability in the intertidal areas in the Wadden Sea (Figure 5.35) which were already low (50 kg/m^3) and should therefore not be any lower than the reference simulation. On the other hand, more erosion also leads to higher suspended sediment concentration, increasing the sediment concentration at Groote Gat with 20 mg/l (Figure 5.32), more in agreement with observations (compare Figure 5.33 with Figure 5.11).

For a larger M_1, the sediment export from the Ems estuary increases (Table 5.9) whereas for a lower value, the estuary is slightly importing (Table 5.9 and Figure 5.34). This is probably the result of non-equilibrium: after 5 years the model has not yet fully adapted to the larger erosion rate, and is therefore still eroding, resulting in sediment export (and vice versa for the lower erosion rate). Siltation is not so much affected by erosion rates: the ports are probably near-perfect sediment traps where most incoming sediment remains deposited. Hence, deposition rates in the ports are primarily determined by the ambient sediment concentration. Since the sediment concentration is lower for lower erosion rates, the sediment deposition rates in the ports are lower as well.

Table 5.8 Scenarios for S1 erosion settings: values relative to the reference scenario (see Table 5.1)

Scenario	M_0	M_1
reference	$2.5\ 10^{-3}$	$1.2\ 10^{-4}$
1	2x larger	1x
2	2x smaller	1x
3	1x	2x larger
4	1x	2x smaller

Conclusively, using a larger M_1 slightly increases the computed suspended sediment concentration in the Dollard during summer conditions (in line with observations), and makes the model less sensitive to storm conditions in the outer estuary. It is not known whether such a lower response to storm conditions is realistic or not. An important drawback of increasing M_1 is that the intertidal areas of the Wadden Sea become depleted of sediment, which is not in agreement with observations. Therefore the reference model settings for S_1 erosion are maintained.

Table 5.9 Estimated fluxes (based on net sinks or dredging volumes) and computed fluxes (both in million ton/year); effect of S1 erosion

Port / area	**Estimated flux**	**reference**	**Alt. 1**	**Alt. 2**	**Alt. 3**	**Alt. 4**
Ems Estuary	1.5	-0.12	-0.12	-0.12	-0.29	0.13
Eemshaven	0.5	0.44	0.44	0.44	0.46	0.40
Delfzijl	0.8	0.76	0.76	0.76	0.85	0.64
Emden port and fairway	1.5	0.55	0.55	0.55	0.64	0.44
Lower Ems River	0.75	0.08	0.08	0.08	0.04	0.13

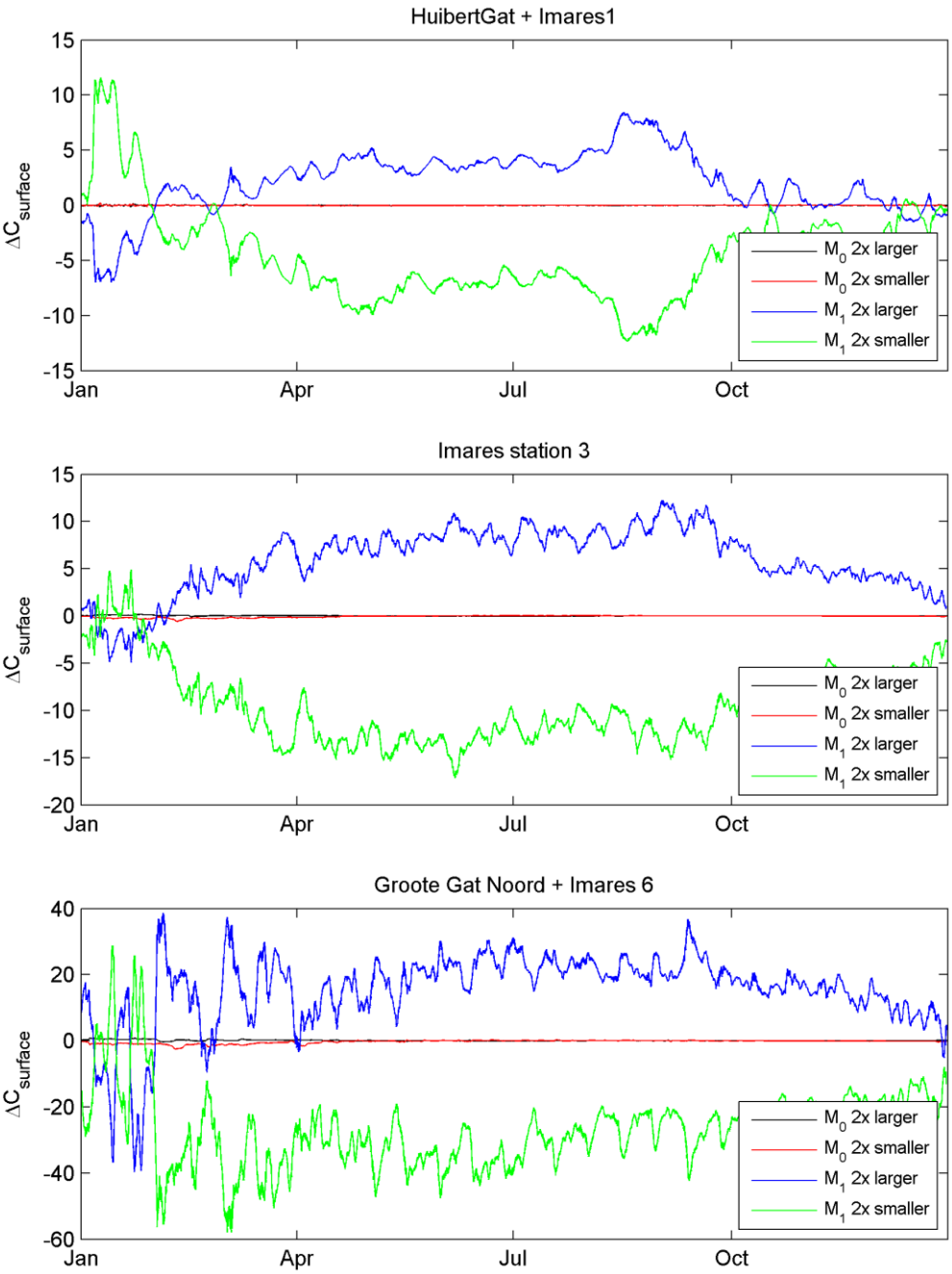

Figure 5.32 Increase in sediment concentration ΔC (relative to the reference simulation, in mg/l) for simulations with 2x larger and lower values for M_0 and M_1; stations Imares 1 (Huibertgat), Imares 3, and Imares 6 (Groote Gat). The sediment concentration is smoothed with a 24-hour running mean.

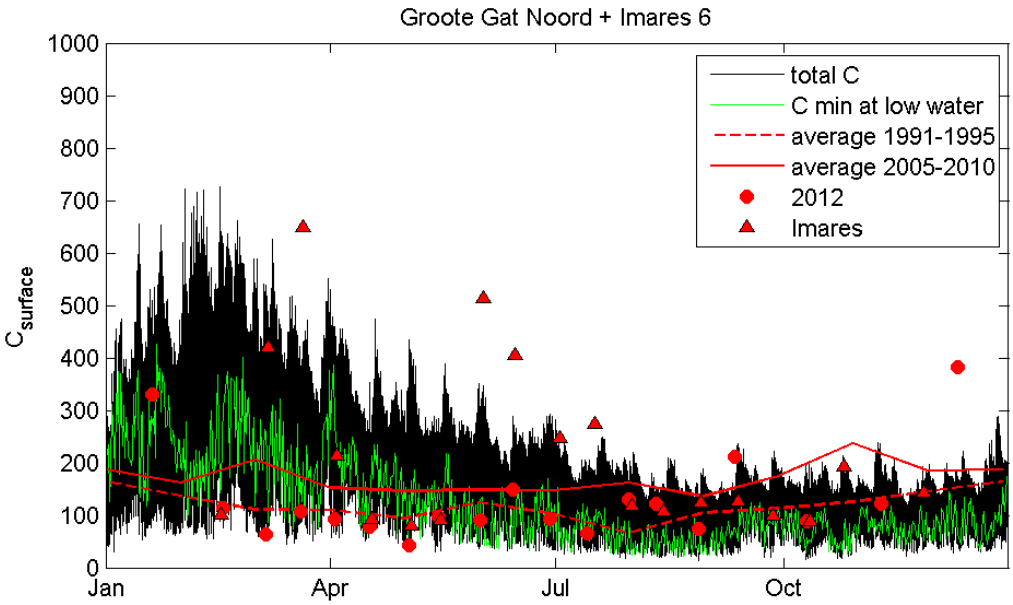

Figure 5.33 Observed and computed suspended sediment concentration (in mg/l) at Groote Gat Noord / Imares 6 for S_1 erosion alternative 3 (M1 2 times larger).

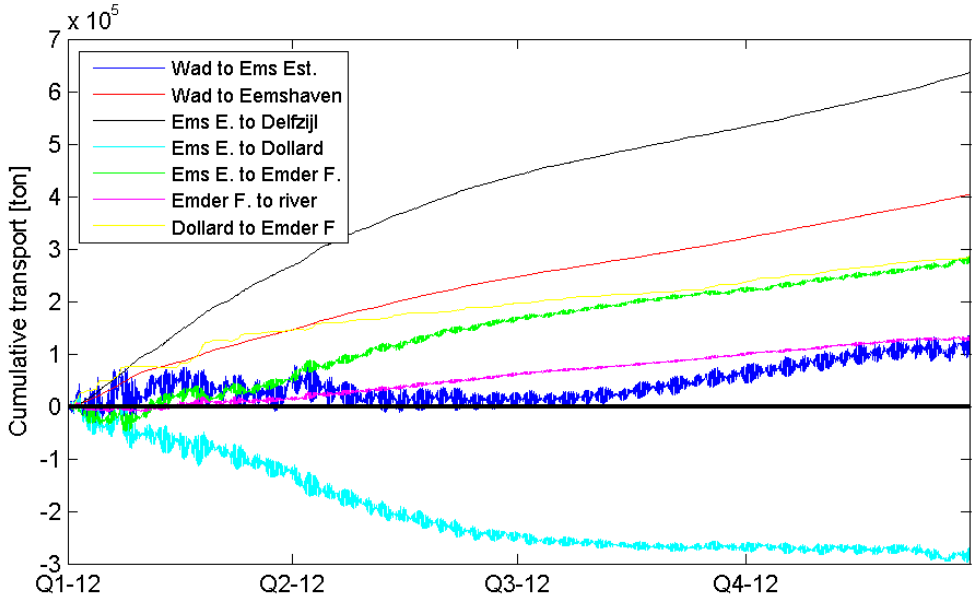

Figure 5.34 Sediment fluxes (up-estuary transport positive) with a 2x smaller value for M_1.

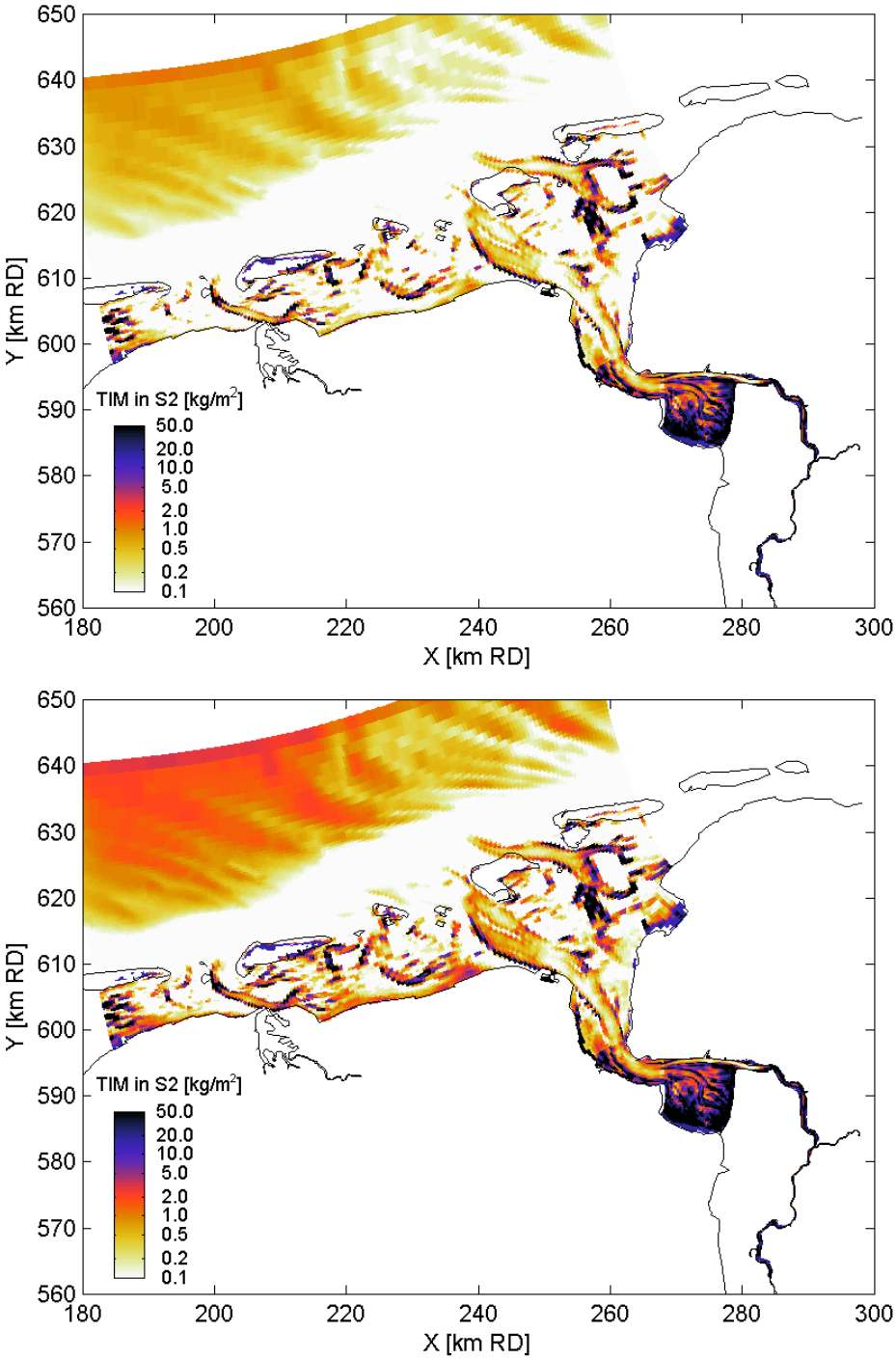

Figure 5.35 Computed sediment mass in layer S_2, using a 2 times larger (top panel) and smaller (lower panel) M_1 (for both IM1 and IM2).

5.4.2.2 *Layer S_2 erosion*

Erosion of layer S_2 is determined by the critical bed shear stress $\tau_{cr,2}$ and the erosion rate parameter M_2. In order to investigate the effect of both parameters, 5 scenarios are defined in which model response to variations in $\tau_{cr,2}$ (scenario 1 -3) and M_2 (scenario 4 - 5) are tested (Table 5.10). Increasing the erosion of the bed (by decreasing $\tau_{cr,2}$ from 0.9 to 0.5 Pa (alternative 1) or increasing M_2 with a factor 2 (alternative 4)) leads to larger suspended sediment concentrations throughout the estuary (Figure 5.36). Near Huibertgat, this increase is mainly during summer (with a reduced response to winter storms, similar to the effect of increasing M_1). In the Dollard (Groote Gat) this increase is largest, and mainly during winter. The suspended sediment concentrations computed with the reference settings in the Dollard is already sufficiently high during winter conditions, and therefore increasing erosion is not an improvement. Reduction of erosion of S_2 (by increasing $\tau_{cr,2}$ to 1.2 or 1.5 Pa or lowering M_2 with a factor 2) leads to lower suspended sediment concentrations (Figure 5.36).

Table 5.10 Scenarios for S_2 erosion settings: erosion rate M_0 relative to the reference scenario (see Table 5.1).

Scenario	$\tau_{cr,2}$	M_2
reference	0.9	6 10^{-5}
1	0.5	1x
2	1.5	1x
3	1.2	1x
4	0.9	2x larger
5	0.9	2x smaller

Stronger erosion (alternative 1 and 4) leads to more deposition in the ports (Table 5.11) because more sediment is available (for deposition in the ports). The ports are efficient sediment traps, and therefore more erosion does not lead to more resuspension from sediment deposited in the ports. As already discussed for erosion of layer 1, the model with larger bed erosion is still not in full equilibrium after 5 years, resulting in export from the estuary. Sediment supplied to the ports decreases with less erosion (alternative 2, 3, and 5) and therefore sediment deposition in the ports decreases. None of alternative 1-5 seems to lead to an overall improvement of port siltation rates. Since port siltation and suspended sediment concentration do not improve with variations in S_2 erosion settings, the response of bed sediment distribution to S_2 settings are not evaluated.

Table 5.11 Estimated fluxes (based on net sinks or dredging volumes) and computed fluxes (both in million ton/year); effect of S_2 erosion

Port / area	**Estimated flux**	**reference**	**Alt. 1**	**Alt. 2**	**Alt. 3**	**Alt. 4**	**Alt. 5**
Ems Estuary	1.5	-0.12	-0.30	0.19	0.09	-0.20	-0.03
Eemshaven	0.5	0.44	0.44	0.34	0.38	0.45	0.42
Delfzijl	0.8	0.76	0.85	0.43	0.55	0.82	0.67
Emden port and fairway	1.5	0.55	0.64	0.30	0.38	0.60	0.48
Lower Ems River	0.75	0.08	0.06	0.05	0.06	0.08	0.07

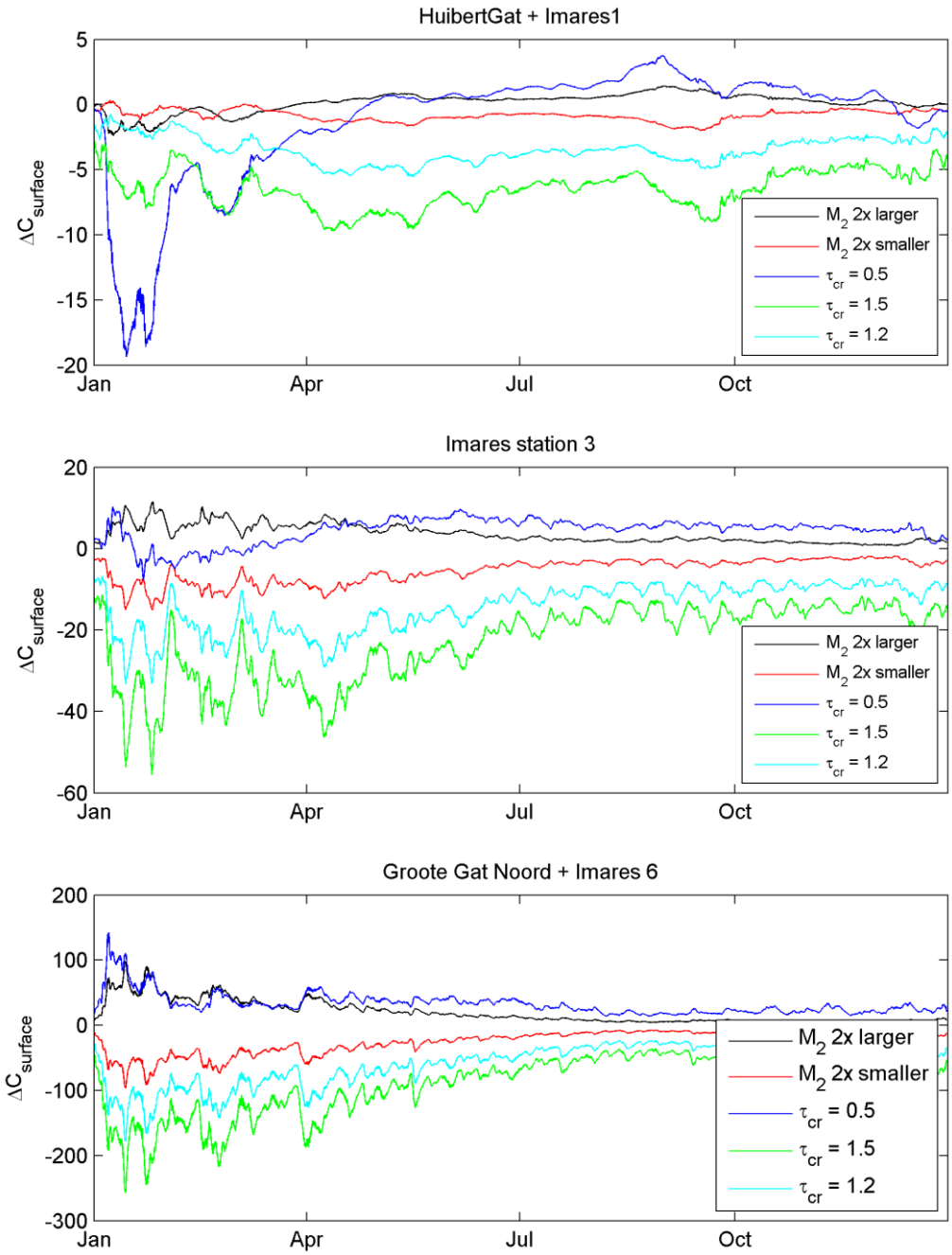

Figure 5.36 Increase in sediment concentration ΔC (relative to the reference simulation, in mg/l) for simulations with 2x larger and smaller values for M_2 and higher and lower values for $\tau_{cr,2}$. The sediment concentration is smoothed with a 24-hour running mean.

Summarizing, the erodability of S_2 influences sediment fluxes and sediment concentration, but does not lead to an improvement. The reference settings for the erosion of S_2 are not adapted.

5.4.3 Other settings for the S_2 layer

In addition to its erosion settings (described above), also the thickness of the S_2 layer and the deposition flux from the water column to S_1 and S_2 influences suspended sediment dynamics are evaluated. The distribution of the deposition flux to layer S_1 and to S_2 is investigated by using a higher and smaller α (Table 5.12).The impact of the thickness of the S_2 layer is evaluated by comparing a thicker and thinner layer with the reference settings (see also Table 5.12).

Table 5.12 Scenarios for the buffer layer thickness (see Table 5.1 for the complete reference settings).

Scenario	α [m]	Thickness S_2 [m]
reference	0.1	0.1
1	0.05	0.1
2	0.2	0.1
3	0.1	0.2
4	0.1	0.05

Increasing the sediment deposition flux to layer S_2 (using a larger α) lowers the suspended sediment concentration throughout the estuary (Figure 5.37) except for Huibertgat during storm conditions. Increasing the thickness of S_2 also leads to lower suspended sediment concentrations as well, but the response to storms is different compared to increasing α (also during storm conditions the sediment concentrations decrease). For a thinner buffer layer, the sediment concentration within the Ems Estuary increases (especially in the Dollard), but decreases closer to the North Sea (Huibertgat): see Figure 5.37. As discussed earlier in the section on erosion settings, this is the result of fine sediment depletion in the North Sea and Wadden Sea: too little sediment is available for erosion during storm conditions. The sediment deposition patterns are very similar for α = 0.2 and thickness S_2 = 0.2 metre (Figure 5.38 and Figure 5.39) (and for α = 0.05 and thickness S_2 = 0.05 metre).

None of these variations relative to the reference simulation leads to an improvement, and therefore the reference simulation is not modified.

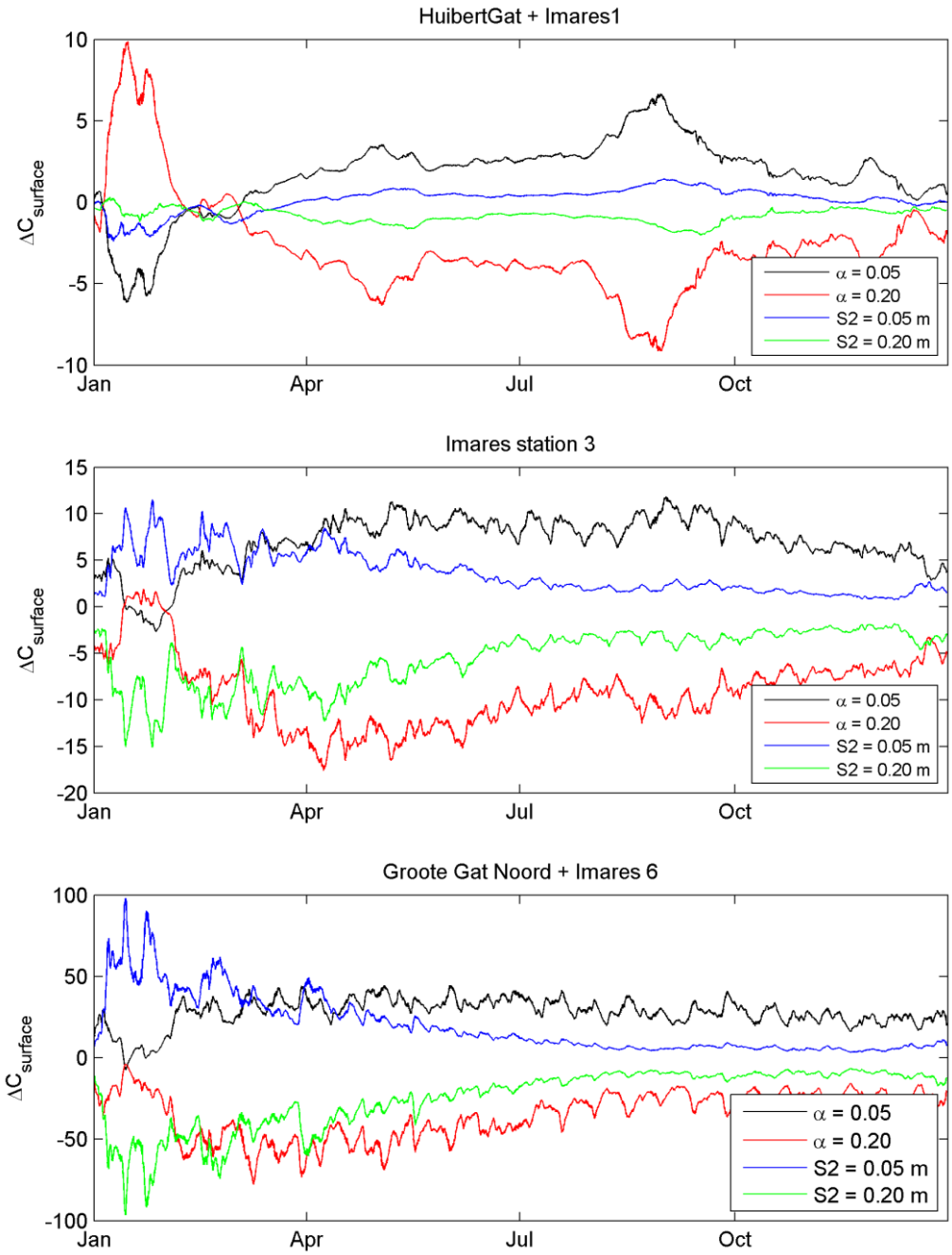

Figure 5.37 Increase in sediment concentration ΔC (relative to the reference simulation, in mg/l) for simulations with a thicker and thinner S_2 layer. The sediment concentration is smoothed with a 24-hour running mean.

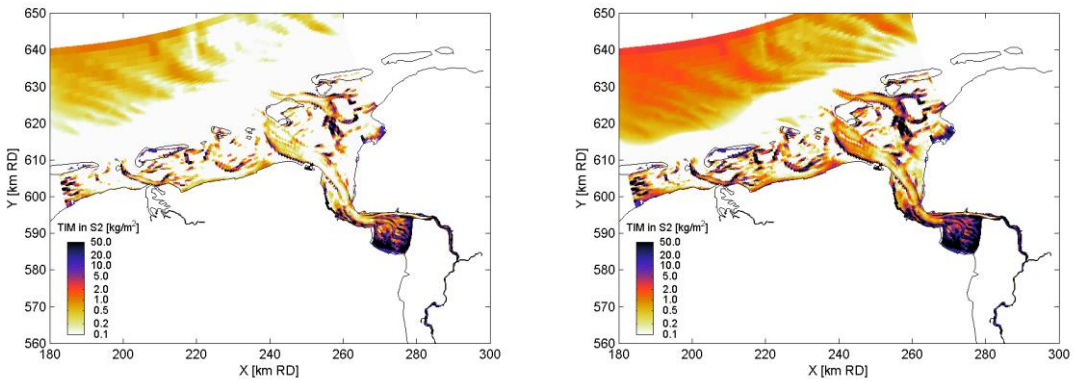

Figure 5.38 Available mass of sediment in layer S2 for a thickness of 5 cm (left) and 20 cm (right)

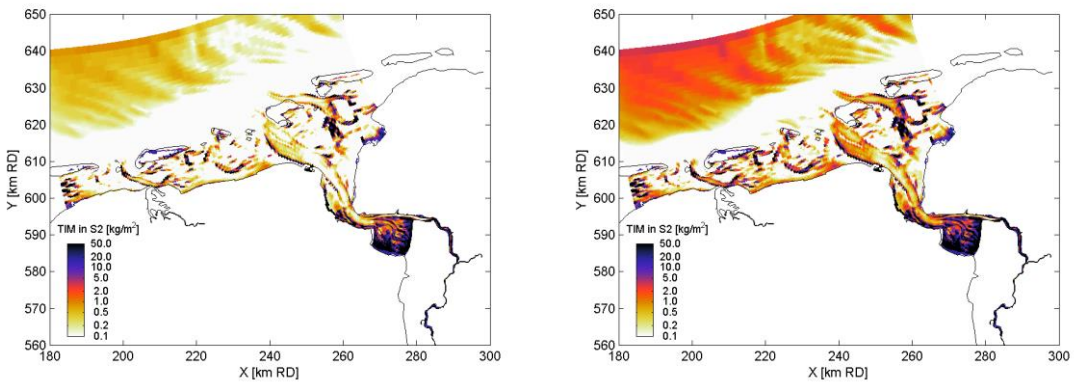

Figure 5.39 Available mass of sediment in layer S2 for a α = 0.05 (left) and α = 0.20 (right)

5.4.4 Seasonal effects: waves and freshwater discharge

Both salinity and wave forcing influence the seasonal variation of SSC. The large sediment concentrations observed and computed in the Dollard in the first half year (Figure 5.11) seem to be more affected by salinity from river discharge (see report 4 and Figure 5.40) than by wave height (Figure 5.41). This suggests a dependence on salinity-driven estuarine circulation, transporting sediment up-estuary. Therefore the model has also been run in barotropic mode (without salinity, but with equal other settings in the hydrodynamic and sediment transport model). The resulting sediment concentration in the Dollard (lower panel in Figure 5.42) is much lower compared to the reference simulation (Figure 5.11). Without salinity, the sediment concentration peaks computed in January to April at Groote Gat (lower panel in Figure 5.42) seem to vary more directly with wave height (Figure 5.41) than the sediment concentration peaks computed with the reference settings (Figure 5.11).

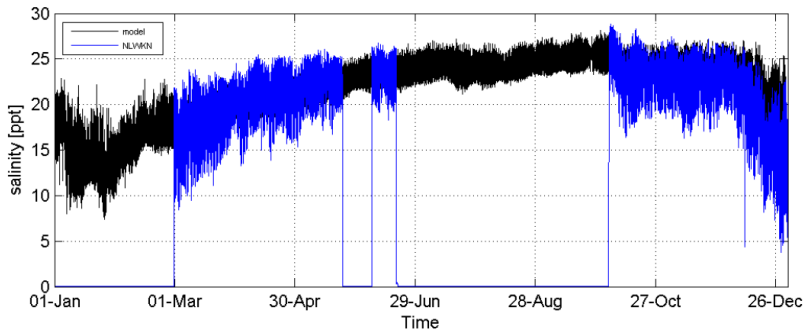

Figure 5.40 Computed and observed salinity at Knock, from report 4.

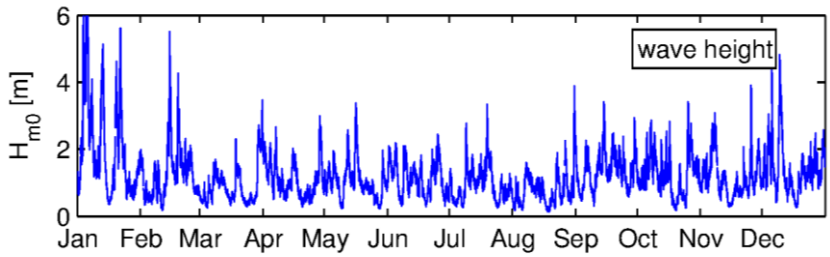

Figure 5.41 Time series of wave height measured at the Schiermonnikoog-Noord buoy in 2012, from report 4.

The dependency of suspended sediment concentration on salinity implies that estuarine circulation is important for transport of fine sediment. Because of estuarine circulation, a pronounced near-bed landward-directed current exists throughout the deeper parts of the tidal channels (see Figure 5.43). Without salinity, the average sediment concentration in the entire estuary decreases, most pronounced in the Dollard (Figure 5.44).

In contrast with Groote Gat, the sediment concentration computed for Huibertgat has changed much less: compare Figure 5.14 with the upper panel in Figure 5.42. Also the seasonal variation in sediment concentration is still pronounced. This is related to wave-induced resuspension (see Figure 5.45), because the wave height is larger in the winter months in general, but especially in January (see Figure 5.41).

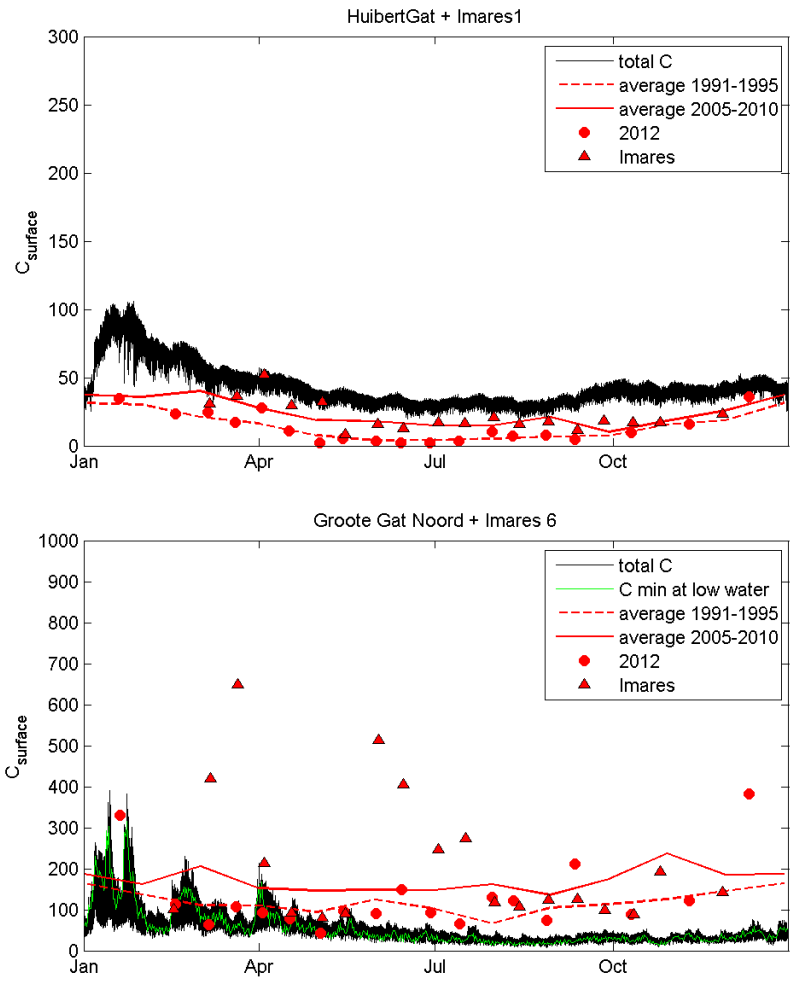

Figure 5.42 Observed and computed surface suspended sediment concentration (in mg/l) at station Huibertgat / Imares 1 and Groote Gat Noord / Imares 6, without salinity

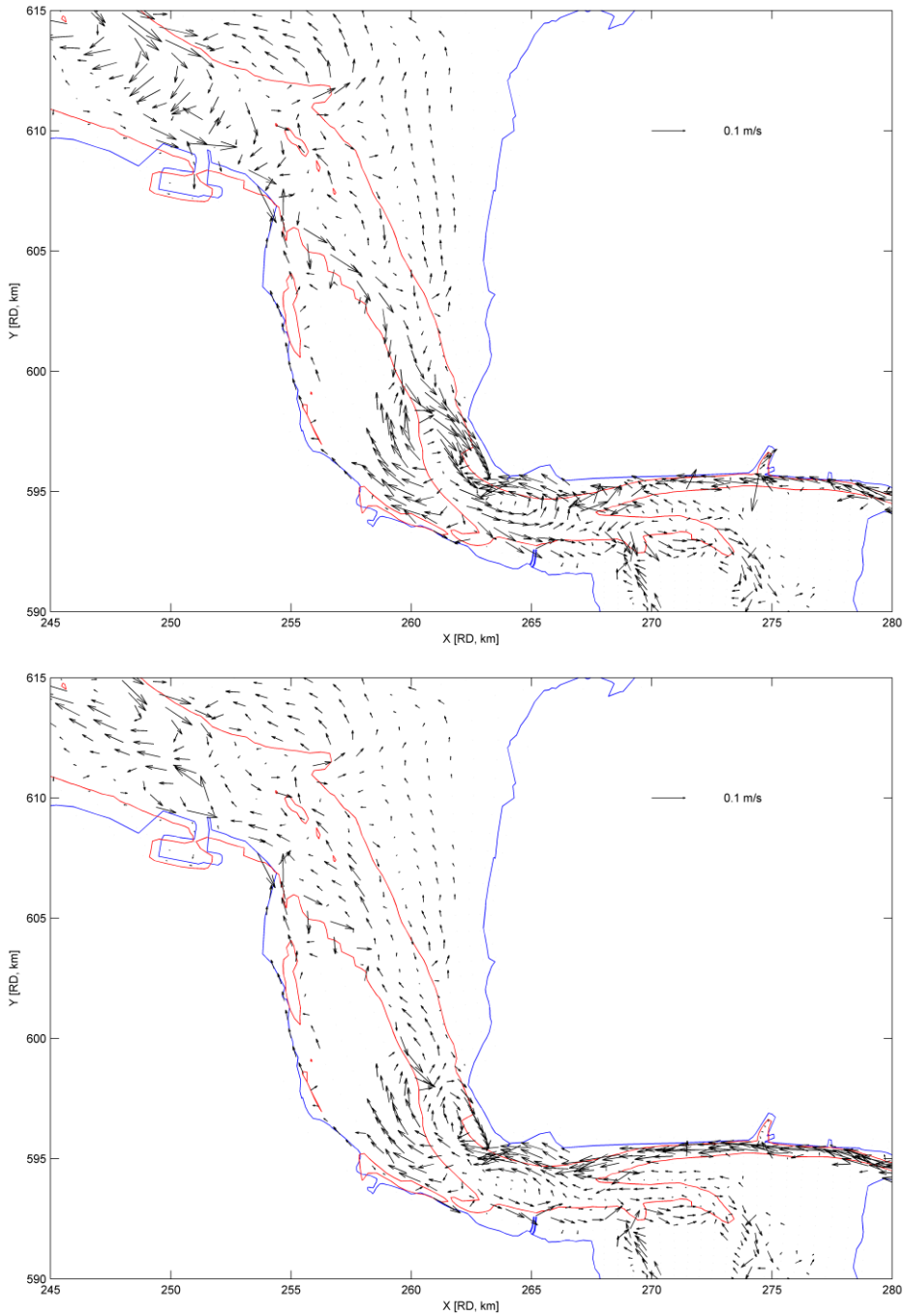

Figure 5.43 Computed near-bed residual flow velocity in January 2012, for bed levels at least 1 m below NAP, with (top) and without salinity effects. The red line is the 6 m depth contour.

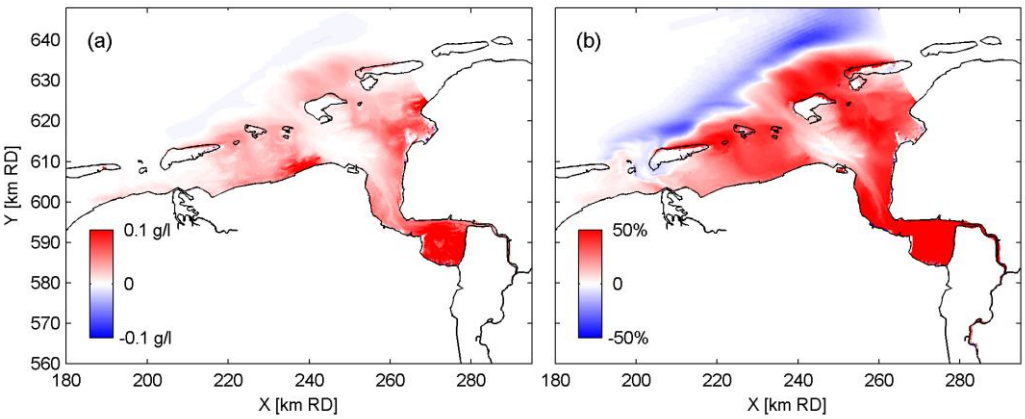

Figure 5.44 Absolute (a, in g/) and relative (b, in %) decrease in yearly averaged suspended sediment concentration relative to the reference scenario by running the model in barotropic mode (compared to baraclinic mode): without density effects the suspended sediment concentrations are much lower.

This leads to the following hypothesis for the mechanisms responsible for the modelled seasonal variation in sediment concentration. Waves resuspend sediment in the winter months, leading to a large availability of sediment and hence sediment concentration at the mouth of the Ems Estuary in January to March. This sediment is subsequently transported up-estuary by salinity-induced residual circulation. The importance of salinity-induced residual circulation is supported by (1) the strong reduction in sediment concentration for simulations excluding salinity (compare Figure 5.11 with the lower panel in Figure 5.42), and (2) the landward-directed near-bed residual flow velocity (Figure 5.43). An important consequence of such a prominent role of salinity-driven circulation is that the model is sensitive to the depth of the tidal channels in the Ems Estuary (estuarine circulation scales with h^3; Hansen and Rattray, 1965).

The wave-induced bed friction is probably much lower for smooth bed conditions, typical for mud-dominated areas, than for their sandy equivalents. However, wave-induced bed friction formulations for mud beds do not yet exist. As an alternative, the SWAN settings used in the hydrodynamic model (report 4) have been modified in such a way that the wave-induced bed shear stress in shallow areas is fairly low, lower then would be obtained with standard SWAN settings. The effect of wave-induced bed friction on sediment dynamics is evaluated hereafter by comparing simulations using (1) no waves, (2) half default SWAN wave-induced bed shear stress, and (3) SWAN default bed shear stress, with the reference settings (using a relatively low wave-induced bed shear stress. Their effect is evaluated on the sediment concentration (Figure 5.45) and bed sediment distribution (Figure 5.46).

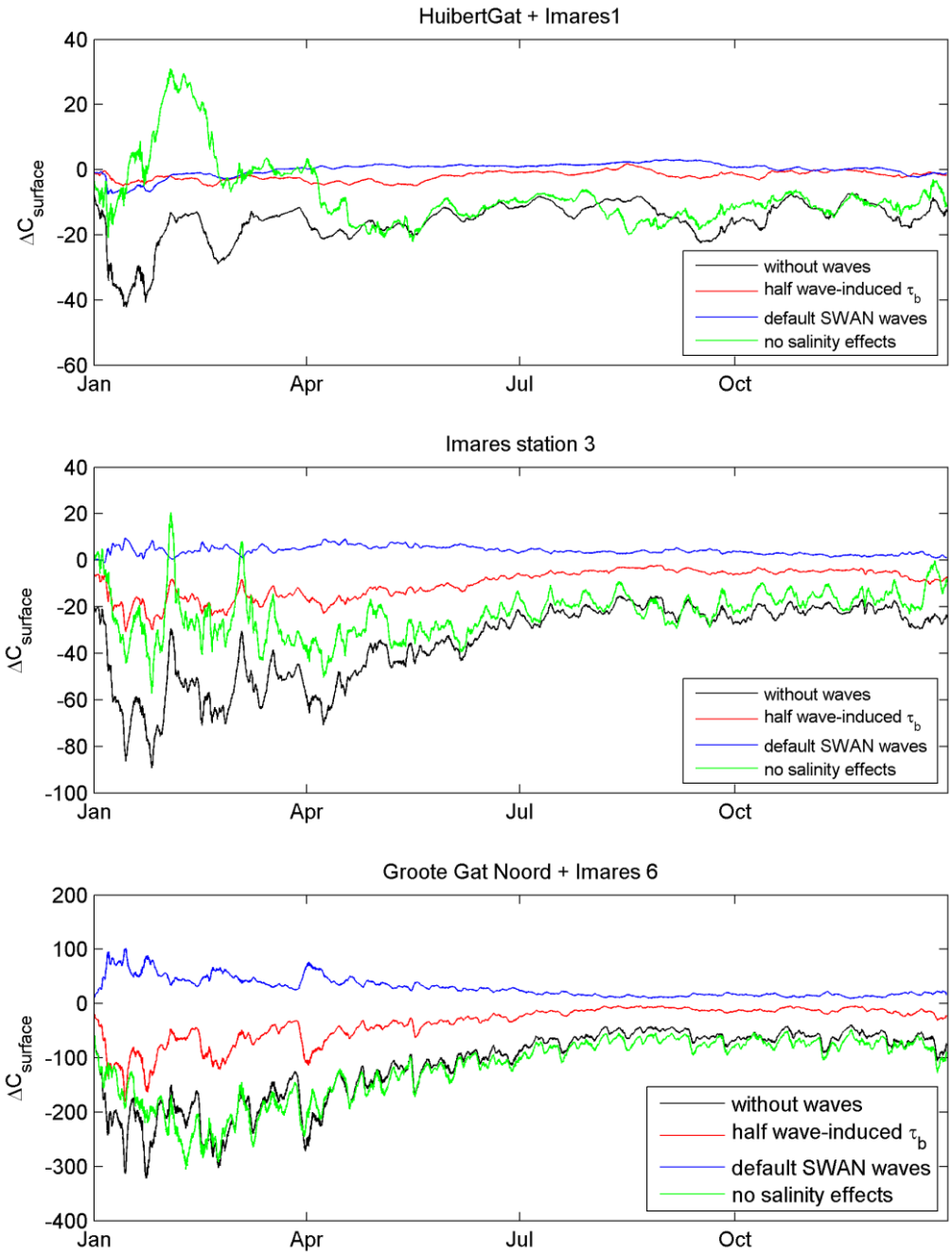

Figure 5.45 Increase in sediment concentration ΔC (relative to the reference simulation, in mg/l) for simulations without waves, simulations with reduced wave-induced bed shear stress, and for default SWAN settings.

Without wave-induced bed shear stress the overall sediment concentrations become low throughout the estuary (Figure 5.45): concentrations drop to levels of several 10's of mg/l. It should be realised though that running the model without waves would require a complete recalibration of the sediment transport model, with much larger erosion rates, which has not been undertaken here. Using the default settings of SWAN (and the reference sediment transport model settings), the sediment concentrations in the Dollard are much larger (several 100 mg/l). The default SWAN settings probably overestimate the bed shear stress in shallow

(intertidal) areas (see the previous section), leading to low sedimentation rates in the Wadden Sea (Figure 5.46). This was the main argument to adapt the settings of the SWAN model (see report 4). The most realistic bed sediment distribution is computed using only half of the wave-induced bed shear stress. Several 10's of kg/m^2 are deposited in the top 10 cm of the Wadden Sea, compared to ~5 kg/m^2 using the reference settings (Figure 5.25). The sediment concentration, however, is also substantially lower (Figure 5.45), because the lower bed shear stress should be compensated with a larger erosion rate. Increasing the suspended sediment concentration to more realistic levels would require a recalibration, probably leading to lower bed sediment content in the Wadden Sea.

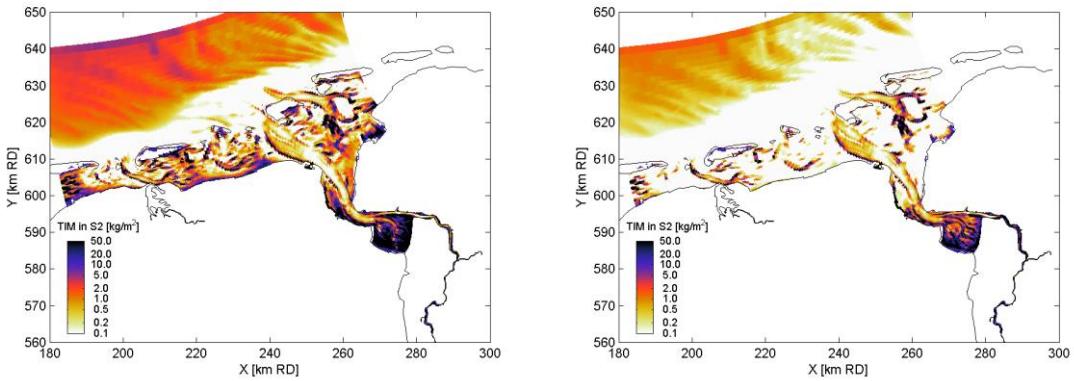

Figure 5.46 Available mass of sediment in layer S2 for half wave-induced bed shear stress (left) and with default SWAN settings (right).

The modelled effect of waves and salinity-induced residual flows can be summarised as follows. Sediment is resuspended in January at the mouth of the Ems Estuary by waves, generating a period of several months where sediment concentrations are large. This sediment is transported into the estuary by estuarine circulation, leading to high sediment concentrations in the Dollard area. In order for sediment to accumulate in the Wadden Sea, modified settings of the SWAN wave model were applied: the bed shear stress is too large using default SWAN settings, resulting in overestimated resuspension of the intertidal areas.

5.4.5 Summary model sensitivity

None of the alternatives to the reference settings (section 5.3) improves the combination of suspended sediment concentration, spatial distribution of mud and port siltation. Therefore the reference settings remain the best representation of the estuarine suspended sediment dynamics, and will be used to model 2013 as well (section 5.5). The model sensitivity to the main input parameters is given below.

The settling velocity influences the along-estuary concentration gradient, especially on the tidal flats. Increasing the settling velocity leads to a more pronounced estuarine concentration gradient. For w_s = 2 mm/s, the sediment concentration on the flats increases, whereas the sediment concentration in the channel is only slightly affected. For a low settling velocity (0.5 mm/s) the sediment becomes more uniformly distributed throughout the estuary. Based on the available sediment concentration data (which have limited time-coverage and introduce inaccuracies as well) it is difficult to determine which value for w_s is more realistic. A value of 1.2 mm/s is used to best reflect the settling velocity obtained from the bed samples.

The values for critical bed shear stress τ_{cr} resulting from the bulk soil parameters (report 8; 1-2 Pa) appeared to be too high to correctly reproduce the sediment dynamics. These values for τ_{cr} are based on the Plasticity Index (and therefore clay content, of the material), which is derived for consolidated material: most samples were in reality poorly consolidated. Therefore a lower value for τ_{cr} was used (0.9 Pa). The critical bed shear stress influences the sensitivity of the model to high energy conditions. With larger τ_{cr}, sediment is only resuspended during energetic events (spring tides, storms). In order to balance the suspended sediment concentration, the erosion parameter M_2 may be set to (very) high values. The net effect of high τ_{cr} combined with high M_2 is that erosion is spatially and temporarily rapidly fluctuating. Smooth erosion behaviour, using lower values for both τ_{cr} and M_2, is more realistic, resulting in a more gradual transition between mud and sand observed in nature.

5.5 Model validation

The model is validated by applying the reference model settings to the hydrodynamics of 2013 (see report 4 for the hydrodynamic validation), comparing the computed suspended sediment concentration with observations, and assessing the computed fluxes and siltation rates.

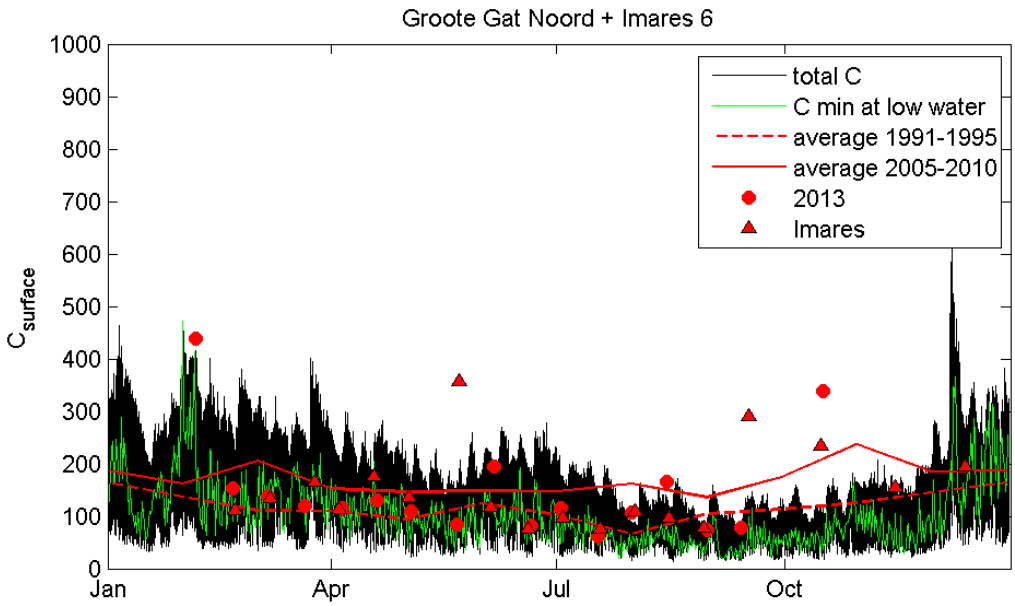

Figure 5.47 Observed and computed surface suspended sediment concentration in 2013 at station Groote Gat Noord / Imares 6 (in mg/l). The MWTL observations are red dots, with red lines representing 5-year average values of MWTL data in the period 1991-1995 (dashed) and 2005-2010 (solid). The Imares observations are red triangles. Model results (reference settings) are denoted with the black line, with the green line representing the sediment concentration at low water (corresponding to the period the MWTL measurements were taken).

At Groote Gat, the computed suspended sediment concentration in 2013 (Figure 5.47) is lower in the first half year compared to 2012 (Figure 5.11). This difference is supported by the Imares observations, which are much lower in 2013 as well (at levels comparable to the MWTL observations, unlike 2012). It was argued in section 5.4 that the sediment

concentration at station Groote Gat are high because sediment is resuspended by waves (mainly in the seaward part of the estuary) and brought up-estuary by estuarine circulation. In 2013, the river discharge (and salinity) was very similar to 2012 (see report 4). However, the wave height during the winter (January – March) was much lower in 2013 (see Figure 5.48): only one storm with H_s > 4 m was registered at the Schiermonnikoog-Noord buoy against five in 2012.

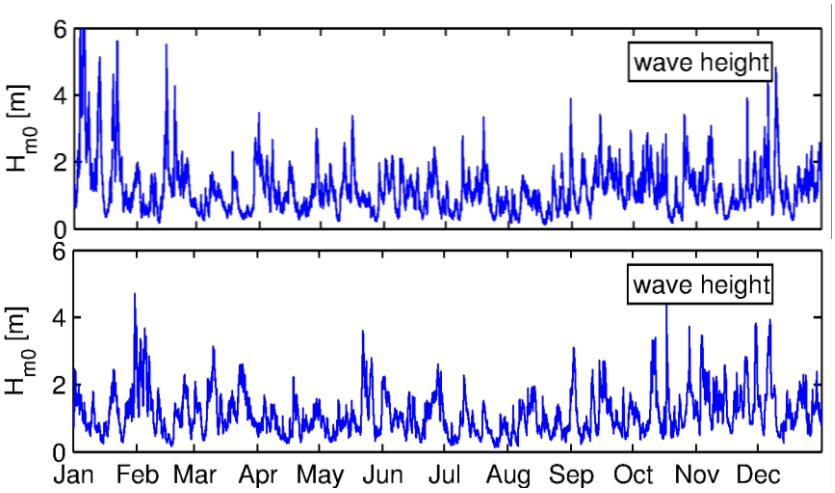

Figure 5.48 Time series of wave height measured at the Schiermonnikoog-Noord buoy in 2012 (top) and 2013 (below), from report 4.

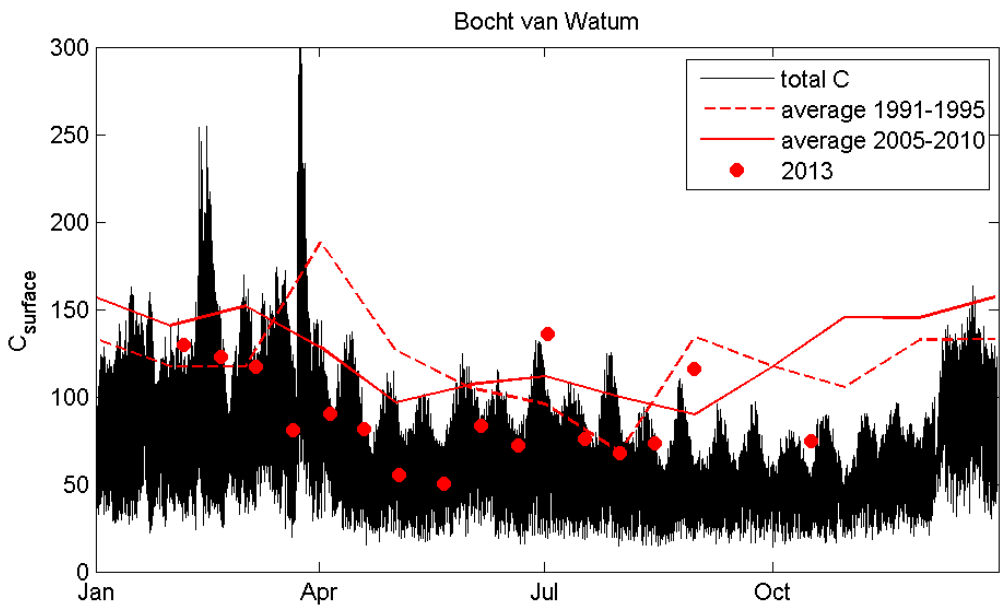

Figure 5.49 Computed (reference settings) and observed surface sediment concentration in 2013 at MWTL station Bocht van Watum (in mg/l). The 2012 observations are red dots, with red lines representing 5-year average values of MWTL data in the period 1991-1995 (dashed) and 2005-2010 (solid).

In the Bocht van Watum, the computed sediment concentration is also higher in the winter of 2012 (Figure 5.12) than in 2013 (Figure 5.49). The observed sediment concentrations in the winters of 2012 and 2013 are similar, however. The observed sediment concentration is slightly larger in the summer (June-September) of 2013 than in 2012. The computed

sediment concentration is the same for 2012 and 2013. The reason for the slightly higher observed 2013 sediment concentrations is unknown, and is (therefore) not computed by the model. However, for both 2012 and 2013, most of the observed suspended sediment concentrations are within the intra-tidal variation computed with the model.

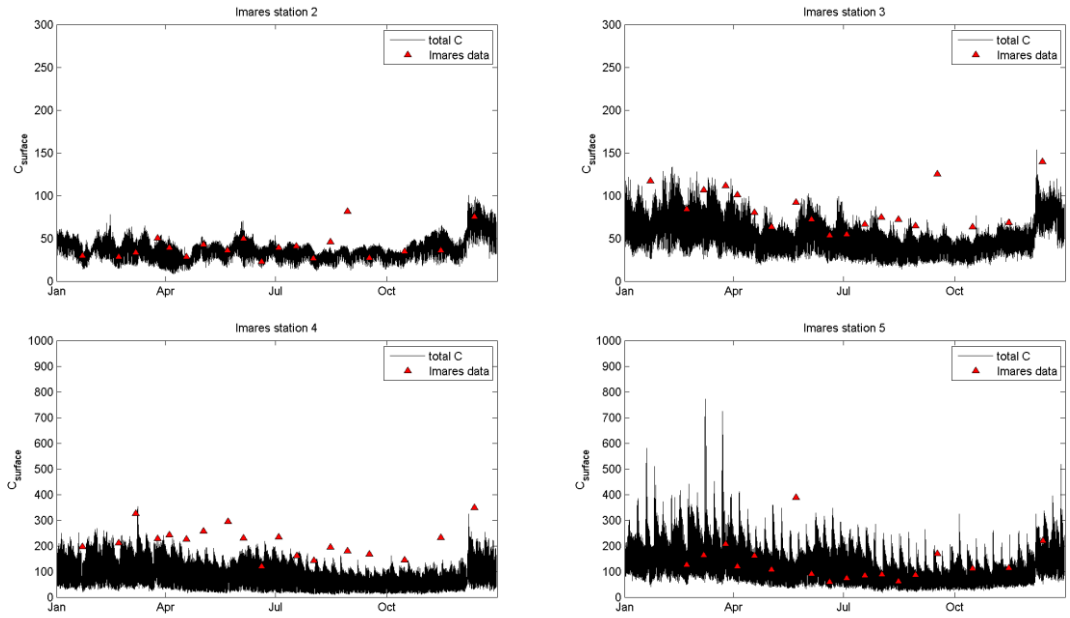

Figure 5.50 Computed (reference settings) and observed surface sediment concentration in 2013 at Imares stations 2-5 (in mg/l).

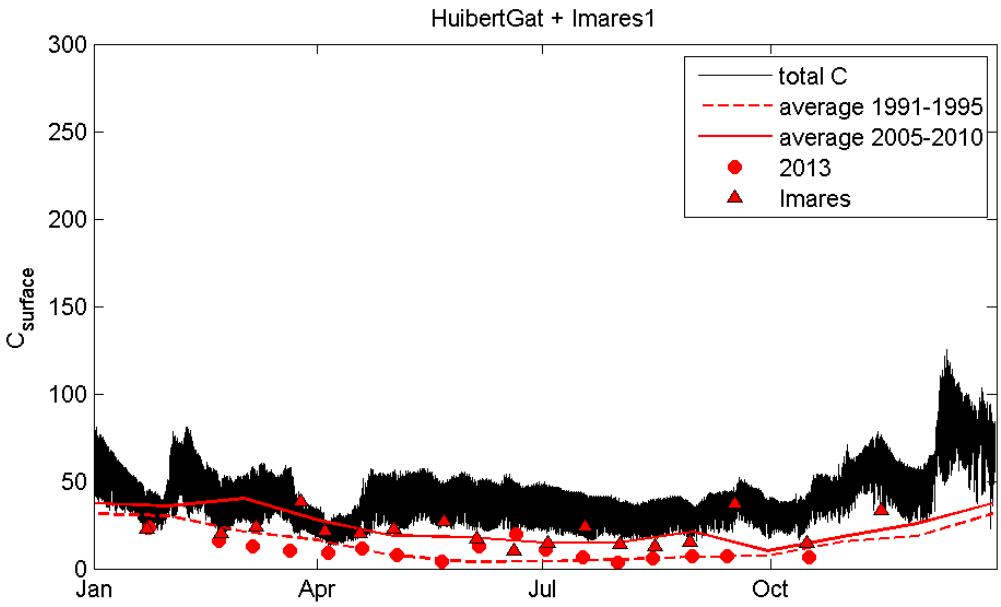

Figure 5.51 Observed and computed (reference settings) surface suspended sediment concentration at station Huibertgat / Imares 1 (in mg/l). The MWTL observations are red dots, with red lines representing 5-year average values of MWTL data in the period 1991-1995 (dashed) and 2005-2010 (solid). The Imares observations are red triangles.

The sediment concentration computed at Imares stations 2 to 5 is lower in the first half year of 2013 (Figure 5.50) than in the first half year of 2012 (Figure 5.13). For the combined four stations the resemblance between observations and computed suspended sediment concentration is similar for 2012 and 2013: in 2012 Imares 2 was the station most poorly reproduced with the model whereas in 2013 Imares 4 is less well simulated. The sediment concentrations observed at Imares 4 in 2013 are higher than those observed in 2012, whereas the computed sediment concentration is slightly higher in 2012 (especially in the first half). Similar to 2012 (Figure 5.14), the computed sediment concentration at Huibertgat is higher in 2013 (Figure 5.51). The sediment concentration is lower in the months January – March, due to the lower wave height (Figure 5.48).

The deposition in the ports of Eemshaven, Delfzijl, and the port of Emden and its approach channel, is approximately 20% lower in 2013 than in 2012 (Table 5.13). The lower port deposition rates are a direct consequence of the lower suspended sediment concentration computed in the first months of 2013 (compare Figure 5.22 with Figure 5.52).

Table 5.13 Estimated fluxes (based on net sinks or dredging volumes) and computed fluxes in 2012 and 2013

Port / area	Estimated flux (million ton/year)	Computed flux 2012 (million ton/year)	Computed flux 2013 (million ton/year)
Ems Estuary	1.5	-0.12	-0.14
Eemshaven	0.5	0.44	0.35
Delfzijl	0.8	0.76	0.62
Emden port and fairway	1.5	0.55	0.42
Lower Ems River	0.75	0.08	0.05

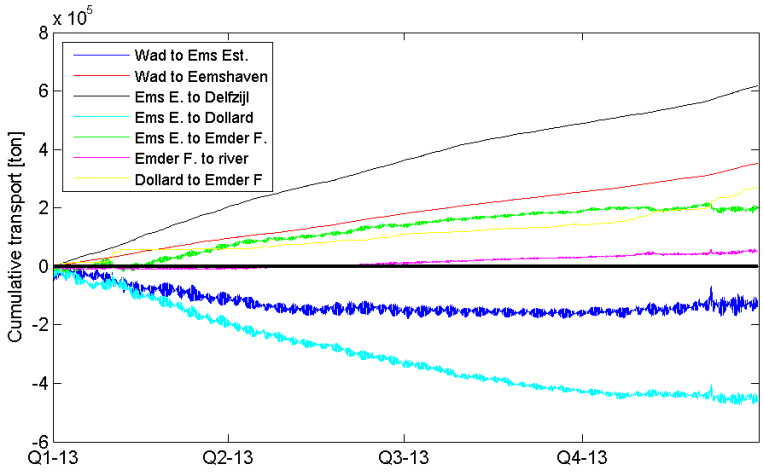

Figure 5.52 Sediment fluxes computed for the reference run for IM1 (w_s = 1.2 mm/s, top panel), IM2 (w_s = 0.25 mm/s, second panel) and combined (third panel), in 2013. See Figure 5.20 for definition of the fluxes.

The observed suspended sediment concentration is lower in 2013 than in 2012, especially in the first half of the year, because the wave height was lower. The modelled suspended sediment concentration was also lower in the first half of 2013 than in 2012. Apparently, the mechanism responsible for sedimentation (wave stirring) is captured by the model. Since the model reproduces this inter-annual variation in sediment concentration, the validation provides further confidence in the model.

5.6 Model accuracy

A method to quantitatively address model uncertainty was developed in the framework of 'KPP B&O Waterkwaliteitsmodelschematisaties' (Harezlak et al., 2014). This method provides a framework with steps to be taken to determine the accuracy of numerical models, including

- Definition of the model aim: which questions does the model have to address?
- Definition of target variables / indicators: which model parameter will be quantitatively compared with observations? And over which period / space should which sort of statistical parameter (mean, exceedance interval) be computed with what accuracy?
- Which techniques should be used to (1) analyse the observations and model, and (2) quantify the relation between observations and model results
- How sensitive is the model to (uncertainties in) the model input?
- And based on the previous steps: what is the uncertainty in the model to address the research questions?

Quantifying model uncertainties is not part of the present report; this will be done in the framework of a separate study (the long-term research project 'KPP B&O Waterkwaliteitsmodelschematisaties'). Although these results are not part of the present report, this more quantitative approach will be part of the overall final project report (report 12). In this section, we relate the aim for the sediment transport model to target variables, and qualitatively discuss the accuracy of the available data and the degree to which the model reproduces these observations.

The aim of the effect-chain model (hydrodynamics, sediment transport, and water quality) is to determine changes in suspended sediment concentration and resulting changes in primary production, resulting from human impacts in the past and future (scenarios for improvement, phase 3 of the project), within the Ems Estuary. The deterministic part of the sediment transport model is provided by the hydrodynamics (see report 4), reproducing

- Waterlevels within several percent of the observations (especially in the Ems Estuary, less well in the lower Ems River),
- Intra-tidal and spring-neap variations in flow velocity, as well as tidal asymmetries,
- Typical salinity variation,
- Residual flow velocity patterns corresponding to the limited information that is available

A sediment transport model is intrinsically less accurate because computation of sediment transport involves a great number of unknowns (such as historical effects and spatially and temporarily varying biologic parameters and processes as well as sediment properties and processes). Not all of these are included in the model: especially biologic processes cannot be described sufficiently quantitative to be part of the model. The key processes to be reproduced with the sediment transport module are (see Chapter 2)

c) Sediment transport mechanisms and typical sediment concentration levels as a result of tides, waves, and density-driven flows
d) Sediment trapping in ports and the long-term effect of subsequent dredging and dispersal on the suspended sediment concentration in the estuary.

These processes are modelled by including resuspension by waves and tidal currents, storage of fine sediment in a deeper bed layer, and transport by tidal, salinity-driven and wind-driven flow. The relative importance of these processes will be evaluated in more detail in report 7. With a good representation of the hydrodynamics and a reasonable reproduction of the sediment dynamics, the model provides a useful instrument to analyse trends in

suspended sediment dynamics of the Ems Estuary. Specific target variables related to the suspended sediment transport module are:

- *Sediment concentration*. The suspended sediment concentration determines the water column transparency, which is essential for modelling primary production. This parameter is directly measured and can be compared with model output.
- *Port siltation*. Port siltation determines the amount of sediment dispersed after dredging, and thereby the effect of dredging and port construction on estuarine sediment dynamics. Port siltation can be estimated based on dredging volumes.
- *Residual sediment transport.* Residual transport by tides and salinity may be very important for the impact of changes in the system on variables such as sediment concentration and port siltation. The tide-induced residual sediment transport has a different response to deepening compared to residual transport by estuarine circulation (which is more sensitive to the water depth). Although important, the computed residual transport is difficult to compare with observations.

<u>Sediment concentration</u>

Sediment concentration is measured for a number of stations in the Ems Estuary, and the model has been primarily validated against the sediment concentration. Quantitatively comparing the computed sediment concentration with the observed sediment concentration is not straightforward because of

(1) Inaccuracies in the data arising from the sampling methodology and equipment. Such inaccuracies become apparent through inconsistencies within the data (as discussed in chapter 3). These inconsistencies mainly concern differences between MWTL and Imares observations at Huibertgat and Groote Gat, but also the strong difference between MWTL-Imares (fairly low concentrations) and GSP (high sediment concentrations). The degree, to which the model fits the data, therefore depends on an assessment which data is most accurate.
(2) The suspended sediment concentration varies strongly over the tidal cycle. When comparing such a variable parameter with a snapshot observation (Imares or MWTL observations), a difference of 1 hour introduces a large error. The comparison in the time domain (Figure 5.18 and Figure 5.19) reveals that the typical patterns (intra-tidal, spring-neap) of the sediment concentration are simulated, but comparing individual points in time may in some cases lead to a very poor comparison.
(3) Not only the absolute value of the sediment concentration (which is typically evaluated in a quantitative comparison): its tidal and spatial variation is at least as, or maybe even more important, for estuarine sediment dynamics.

Typically, the observations fall within the tidal range of the computed sediment concentration. Therefore the model is considered to reproduce the suspended sediment concentration with reasonable accuracy. Note that the area of interest is the Ems estuary, and not the lower Ems River. In the lower Ems River, hyper-turbid conditions occur, which the model cannot reproduce (see also chapter 6).

<u>Port siltation</u>

Siltation in the ports of Delfzijl and Eemshaven is in good agreement with observations. In these ports, which probably act as near-perfect sediment traps, the siltation rate is primarily depending on the ambient suspended sediment concentration. The sediment concentration in these areas is well reproduced (see section above), and therefore also siltation rates (with computed siltation rates within 20% of the observations). Siltation in the Emden navigation channel is strongly underestimated because too little sediment is transported there. Why the sediment transport into the Emden navigation channel is so large remain insufficiently understood, and could be the result of

1) Hydrodynamic processes. A rapid bed level change exists nearby the port of Emden (see Figure 3.13). Probably, a salinity-driven estuarine circulation pattern exists (with up-estuary directed near-bed flows) which delivers fine sediment to the up-estuary end of the deep channel (nearby the port of Emden), leading to the high sediment concentrations and rapid sedimentation rates. The WED model uses vertical σ-layers, which vary spatially in thickness. This may introduce artificial vertical mixing along steep bed level gradients, and may therefore underestimate such a near-bed up-estuary directed current (and as a result, the large sediment transport towards the navigation channel). Furthermore, the number of vertical cells in the model is too low to describe salinity-driven flow in detail.
2) Complex and poorly understood sediment transport processes such as consolidation, flocculation and sediment-induced density effects, resulting in fluid mud formation. Also these processes are not part of the WED model.

While a large amount of sediment is annually dredged from the Emden navigation channel, no sediment is dredged from the port of Emden. Since the early 1990's, sediment in the port of Emden is re-aerated and ships entering the port sail through fluid mud. Any sediment depositing in the port is thereby transported out of the port through semi-natural processes. In the model, sediment depositing in the port of Emden is dredged, and dispersed on the same disposal locations as the navigational channel. In this way, sediment dredging and disposal quantities from the Emden navigation channel are modelled more realistically. Still, despite adding the port of Emden, the dredge spoil from the combined port and its approach channels are underestimated with a factor 3 (~0.5 million ton per year instead of 1.5 million ton/year).

Residual transport

Over timescales of several years, the residual up-estuary transport is equal to sediment stored in sediment sinks. In the Ems estuary, the most important sinks are the lower Ems River and the Bocht van Watum. Both are not reproduced by the model, and therefore the model does not predict a net up-estuary transport. The seasonal variation in sediment concentration, as observed and computed in the Dollard (station Groote Gat), is probably resulting from a combination of estuarine circulation and wave-induced resuspension at the estuary mouth. In 2013, the wave-induced resuspension at the estuary mouth was much lower than in 2012, and as a result, the computed suspended sediment concentration in the Dollard was lower as well. This is supported by observations, revealing lower concentrations in the Dollard in 2013 than in 2012. The barotropic (i.e. no salinity) simulation for 2012 demonstrates that salinity effects are very important for the sediment concentration, generating up-estuary transport during high discharge. Even though the net sinks are not part of the model, it seems the seasonal variation in residual sediment fluxes (strongly influenced by estuarine circulation) is reasonably reproduced. This then suggests that the model is suitable to compute the effect of changes in channel geometry (which strongly influence the estuarine circulation).

5.7 Recommendations

The model can be improved further on several aspects. The model underestimates the transport into the Emden navigation channel and the net accumulation in the Bocht van Watum (a degenerated tidal channel). These aspects may be improved through modifications in the hydrodynamic model or in the sediment transport model. For both cases, substantial improvements can only be made if the efforts for improvement can be verified with additional

data sources, preferably in the form of (several) long-term observations. These aspects will be elaborated below.

1) As already indicated in report 4, the reproduction of salinity may be improved, especially by modifying the offshore salinity boundary conditions. Residual flows are strongly influenced by salinity, so this may improve simulation of residual flows. However, there is insufficient data to quantify how well the residual flow is reproduced. This requires several long-term observation stations at several locations in the estuary (and at multiple depths).
2) The underestimation of transport into the Emden navigation channel points to a possible additional area of improvement. The vertical σ grid used in the WED model generates numerical mixing over a steep bed level gradient such as near Emden. This would then reduce the strength of the estuarine circulation pattern transporting sediments into the Emden navigation channel. A solution is to use vertical z-layers, which have a spatially constant grid cell thickness (in contrast with σ-layers). Since such layers introduce less vertical mixing, they reproduce salinity-driven flows over steep bed level gradients more accurately. However, many functionalities in Delft3D have only become available for z-layers very recently, and could not be used within this project.
3) The sediment dynamics in the Emden navigation channel are influenced by flocculation and consolidation processes because of the high sediment concentration, as well as sediment-induced density effects. Adding such processes would lead to a more realistic description of the sedimentary processes – especially the coupling between sediment concentration and water density will likely increase the sediment import into the lower Ems River. Even though adding such processes may be relevant for the Emden navigation channel (because the sediment concentrations are so high) it may not solve the underlying question why so much sediment converges in the Emden navigation channel. This may also be (partly) related to the hydrodynamics (see point 1).
4) The model does not simulate the net accumulation in the Bocht van Watum. This requires a model in which more sediment can accumulate in a deeper layer (in the present model setup the deeper layer is fixed at 10 cm), preferably as a consolidation process. Most accurately is to use a full morphodynamic coupling, but given the other demands to the model (simulation of long timescales) this is difficult to realize.
5) To understand how well the model reproduces the actual concentration levels, but even more to understand how well the model reproduces the typical sediment transport processes, more continuous measurements are needed within the Ems Estuary. Most needed are observations in the mouth of the estuary, in the middle of the estuary, and in the Dollard on the vertical distribution of velocity and concentration, preferably as a near-continuum (ADCP).

5.8 Summary

The sediment transport model developed for the WED domain reasonably captures the suspended sediment dynamics in the Ems estuary. The observed concentrations are reproduced, with an error between computed and observed concentration which is comparable to the difference between different data sources. The differences in observed sediment concentrations are largest in the Dollard basin.

The model input parameters with largest uncertainty are the settling velocity and the erosion parameters. The settling velocity influences the along-estuary distribution of the sediment concentration. With the available concentration data, it was difficult to determine which settling velocity was more accurate. Therefore the value resulting from the soil sampling analyses (which are close to the average value of earlier observations of the settling velocity, but with a wider range) is used. The critical shear stress for erosion (derived from the same

samples) is probably too large – existing formulations to relate the clay content to erosion rate insufficiently account for the state of consolidation. Based on model calibration, a lower value then obtained from the soil samples is used.

In January 2012, the concentrations in the exposed outer estuary are highest, corresponding to the period of largest wave heights. This seasonal variation in suspended sediment concentration, as predicted with the model, is observed at Huibertgat (Imares and MWTL observations), Bocht van Watum, and Groote Gat (in the Imares observations, not in the MWTL), but not in the 4 Imares stations located in-between these 3 stations. In 2013, when the wave heights were much lower than in 2012, the sediment concentration in the first half year was also lower, especially in the Dollard (in the model and in the observations). Numerically, seasonal variations in SSC are generated by river discharge and by waves; all other forcings are constant in time. The observed seasonal variation in SSC may also be caused by additional effects. Biological processes (e.g. effect of temperature and algae on flocculation, bio (de) stabilization of mudflats) or seasonal variations in offshore sediment supply will also play a role. Biological processes are not included since their impact cannot be quantified sufficiently accurate. The offshore sediment supply is held constant in order to better understand the effect of waves and river discharge on turbidity.

6 Set up and calibration of the ER model

6.1 Introduction

The high sediment concentration in the Ems requires a transport model with feedback between turbulence, hydrodynamics, sediment concentration and morphology, for which Delft3D sediment-online is used. This model is set up to (1) better understand and quantify the exchange of sediment between the lower Ems River and the Ems Estuary, and (2) to evaluate the impact of man-induced changes in the lower Ems River on the Ems River itself and on the Ems Estuary. The aim of this chapter is to set up and calibrate a sediment transport module for the ER hydrodynamic model (see report 4). The exchange of sediment between the Ems Estuary and the lower Ems River, and the impact of human interferences on the lower Ems River, is analysed in report 7.

6.2 Model set up

6.2.1 Model domain

The domain of the ER model (more detail in report 4) extends from Knock to Herbrum (Figure 6.1). The seaward domain is forced with water levels observed at Eemshaven, and the river inflow (of the Ems and Leda) is prescribed as discharges. Since the focus is on the lower Ems River and the exchange with its estuary, which is predominantly driven by river and tidal flow (see section 4.2), no wave forcing is applied.

6.2.2 Model formulations

The sediment transport is computed with a morphodynamic model in which the bed level is adjusted during each computational time step (note that the morphological changes in the model are only related to mud, not to sand). The transport of sediment is simulated with the advection-diffusion equation (in the water column) and formulations for the exchange of sediment between the water column and the bed. Erosion is computed with the Partheniades equation for erosion *E*, and deposition *D* as a shear-stress independent flux:

$$E = M\left(\frac{\tau}{\tau_{cr}} - 1\right)$$

$$D = w_s c$$

Herein *M* is the erosion parameter (kg/m^2/s), τ is the bed shear stress, τ_{cr} is the critical bed shear stress for erosion, w_s the settling velocity (m/s) and *c* the sediment concentration (kg/m^3). The sediment settling velocity is composed of a clear water settling velocity w_{s0} which is reduced by hindered settling effects using a simple power law equation based on Richardson and Zaki (1954):

$$w_s = w_{s0}\left(1 - C / C_{\text{ref}}\right)^5$$

Here C_{ref} is a maximum sediment concentration that can be attained: for sand this is typically around 1600 kg/m^3 but for mud it typically is 50-150 kg/m^3. In the Ems River, a value of 100 kg/m^3 is used (see section 6.2.3).

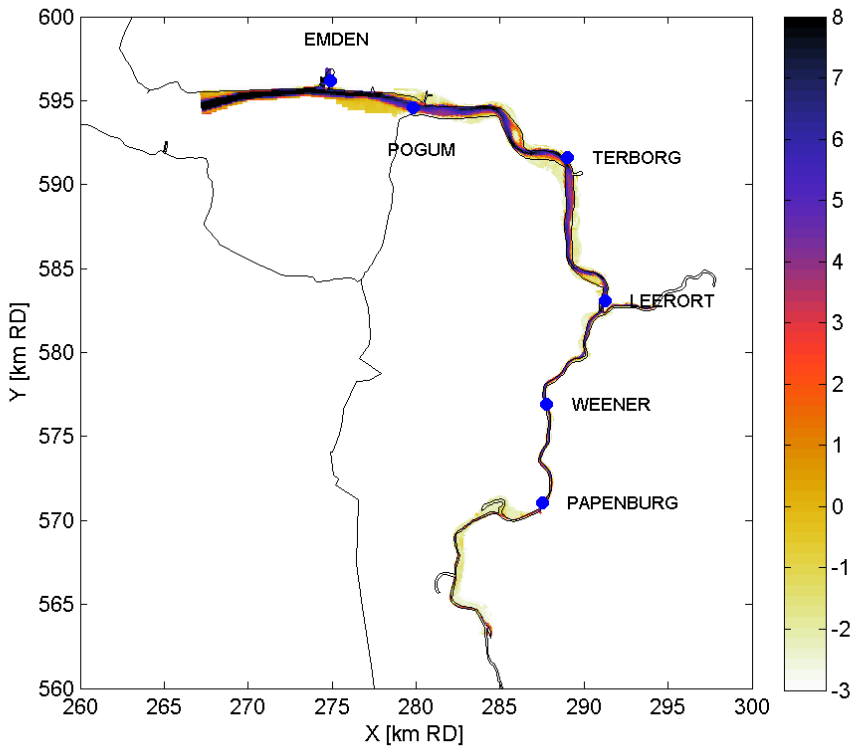

Figure 6.1 Initial bed level of the model, based on 2005 soundings, and observation stations.

The most characteristic physical process in the lower Ems River is the occurrence of thick HCBS or fluid mud layers. These layers cannot be predictively and accurately modelled within Delft3D on time and spatial scales of interest to this study. The processes relevant for consolidation and entrainment require a very large vertical resolution, and hence computational time. In addition, the governing physical processes are still insufficiently quantitatively understood. As an alternative, we model fluid mud as a single dynamic bed layer.

In the Ems River, the fluid mud is probably regularly resuspended (e.g. Talke *et al.,* 2009; Wang; 2010). The sediment mass is large, and therefore the fluid mud thickness is typically 1-2 m. The consolidation rate of bed sediment scales with the squared thickness of the consolidating bed. With regular resuspension (as in the lower Ems River, see section 3.2), such a thick fluid mud layer has no time to consolidate, and the vertical variation in density should be fairly low. Therefore the fluid mud may be approximated by a simple bed evolution model consisting of easily erodible sediment with a low density ρ_{dry}.

The high sediment concentrations in the bed and the water column strongly reduce the hydraulic drag. The effect of sediment on the hydrodynamics is modelled by (1) including the sediment concentration in the computation of the water density, resulting in suppression of

turbulent mixing, and consequently a lower apparent hydraulic roughness, and (2) a lower bed roughness in the hydrodynamic model (for which Manning's *n* is used, see report 4). The additional lower bed roughness needs to be additionally prescribed because (i) the vertical resolution in the model needs to be very high to adequately model the effect of sediment on turbulent mixing and hydraulic roughness, and (ii) the bed itself approaches a no-slip condition.

The model is typically run for one year, starting from empty bed conditions. Longer periods are not feasible given the long required computational time. In order to reach dynamic equilibrium within this period, sedimentation is only allowed in the main channel of the Ems River; exchange between the water column and the bed is switched off in shallow (low energy) areas. This speeds up the time needed to reach dynamic morphological equilibrium (this timescale depends on the total mass of sediment in the system). The physical rationale for excluding mudflat sedimentation is that the mudflats along the lower Ems River were formed in the past, and presently a dynamic equilibrium exists between the flats and the river without much exchange of sediment. Excluding sedimentation on the flats of the lower Ems River has the following consequences:

- The total mass of sediment in the system is underestimated (sediment is only present in the channel, not on the flats). This implies that the speed at which the system reaches dynamic equilibrium is overestimated. Therefore the model cannot predict the timescales associated with the historic shift from a sand-dominated system to a mud-dominated system.
- Without sedimentation on the flats, the model cannot be used to evaluate the effect of enlarging intertidal areas on sedimentation and resulting extraction of sediment from the system. However, sedimentation in such intertidal areas can be easily included in a later stage of the project.

6.2.3 Model settings, initial conditions, and boundary conditions

Fine sediment in estuarine settings has a wide range of settling velocities, dependant on the primary particle size and the degree of flocculation. For the morphodynamic behaviour of fine sediment, only flocculated sediment is relevant. Flocculated sediment often exist as larger flocs and as smaller flocs (macro and micro flocs), typically with different settling velocities. Therefore we define two sediment classes: sediment with a large settling velocity (IM1) and sediment with a smaller settling velocity (IM2). The sediment settings for these 2 fractions are given in Table 6.1.

The values for τ_{cr} is based on typical sediment properties and on interpretation of the hydrodynamics. The critical shear stress for erosion of cohesive mud may range from around several 0.01 Pa to several Pa, depending on the degree of compaction. Typical values for non-consolidated to loosely consolidated clay are several 0.1 Pa (see e.g. Widdows *et al*., 2007; Dickhudt *et al*., 2011). However, the critical shear stress for erosion strongly depends on the measuring device deployed, introducing a factor 10 range in measured erosion shear stress (Widdows *et al*., 2007). In addition to this uncertainty, the hydrodynamic model computes a bed shear stress by applying formulations valid for a rigid bed. This is not valid for a water–fluid mud interface such as a consolidating bed. Therefore we estimate the erodibility of the sediment differently, as explained below.

Table 6.1 Sediment transport model settings for the ER model for fraction IM1 and fraction IM2. The only difference between IM1 and IM2 is the settling velocity

Parameter	Description	IM1	IM2
$w_{s,0}$ [mm/s]	Settling velocity	1	0.2
M [kg/m^2/s]	Erosion parameter	0.01	
τ_{cr} $\tau_{cr,1}$ [Pa]	Critical bed shear stress	0.5	
C_{ref} [kg/m^3]	Reference concentration for hindered settling	100	
ρ_{dry} [kg/m^3]	Dry bed density	100	
S_{init} [m]	Initial bed sediment	0	
C_{init} [kg/m^3]	Initial suspended sediment concentration	0	

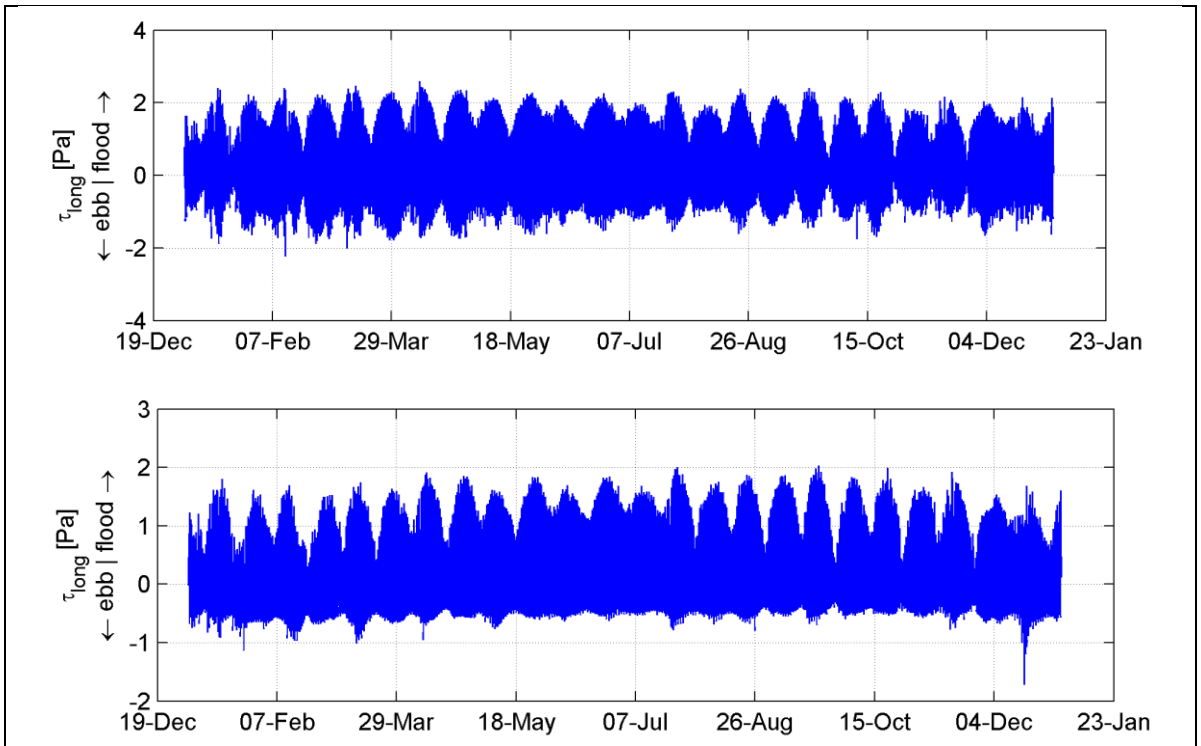

Figure 6.2 Computed bed shear stress at Pogum (top panel) and Weener (lower panel) using the hydrodynamic model

The tides in the lower Ems River are strongly asymmetric, with a larger flood current velocity than ebb current velocity (and consequently bed shear stress). Sediment transport during the flood is therefore considerably larger than during the ebb (Winterwerp, 2011), resulting in large up-estuary transport of fluid mud (section 3.2). The bed shear stress computed in the main river channel near Pogum and Weener is given in Figure 6.2. At Pogum, both ebb and flood shear stresses are around 2 Pa, although the flood bed shear stress is slightly larger. At Weener, the bed shear stress is strongly asymmetric, with maximum τ_b typically around 1.5 Pa during the flood, but 0.5 Pa during the ebb. This asymmetry is fairly representative for large parts of the lower Ems River. Using a value for τ_{cr} in-between 0.5 and 1.5 Pa (which are realistic values for moderately consolidated sediment) would therefore result in up-esuary sediment transport by tidal asymmetry. In order to reproduce the observed large up-estuary

transport in the lower Ems River, we use τ_{cr} = 0.5 Pa, but perform a sensitivity analysis on the effect of τ_{cr}.

For the settling velocity w_{s0} typical values for mildly to moderately flocculated mud are used. The settling velocity of unflocculated mud is 0.01 mm/s or lower; flocculation results in larger settling velocities up several mm/s. Floc settling velocities in the Ems Estuary of up to 0.5 – 2 mm/s were observed by van Leussen and Cornelisse (1996): see Figure 6.3. Sediment in the lower settling velocity range (< 0.1 mm/s) is fairly insensitive for hydrodynamic asymmetries (van Maren and Winterwerp, 2013) and mostly act as washload (suspended throughout the tidal cycle, including slack tide). We therefore use values of w_{s0} = 0.2 and 1 mm/s as default, although the effect of w_{s0} is studied through a sensitivity analysis.

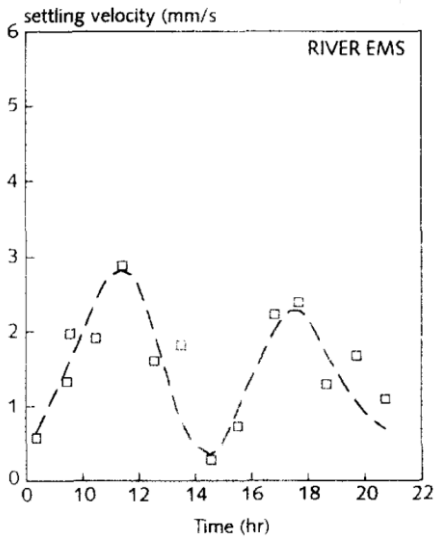

Figure 6.3 Settling velocity of flocs measured in the River Ems (van Leussen and Cornelisse, 1996).

The dry density of fluid mud typically varies between 50 and 150 kg/m^3; in this study we use an intermediate value of 100 kg/m^3. Such a value is supported by observations of suspended sediment concentrations, exceeding the maximum value of 50 kg/m^3. In order to have a smooth transition from the bed phase to the water phase, the reference sediment concentration is also set to 100 kg/m^3.

With physically-based values for τ_{cr} and w_{s0}, the value for the remaining parameter *M* can be solved through calibration. As an initial estimate, *M* is set to 0.01 kg/m^2/s (a value more often used to model fairly dynamic fine sediment, e.g. van Maren and Winterwerp, 2013).

The downstream model boundary conditions are based on observations at Knock in 2005: water levels (not shown), salinity (middle panel in Figure 6.4), and sediment concentration (lower panel in Figure 6.4). The landward boundaries consist of observed daily averaged discharges (upper panel in Figure 6.4) at a salinity of 0.2 ppt, and no sediment in flux. A uniform water level (equal to Mean Sea Level) and salinity (ppt) is used to initialise the model; initially no sediment is present in the model.

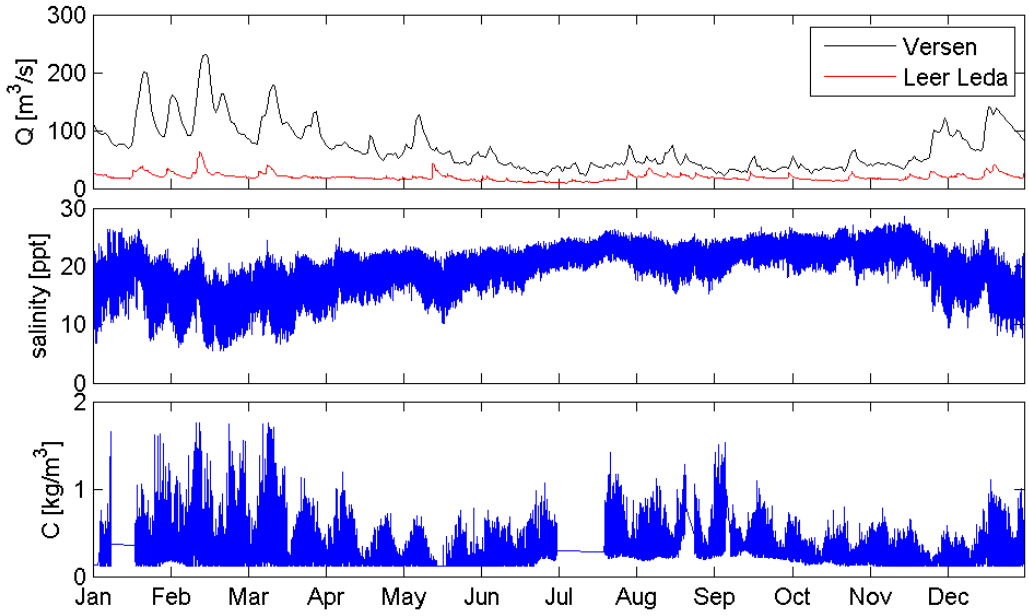

Figure 6.4 Daily averaged discharge at the upstream model boundaries (upper panel: Versen and Leer-Leda), and salinity (middle panel) and sediment concentration (lower panel) at the downstream boundary (Knock), 2005. The unrealistic lower limit of the measured suspended sediment concentration indicates a malfunctioning instrument or results from the calibration procedure.

6.3 Model calibration

The sediment transport module is semi-quantitatively analysed by comparing the computed sediment transport rate with available observations. Subsequently, the computed time series of suspended sediment concentrations are compared with observations in the Ems River for the intra-tidal, spring-neap, and seasonal variation of SSC.

6.3.1 Computed sediment transport

Applying the reference settings (Table 6.1) results in a yearly up-estuary net transport of 2 million ton of sediment into the lower Ems River (here defined by the cross-section at Pogum): see Figure 6.5. In the first months, sediment enters the model domain despite a fairly large river discharge. However, sediment export during these first months is not possible since initially no sediment is in the model domain. Sediment is continuously transported into the model throughout the low discharge summer conditions. At the start of winter, sediment is transported downstream by the increasing river discharge. At dynamic equilibrium, the model would probably also simulate sediment export. However, large amounts of sediment are annually extracted from the lower Ems River (1-2 million m^3, close to 1 million ton of fine sediment; see section 3.3), so the lower Ems River is not in dynamic equilibrium.

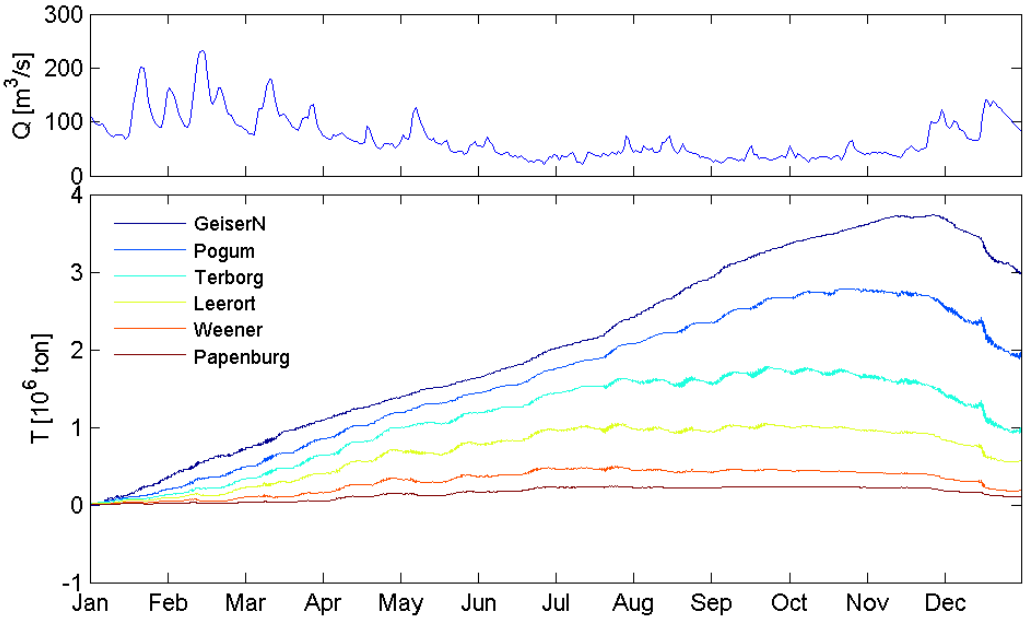

Figure 6.5 River discharge at Versen (top panel) and cumulative sediment transport into the lower Ems River in year 1, computed with the reference settings (Table 6.1) (lower panel). The cross-section GeiserN is close to the model seaward boundary.

The seasonal variation of import and export is in line with the river-induced flushing that is suggested by the observations in Figure 3.2 and Figure 3.3. Moreover, the computed bed shear stress asymmetry in the upper reaches of the lower Ems River (Leerort, Papenburg) varies seasonally, with a larger ebb/flood ratio of the bed shear stress at large river discharge events (Figure 6.6). The impact of river discharge is much smaller in the lower reaches of the lower Ems River (Pogum – Terborg; see Figure 6.6) because the cross-sectional area is much larger. With a seasonal variation in tidal asymmetry as pronounced as in Figure 6.6, seaward flushing during large discharge events seems the most likely explanation for the lower suspended sediment concentrations at Papenburg and Weener during winter (Figure 3.3).

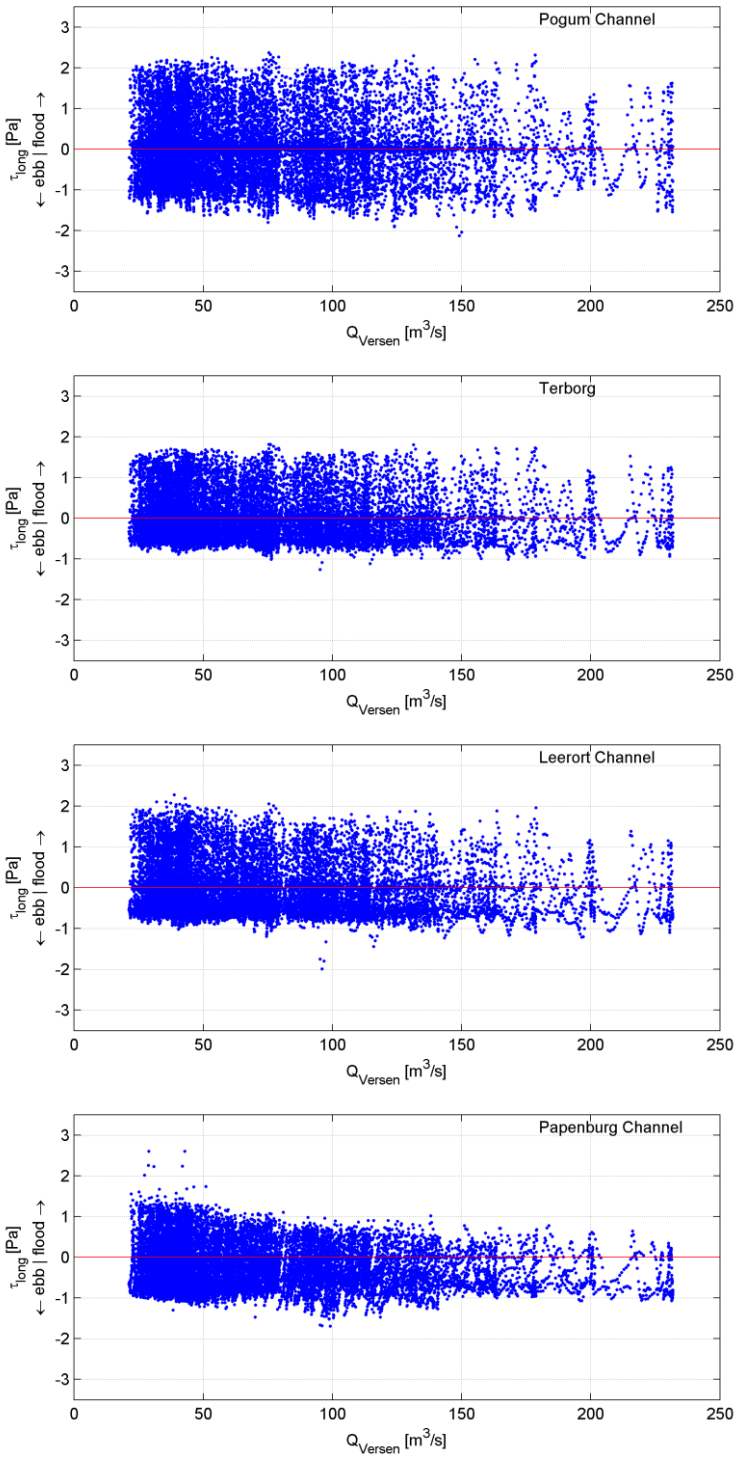

Figure 6.6 Computed bed shear stress from Pogum to Papenburg as a function of river discharge at Versen

The amount of sediment transported into the lower Ems River (2 million ton in one year) agrees well with dredging numbers and ADCP observations. Near Pogum, tide-averaged transport rates of 7.6 million kg/tide was measured during low discharge conditions by BAW (Weilbeer and Uliczka, 2012), using ADCP observations (equivalent to 5.3 million ton/year). The annual sediment extraction through dredging is 1 million ton of fine sediment. The deviation between the net extraction (which is approximately the real residual transport rate)

and the low-discharge observed sediment import (5.3 million ton/year) supports the seasonal variation suggested by the model. The net computed sediment import at Pogum (2 million ton/year) is close to the net sediment extraction and in-between the dredging information and the ADCP observations.

Modifying the settling velocity of both sediment fractions has a limited effect on the residual transport. Using a 2 times larger (Figure 6.7) or smaller (Figure 6.8) settling velocity result in similar seasonal variation, although the sediment dynamics become more sensitive to the river discharge at lower w_{s0}. The computed net import rates is 1.1 million ton/year at Pogum for a large settling velocity (w_s = 2 and 0.4 mm/s) but 1.9 million ton/year for low (w_s = 0.5 and 0.1 mm/s) settling velocity. Most sediment enters the lower Ems River for intermediate settling velocities (2 million ton, see Figure 6.5). Increasing the critical bed shear stress τ_{cr} to 0.7 Pa (Figure 6.9) leads to similar import rates as the reference conditions. However, export during the winter large discharge events is much lower. The low influence is probably the result of hindered settling (see section 6.2.2): using a C_{ref} of 100 kg/m^3, the settling velocity is reduced with 40% to 67% for concentrations from 10 to 20 kg/m^3 (which are typical, see Figure 6.11).

Using the reference settings, the difference in residual transport between Pogum and Geiser North is 1.2 million ton (Figure 6.5), settling in the Emden fairway. This is close to the amount of sediment annually dredged (~1 million ton, see report 3). Sedimentation in the Emden fairway is further supported by the rapid increase of sediment concentrations throughout the Ems River following large discharge events (Figure 3.2 and Figure 3.3).

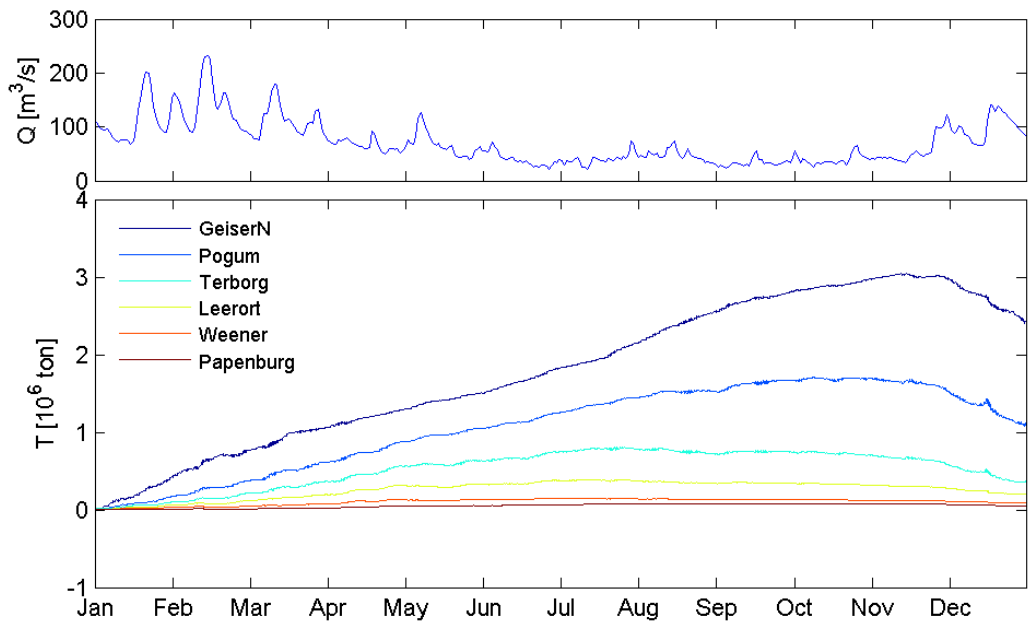

Figure 6.7 Cumulative sediment transport into the lower Ems River in year 1, computed with a 2 times larger settling velocity (0.4 and 2 mm/s). See also Figure 6.5 for comparison.

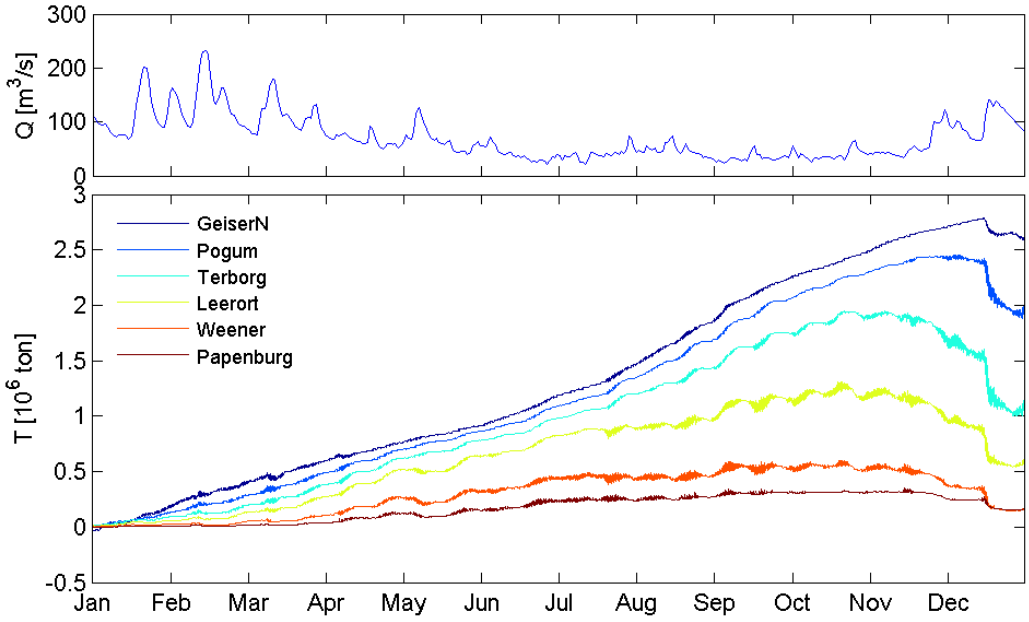

Figure 6.8 Cumulative sediment transport into the lower Ems River in year 1, computed with a 2 times smaller settling velocity (0.1 and 0.5 mm/s). See also Figure 6.5 and Figure 6.7 for comparison.

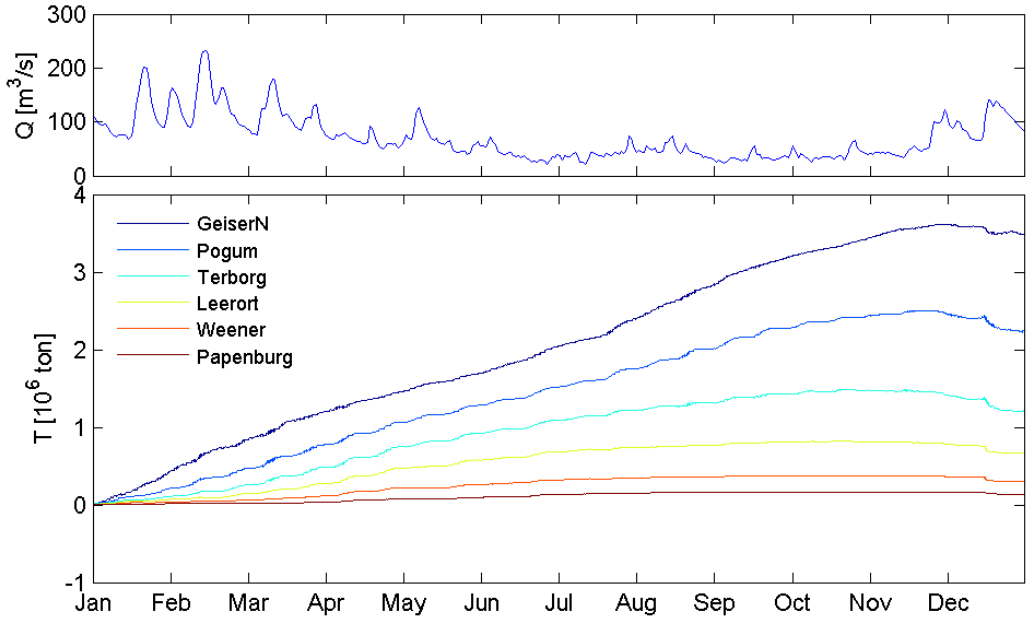

Figure 6.9 Cumulative sediment transport into the lower Ems River in year 1, computed using τ_{cr} = 0.7 Pa. See also Figure 6.5 and Figure 6.7-Figure 6.8 for comparison.

6.3.2 Sediment concentrations

The computed peak sediment concentrations (Figure 6.10) are typically within a factor 2 of the observations. Furthermore, the seasonal and spring-neap variations have similar patterns. Starting at the seaward station Knock (Figure 6.4), the sediment concentration increases up to Weener, but then decreases further landward. For Terborg to Papenburg, the sediment

concentration increases at the beginning of April, when large discharge events no longer occur. Even though the model is initialised without sediment on the bed, the computed timing of increase in sediment concentration coincides well with the measurements. Only at station Pogum does the model substantially overestimate the observed sediment concentrations.

Because of the long period, the relation between modelled and observed concentrations in Figure 6.10 is not clear. Therefore these computed suspended sediment concentrations are compared in more detail with observations during low discharge (a period with sediment import, April; see Figure 6.11) and high discharge (exporting sediment, December; see Figure 6.12). For both conditions, the intra-tidal, spring-neap and seasonal variation of suspended sediment transport is reasonably reproduced; some stations better than others. The computed intra-tidal variation computed at the two seaward stations Pogum and Terborg corresponds to observations during both April and December: a concentration peak occurs at the end of ebb and the beginning of flood, merging in an apparent double-crested single peak. An important observation is that for the most seaward station within the model domain (Pogum: station Knock provides boundary conditions, so cannot be used for analysis) both the computed and the observed concentration peaks during ebb and during flood are almost symmetrical.

The double-crested concentration peak around LW is more clearly illustrated by Figure 6.13: the sediment concentration strongly increases at the end of ebb, in response to the larger flow velocity. The period of low water slack (LWS) is short (the period with the flow velocity $u < 1$ m/s is about 30 minutes – see top panel in Figure 6.13). Vertical mixing rates are high at the end of ebb and the beginning of flood (middle panel of Figure 6.13). Therefore most sediment remains in suspension, explaining the apparent single (but double-crested) concentration peak around LW. Even though the model-data agreement is fairly good, the model tends more to a single peak behaviour than the observations (Figure 6.10). The peak flow velocity during flood is larger than the peak flow velocity during ebb (top panel in Figure 6.13), and occurs at the beginning of the flood. Both the short LWS period and the larger peak flow velocity during flood promote up-estuary transport of sediment.

Further upstream, the agreement between observations and the model decreases (Figure 6.11 and Figure 6.12). At Weener, the computed and observed sediment concentration is highest (several 10's of g/l), but here the computed intra-tidal variation is not corresponding to the observed intra-tidal variation. The predicted model concentration peak only occurs at the beginning of flood, during a period with large flow velocities (Figure 6.14). The observed large (and modelled) high sediment concentrations last throughout the flood period (see Figure 6.15). However, the observed asymmetry in concentration is so large that either the residual upstream sediment transport is even larger than the model predictions (which already correspond to larger sediment volumes than actually dredged from the system, and hence seems unlikely), or the vertical distribution of sediment concentration is strongly differing during ebb and flood. Possibly, the model overestimated vertical mixing. The eddy viscosity computed at Weener (middle panel of Figure 6.14) is largest during ebb and not during flood (when flow velocities are larger), indicating that mixing is at least partly suppressed by the vertical concentration gradient (see Winterwerp, 2001).

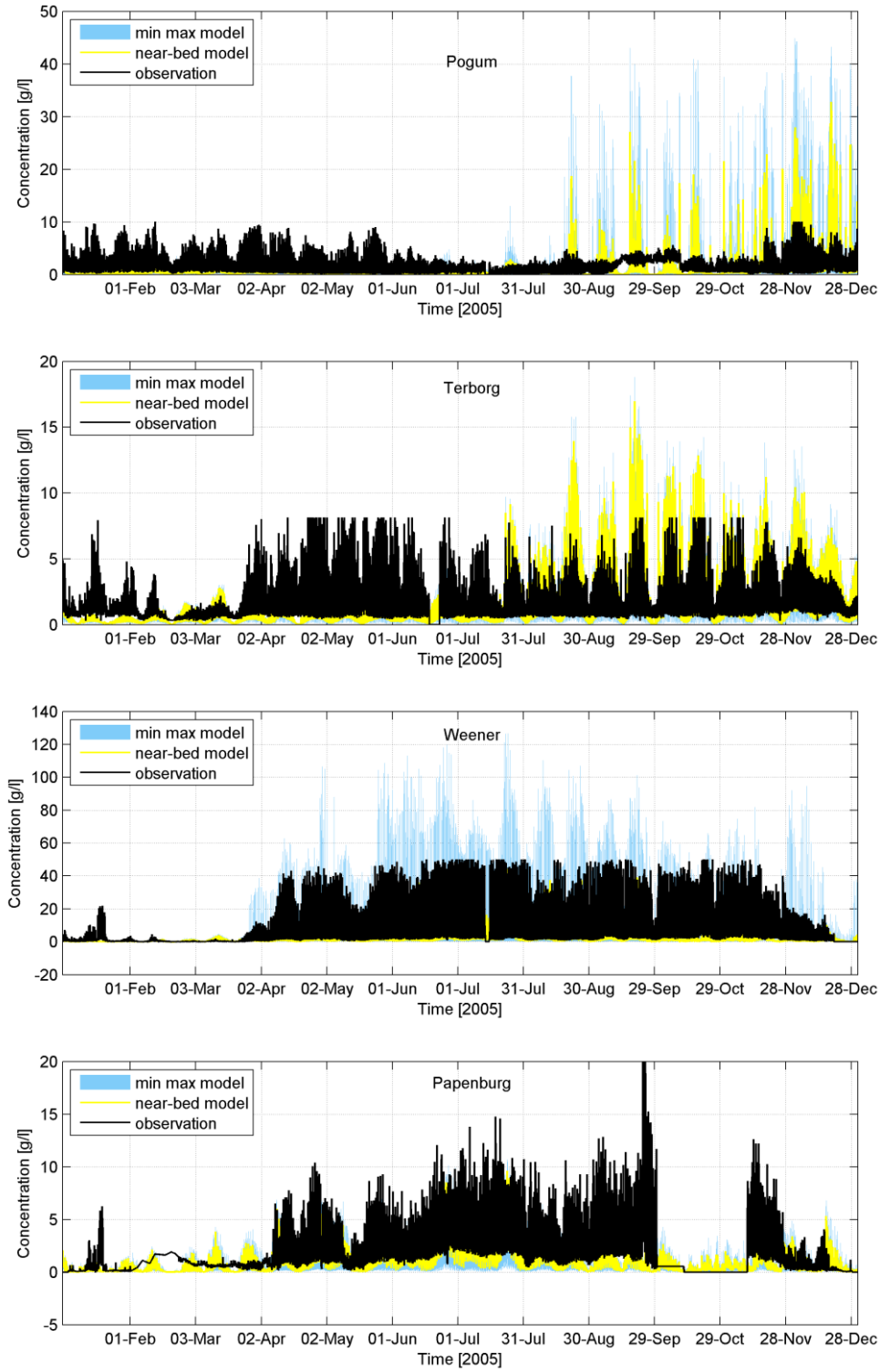

Figure 6.10 Observed (black line) and computed sediment concentration in 2005 at stations Pogum, Terborg, Weener and Papenburg. The yellow line is the concentration in the lower 10-30% of the water column, which best approximates the location of the sensor. The light blue area indicates the range of concentrations from surface to bed ranging from minimum sediment concentrations at the surface to maximum concentrations near the bed. Note the data cut-off for some of the stations, at 8 g/l at Terborg and 50 g/l at Weener.

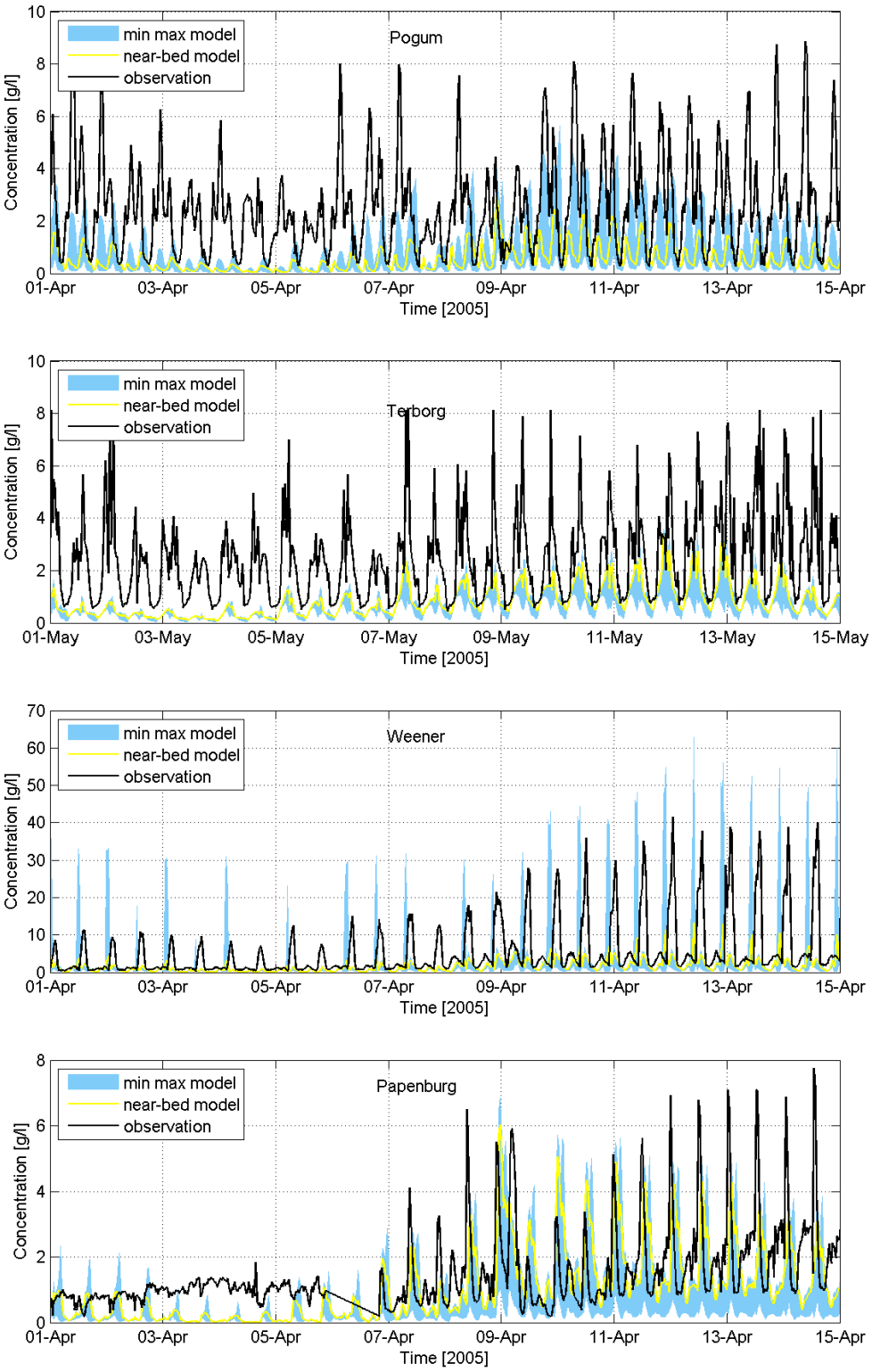

Figure 6.11 Observed (black line) and computed sediment concentration in April 2005 at stations Pogum, Terborg, Weener and Papenburg. The yellow line is the concentration in the lower 10-30% of the water column, which best approximates the location of the sensor. The light blue area indicates the range of concentrations from surface to bed ranging from minimum sediment concentrations at the surface to maximum concentrations near the bed.

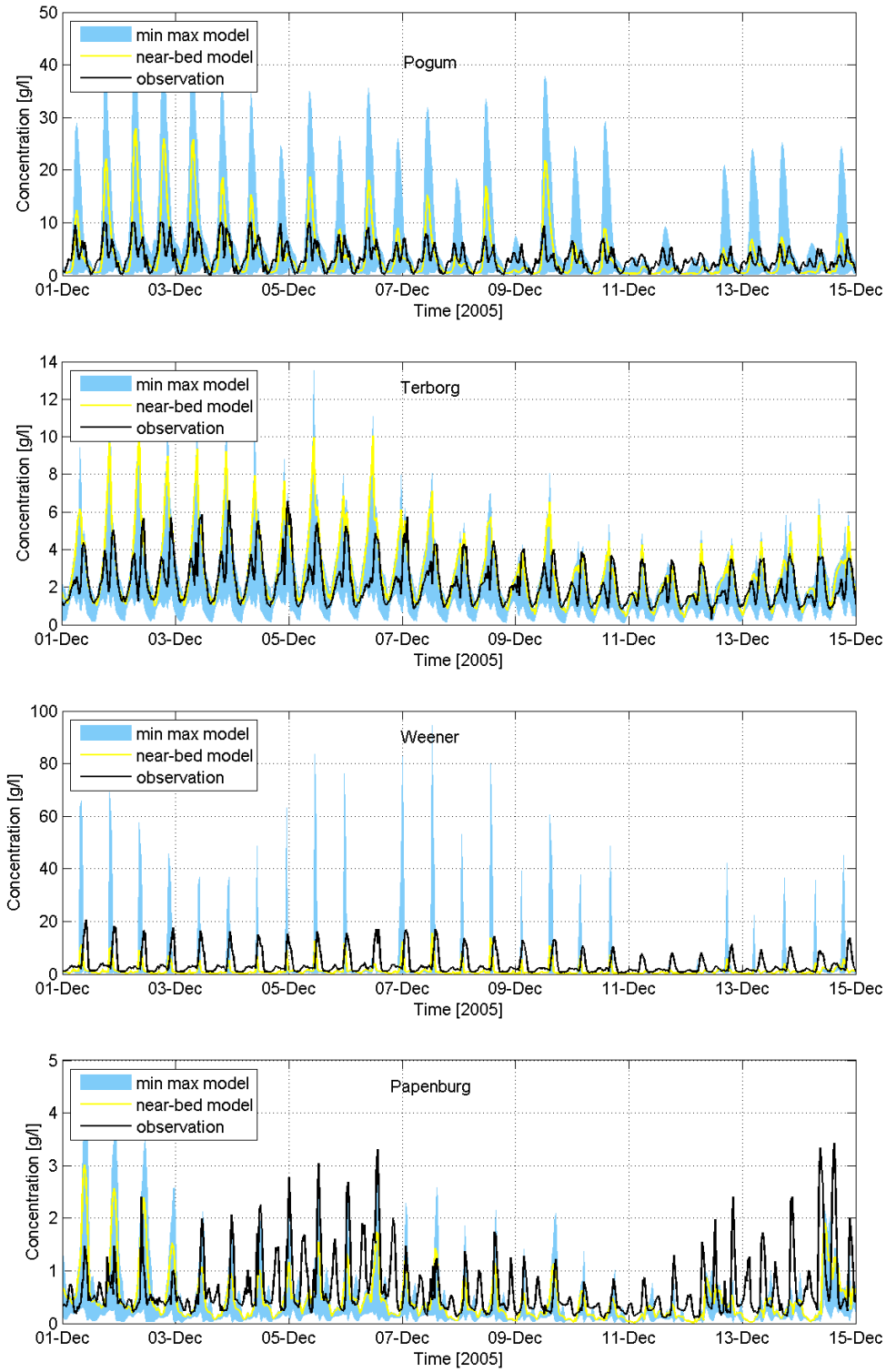

Figure 6.12 Observed (black line) and computed (yellow) sediment concentration in December 2005 at stations Pogum, Terborg, Weener and Papenburg. The yellow line is the concentration in the lower 10-30% of the water column, which best approximates the location of the sensor. The light blue area indicates the range of concentrations from surface to bed ranging from minimum sediment concentrations at the surface to maximum concentrations near the bed.

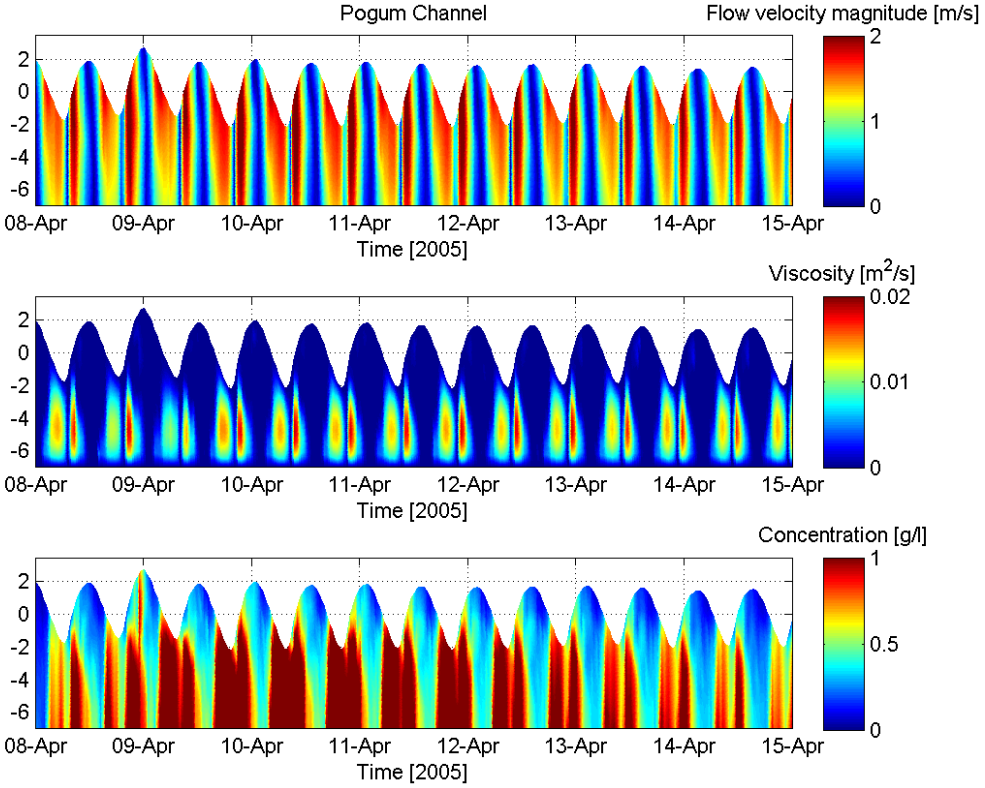

Figure 6.13 Computed flow velocity, eddy viscosity, and sediment concentration in the main channel near station Pogum.

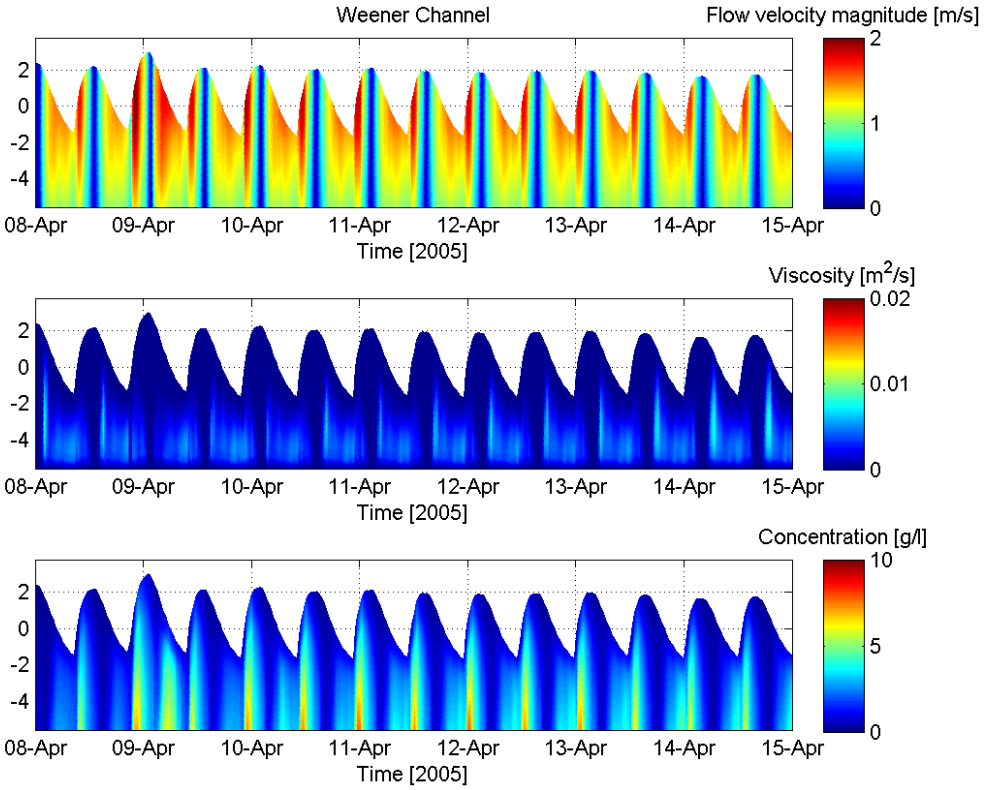

Figure 6.14 Computed flow velocity, eddy viscosity, and sediment concentration in the main channel near station Weener.

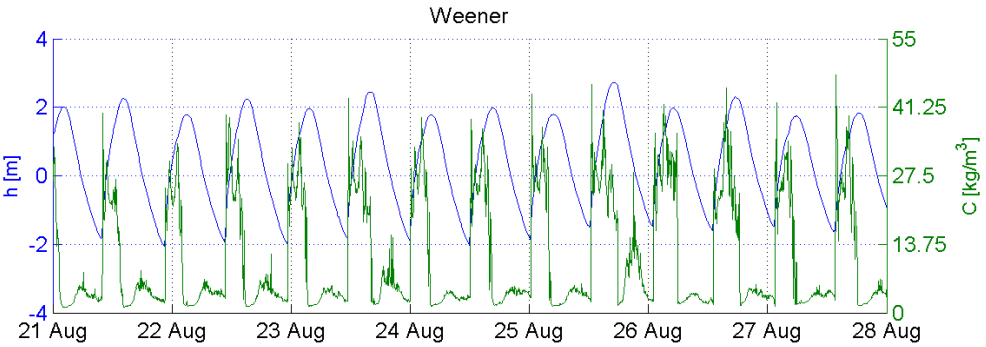

Figure 6.15 Computed sediment concentrations and water levels at Weener in August 2005

6.4 Model accuracy

A method to quantitatively address model uncertainty was developed in the framework of 'KPP B&O Waterkwaliteitsmodelschematisaties' (Harezlak et al., 2014), see section 5.6 for details. In this section, we relate the aim for the sediment transport model to target variables, and qualitatively discuss the accuracy of the available data and the degree to which the model reproduces these observations. The aim for which the ER model has been setup is to analyse and explain the historic changes in the sedimentary regime of the lower Ems River, and determine the impact of these changes on the Ems Estuary (as part of report 6). To achieve this goal, the key processes in the sediment transport module are (see Chapter 2):

c) Sediment transport mechanisms and typical sediment concentration levels as a result of tides, waves, and density-driven flows
d) Sediment trapping in ports and the long-term effect of subsequent dredging and dispersal on the suspended sediment concentration in the estuary.

These processes can be translated into target variables:

- *The suspended sediment concentration*. The present-day high sediment concentration is the main issue in the lower Ems River. This is a parameter which is frequently measured, and can be directly compared to model output.
- *Residual sediment transport*. The residual transport of sediment determines the long-term estuarine sediment dynamics, and is mainly the combined result of tidal asymmetry and riverine flushing. This parameter cannot be directly measured.

<u>Suspended sediment concentration</u>

As explained in section 6.2, the sediment transport processes in this system are too complex to simulate in full process-based detail. The model does not include flocculation and consolidation processes, which influence the sediment dynamics. The computed sediment concentration will therefore not be in full agreement with observations. Nevertheless, the computed sediment concentration does reproduce some of the characteristics of the sediment concentration observations. The computed peak sediment concentrations during spring tides are 2-3 times larger than during neap tides. In the up-estuary stations (Leerort to Papenburg), the model reproduces the reduction of suspended sediment concentrations during the winter (high river discharge) months. The intratidal variation is only reproduced at the two down-estuary stations of Pogum and Terborg. Up-estuary, the modelled intra-tidal variation of the sediment concentration poorly corresponds to observations, probably because processes related to resuspension / entrainment of fluid mud (which are not modelled) become dominant here. The predictive capacity of the model developed in this chapter will be

tested by running the historic hydrodynamic scenarios (report 4) with this sediment transport model, which is part of report 7.

Residual transport of sediment

The reduction in sediment concentrations at the up-estuary stations during periods of high river discharge indicates that the residual flux related to river flushing is modelled realistically. The tide-induced up-estuary sediment flux is related to tidal asymmetry, for which the intra-tidal variation in currents and sediment concentration is most important. At the two down-estuary stations of Pogum and Terborg, the hydrodynamic asymmetry (see report 4) and the tidal variation in sediment concentration correspond to observations. Therefore the flux from the Ems Estuary to the lower Ems River seems to be reproduced. This is supported by the large up-estuary transport capacity of the model (2 million ton/year).

For the accumulation of sediment in the lower Ems River, the net sediment flux is important but for the Ems Estuary, the gross fluxes are evenly or even more important. The net up-estuary flux implies that sediment is extracted from the Ems estuary, which may lead to a reduction in SSC. The gross fluxes generate episodic sediment pulses from the lower Ems River into the Ems Estuary. This seaward flushing of sediment is represented in the model.

6.5 Summary

The physical processes in the lower Ems River are very complex, including extensive fluid mud formation (Talke *et al.,* 2009), consolidation and entrainment of the water-bed interface (Wang, 2010), sediment-induced turbulence suppression and probably also asymmetries in flocculation (Winterwerp, 2011). These processes are not included in the model: erosion (or entrainment in case of fluid mud) is parameterized with a simple erosion formula. The density of the sediment bed is set at 100 kg/m^3, creating a strong morphodynamic coupling of morphology and water flow. A depth-averaged concentration of 10 kg/m^3 and a water depth of 5 m correspond to 50 kg of resuspended sediment, which is equal to half a meter of eroded bed sediment. Such erosion volumes significantly influence flow velocities and therefore erosion rates and sediment dynamics. The transition from the water phase to the bed phase is gradual through the use of a hindered settling formula with a maximum sediment concentration equal to the sediment bed dry density.

Despite its simplicity, the sediment transport model in the ER model can reproduce typical sediment concentrations in the Ems River. At a number of stations, the computed intra-tidal and spring-neap variation in suspended sediment concentrations shows fair agreement with observations. Sediment is flushed seaward during larger discharge conditions. In the most up-estuary sections of the lower Ems River, this results in a pronounced decrease in suspended sediment concentration

The developed sediment concentration model will be used in report 7 to analyse historical changes in sediment dynamics (applying the model to the historical cases developed in van report 4), and the impact of the lower Ems river on the Ems Estuary.

7 Synthesis

Two sediment transport models have been developed, both for different purposes. Both these models, their suitability for scenario studies, and recommendations for future work are shortly summarised below.

7.1 The Ems Estuary

A large-scale model, aiming at long-term (several years) simulation of sediment dynamics throughout the Ems Estuary, has been calibrated against a number of SSC observations, bed sediment distribution, and sediment fluxes. The model is forced by river discharge, tides, wind, waves, and includes dredging and disposal. The difference between various suspended sediment concentration observations is similar to the differences between observations and model results. The sediment fluxes, including port siltation and resulting dredge volumes, are reproduced for the ports of Delfzijl and Eemshaven, but siltation (and hence dredging) is underestimated in the Emden navigation channel. The model is a tool which can be used to preliminary explore the effect of historic changes on the sediment dynamics in the Ems Estuary, and measures to improve the water quality of the estuary. Given the range in uncertainties in the present-day data, shortage of historic data, and simplifications in and shortcomings of the numerical model, such scenarios can only be interpreted qualitatively and relative to the baseline scenario (i.e. trends as a results of measures). In the model analysis (report 7), the effect of changing dredging strategies, port development, Wadden Sea concentrations, and morphology will be analysed. The computed (changes in) sediment concentration will also provide input for the primary production. In the scenario study (report 11), the model will be used to quantify the effect of measures on the water quality of the Ems Estuary.

7.2 The lower Ems River

This smaller-scale model is set up for the lower Ems River only. The model reasonably reproduces the (very high) suspended sediment concentrations in the lower Ems River, despite the use of fairly simple sediment transport formulations compared to the complexity of the sediment dynamics. Also the net import rates seem realistic (~2 million ton / year), in-between the annually dredged sediment mass and fluxes computed from ADCP transects. Based on this model, it seems that approximately 0.5 - 1 million ton may be annually flushed into the Ems estuary. The impact of historic changes in the lower Ems River on sediment dynamics will be analysed in more detail in report 7.

7.3 Scenario studies

The model chain developed in this report and report 4 (hydrodynamics) and report 6 (water quality) will be applied to explore mechanisms responsible for changes in suspended hydrodynamics, sediment concentrations and water quality in the Ems Estuary in the past decades (report 7) and to evaluate potential measures (report 11). In Chapter 2, a number of processes were defined which are important for the model to reproduce, in order to be suitable to explore the effect of changes in the system. The most important sediment transport processes were defined as:

c) Sediment transport mechanisms and typical sediment concentration levels as a result of tides, waves, and density-driven flows
d) Sediment trapping in ports and the long-term effect of subsequent dredging and dispersal on the suspended sediment concentration in the estuary.

The computed suspended sediment concentration in the WED model reproduces typical levels and asymmetries in sediment concentration levels, as well as the spring-neap variation. The intra-tidal variation is lower compared to measurements. The instantaneous tide-induced transport is therefore slightly underestimated, but within the proper range. The comparison with wave resuspension (which probably is important in the Dollard) is more difficult because the necessary data is not available. Residual sediment transport depends on density-driven flows and tidal asymmetries. Tidal asymmetries are relatively small in the Ems Estuary (not so in the lower Ems River). There is no data available for a quantitative comparison of transport by density-driven flow – a scenario analysis will be done in report 7. The computed sediment deposition in the ports of Eemshaven and Delfzijl is within several 10 percent of observations. The effect of dredging on sediment concentration then mainly depends on the buffering capacity of the sediment bed. With the buffering approach applied in this model, the effect should be reasonably approximated. Better quantifying the effect of dredging requires better data, including prolonged periods without dredging, which is difficult to realize.

The computed sediment concentration in the lower Ems River agrees less well to observations compared to the WED model. The agreement between computed and observed sediment concentration is best near the entrance of the lower Ems River (Pogum and Terborg), suggesting that the transport of sediment from Ems Estuary into the Ems River may be reasonably reproduced. Deeper into the lower Ems River, the intra-tidal variation becomes progressively worse: intra-tidal sediment redistribution is poorly reproduced here. The seasonal variation is better: during high discharge events the sediment is flushed seaward, in line with observations. The sediment transport model will be combined with hydrodynamic historic scenarios, in order to better understand the historic changes in the sediment dynamics of the lower Ems River.

7.4 Recommendations

Although the developed models reproduce the basic sediment dynamics of the estuary, some of the simulated processes can still be improved. The developed models can be improved by

- A more accurate representation of hydrodynamics (especially salinity and salinity driven-flow). This requires the development or use of a more accurate large-scale (North Sea) model to obtain spatially and time-varying salinity boundaries, and use of vertical z-layers instead of σ-layers.
- Adding process formulations related to high suspended sediment concentrations such as consolidation and flocculation.
- A full feedback between hydrodynamics, sediment dynamics and bed level. Such a full coupling (as used in the ER model) can be combined with the sediment transport model applied in the WED model, because the buffer model has been recently implemented in Delft3D sediment-online (in addition to Delwaq, where it was originally implemented).Such a full coupling may not be realistic though for studies in which several years have to be simulated, but may be useful to study specific processes at shorter timescales.
- Collection of continuous data, preferably at several strategic locations in the estuary, and covering several vertical positions.

The sediment transport model will be used to understand historic changes in the system (report 7) and explore the effect of mitigating measures (report 11). As any model, it is a schematisation of the real world, and is therefore limited by model assumptions, process descriptions and simplifications. The outcome of the sediment transport model (and the water

quality model it provides input for) should therefore be used as a tool to understand the functioning of the system, in addition to other sources of information. It is further recommended to

- Perform a more quantitative uncertainty analysis on individual model components (such as the sediment transport module) but also the interaction with the water quality model. This is part of future work that will be part of the final advise (report 12).
- Develop and compare the outcome (and underlying assumptions) of this model with other, comparable, models. This may provide insight into the effect of uncertainties on the simulated scenarios.

The most important long-term source of information available to detect changes in the system, but also to calibrate numerical models, are the MWTL observations. Especially in recent years, the MWTL data is inconsistent (unrealistically large salinity values as discussed in report 4, and the strong decrease in SSC discussed in Chapter 3 and 5 since 2012). It is recommended to increase the quality assurance on the MWTL data. It is also recommended to regularly analyse the MWTL data for (changes in) trends because these may reveal (important) changes in the system but also errors / inconsistencies in the collection of the data.

8 Literature

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