Mud dynamics in the Ems Estuary, phase 2

Model analysis

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1205711-001

Deltares

Title
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Client	Project	Reference	Pages
Rijkswaterstaat	1205711-001	1205711-001-ZKS-0005	92

Keywords
Ems River, Ems Dollard Estuary, Water Framework Directive, Hydrodynamic model, Sediment transport model, water quality model

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.

The suspended sediment concentration (SSC) in the Ems Estuary has probably been increasing in the past decades. The reasons for this apparent increase are still poorly understood, but higher SSC's may negatively impact primary production and the associated ecological status of the estuary. As part of this project, numerical models have been developed, which are applied to understand mechanisms that may have contributed to a change in the suspended sediment concentration and primary production. The main results of this analysis, reported here, are that (1) SSC in the lower Ems River increased as a result of deepening and associated reduction in hydraulic drag; (2) SSC in the Ems Estuary increased because of dredging strategies and deepening, and (3) pelagic primary production is light-limited whereas benthic primary production is nutrient-limited.

References
Offertenummer 1205711-000-ZKS-0004, toekenningbrief RWS/WD-2011/3497

Version	Date	Author	Initials	Review	Initials	Approval	Initials
0.1	May 2013	Bas van Maren					
1.0	Oct 2013	Bas van Maren		Han Winterwerp			
1.1	Dec 2013	Willem Stolte		Hans Los			
2.0	Jun 2014	Bas van Maren		Johan Boon			
2.1	Okt 2014	Willem Stolte		Hans Los			
3.0	Okt 2014	Bas van Maren					
3.1	Nov 2014	Willem Stolte		Marcel Taal			
4.0	Dec 2014	Bas van Maren		Marcel Taal			
4.1	Feb 2015	Anna de Kluijver					
4.2	Mar 2015	Willem Stolte		Hans Los			
5.0	Jun 2015	Willem Stolte		Hans Los		Frank Hoozemans	

State
final

Contents

1 Introduction

1.1 Project setting

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).

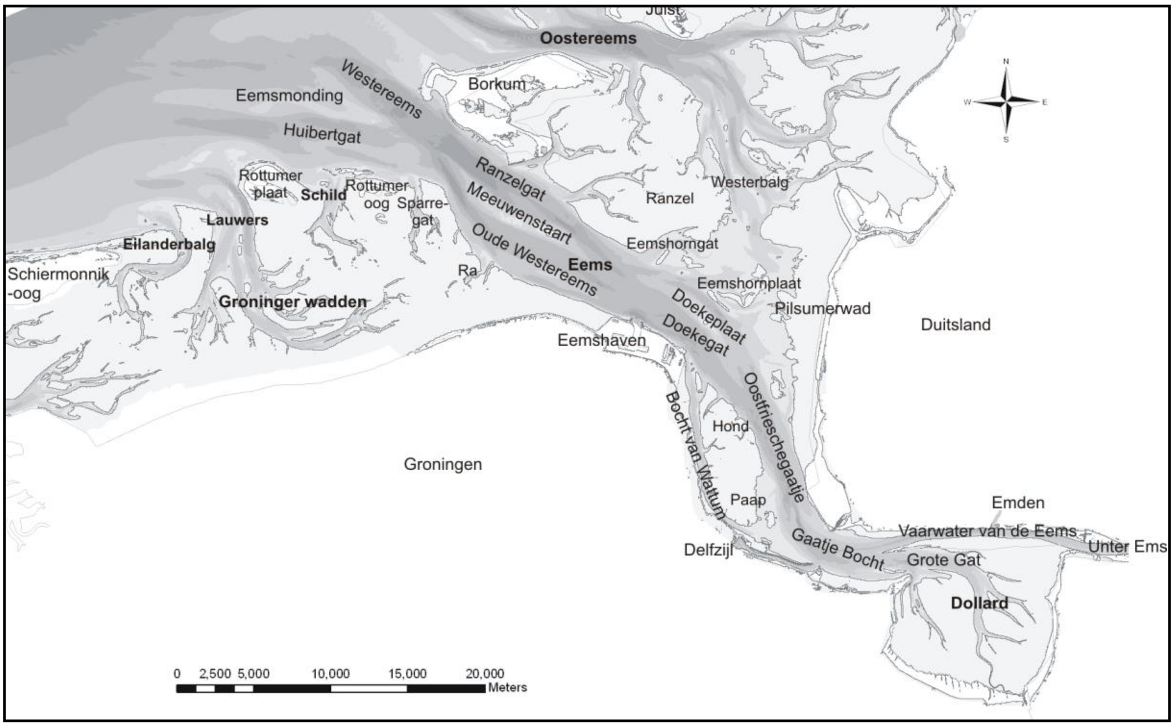

Figure 1.1 Map of Ems Estuary with names of the most important channels and flats (Cleveringa, 2008) in Dutch and German. The English name of the 'Vaarwater van de Eems' is the Emden navigation channel or Emden Fairway. The English name of 'Unter Ems' is the lower Ems River.

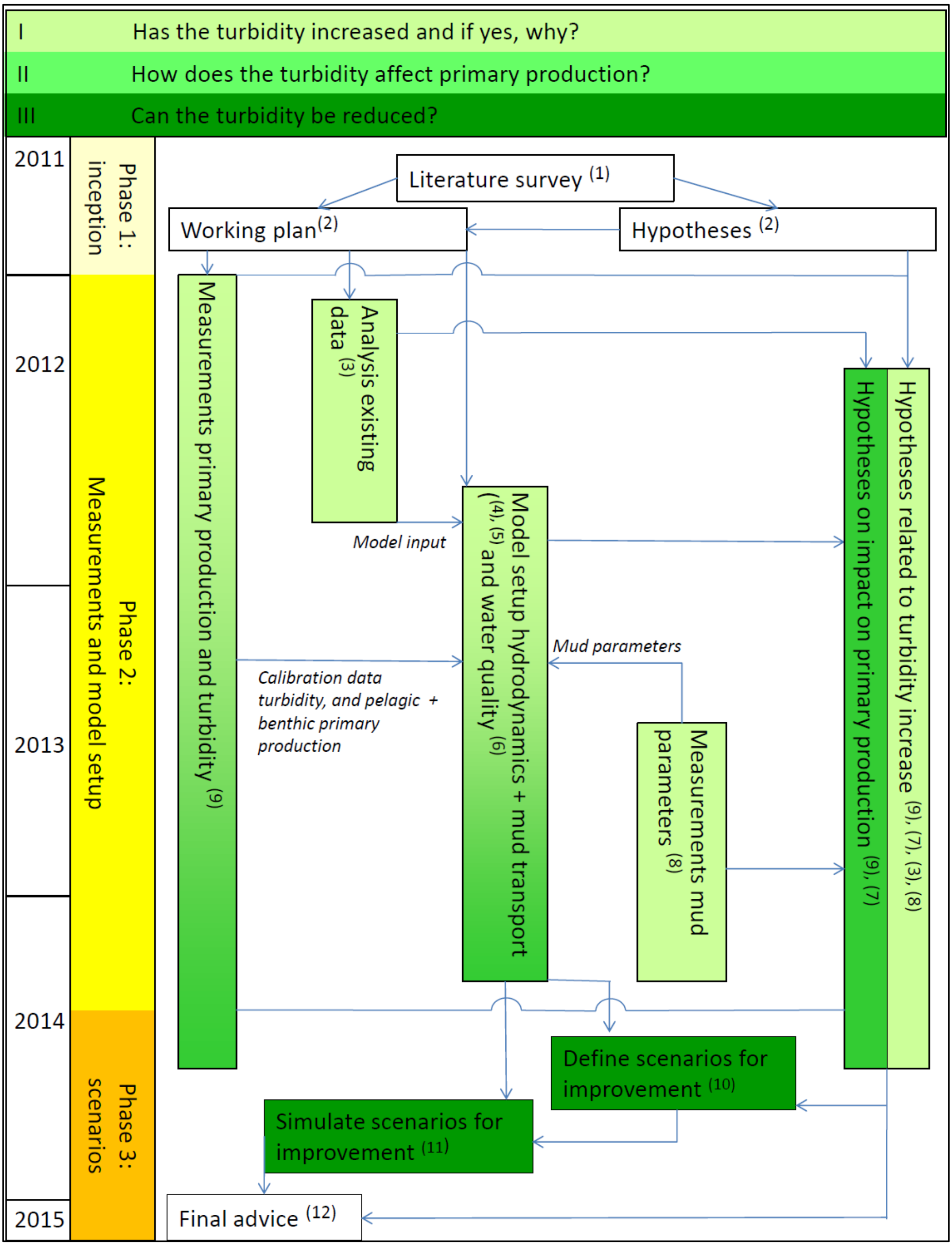

Figure 1.2 Flow chart for the structure and timetable of the study. Green colouring of the phase 2 activities relates to the colour of the main research questions I, II, and III. See Box 1 for a description and Table 1.1 for the references (1) – (12).

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

The structure of this report is as follows. In section 1.2, the hypotheses as formulated in report number 2 (see Table 1.1) are summarised, and their analysis is described. In chapter 2, a short description of the applied numerical models is given. Chapter 3-5 addresses the hypotheses related to hydrodynamics and sediment dynamics, of which Chapter 3 focusses on changes in the lower Ems River, Chapter 4 on changes in the Ems Estuary, and Chapter 5 on external changes. Chapter 6 addresses hypotheses related to primary production. The results are summarised in Chapter 7.

1.2 Hypotheses

In phase 1 of the project (report number 2 in Table 1.1), a number of hypotheses were formulated on changes in suspended sediment dynamics and water quality, which will be tested with a combination of models, data and expert judgement. The hypotheses formulated in report 2, related to **suspended sediment dynamics** and **hydrodynamics** are:

1) *Based on a statistical analysis of MWTL data on suspended matter, it can be proven that the increase in the sediment concentration in the Ems estuary is statistically significant.*
2) *The sediment dynamics in the Dutch Eastern Wadden Sea have remained constant despite changes in salt marsh works and biological factors. As long as the hydrodynamics in the Ems Estuary remain unchanged, so does the flux from the Dutch Eastern Wadden Sea into the Ems Estuary.*
3) *Sediment trapping in the Lower Ems River (the tidally influenced part of the river Ems) should lead to a reduction of the total sediment mass in the Ems estuary. This is partly compensated or reversed through flushing at high river discharge events. This exchange of sediments between the Ems estuary and Lower Ems River is strongly influenced by the Geisedam.*
4) *The sediment concentration in the Ems Estuary has increased because of a loss of tidal flats, leading to (1) modified tides and (2) less sediment sinks.*
5) *The sediment dynamics in the Dollard area have marginally changed, so the Groote Gat station (where the sediment concentration does increase) is not representative for the Dollard area.*
6) *Sea level rise does not change the sediment dynamics of the Ems estuary.*
7) *The sediment concentration in the Ems Estuary has increased due to dredging and dumping activities because of:*
    a. *recirculation processes*
    b. *fining of the sediment bed (i.e. the grainsize of the sediment in the bed becomes finer over time).*

8) *Long-term natural and anthropogenic changes in the intertidal areas and the tidal channels of the Ems Estuary have sufficiently modified the tidal propagation to significantly influence sediment dynamics.*
9) *The deepening and realignment of the lower Ems River has so much influenced the tides in the Ems Estuary that (1) the Ems Estuary is importing more fine sediments from the North Sea and (2) the Lower Ems River is importing more fine sediments from the Ems estuary.*

Hypothesis 1 states that the suspended sediment concentration has increased, whereas hypotheses 2 to 9 provide mechanisms responsible for this increase. It was shown in report 3 (Table 1.1) that the suspended sediment concentration in the Ems Estuary has indeed significantly increased in the past 20 years (see Figure 1.3 for a summary), although the most recent SSC observations suggest that the concentration may have decreased again since 2011 – see section 3.3.2 in report 5. Hypotheses 2 to 8 will be addressed in three chapters of this report, using the models developed in reports 4 and 5 and using data introduced in report 3. A distinction is made between effect of changes in the lower Ems River (chapter 3, hypothesis 3 and 9), changes in the Ems estuary (chapter 4, hypothesis 4, 5, 7, and 8) and external forcing (chapter 5, hypothesis 2 and 6).

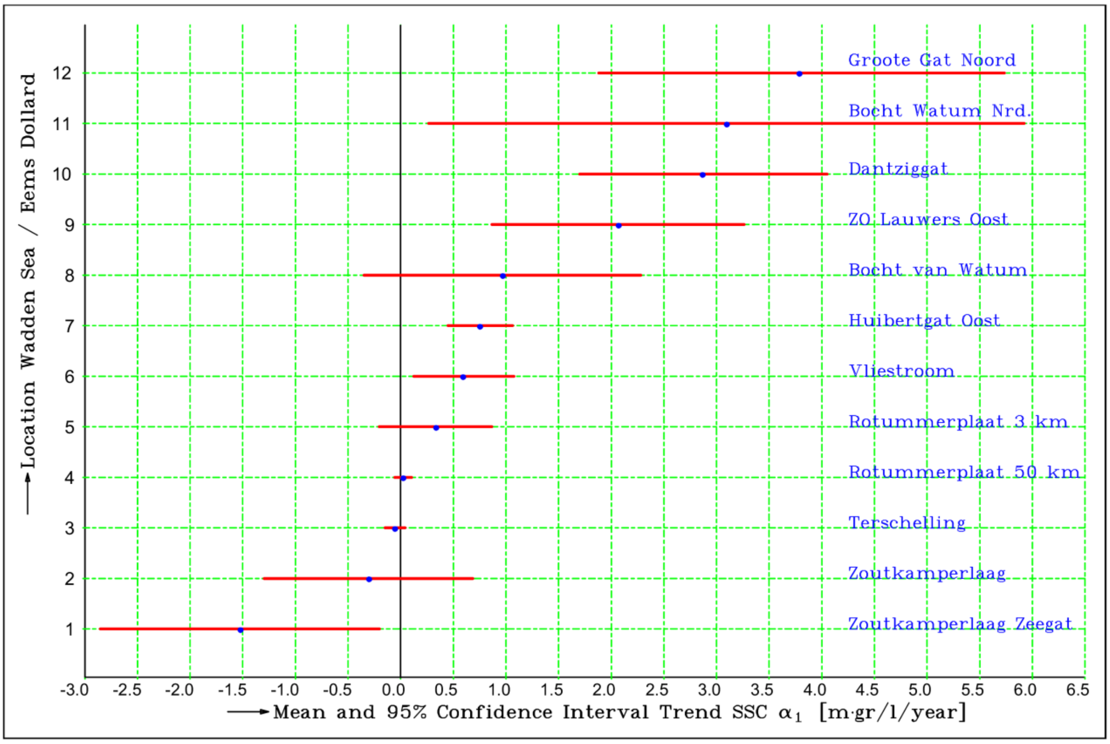

Figure 1.3 Change, and 95% confidence interval, of suspended sediment concentration, at 12 subsequent locations in the Wadden Sea and the Ems estuary measured from 1990 to 2011 at the surface. See Report 3 for details.

The formulated hypotheses related to **water quality** will be discussed in chapter 6, and are:
1) ***Pelagic primary production is controlled by turbidity in the Estuary.***
2) ***Benthic primary production is mainly controlled by nutrients and resuspension.***
3) **Measures to reduce turbidity in the estuary will increase the primary production by phytoplankton and therefore contribute to higher carrying capacity for higher trophic levels.**
4) **The effect of decreased nutrient loads from land will reduce the benthic production, counteracting the effect of decreased turbidity in the estuary.**
5) **Changes in turbidity and nutrient availability will change algal composition.**

6) *The carrying capacity for higher trophic levels in the ecosystem, reflecting in the primary production, has been reduced since the late seventies as a consequence of increased turbidity*
7) ***The three MWTL stations in the Ems Estuary are sufficiently representative in order to estimate the ecological status with regard to phytoplankton abundance.***

Hypotheses 1, 2 and 7 will be investigated with a combination of literature research, monitoring and model analysis. Hypotheses 3, 4 and 5 will be primarily studied with the numerical model. Hypothesis 6 will be mainly addressed using literature research. The hypotheses in bold are those where the model can contribute, italics indicate a contribution from monitoring data. The used model is a Delft3D water quality and primary production model for the Ems estuary. It describes the transport and fate of nutrients, algae, and detritus as a function of external forcing functions and loadings.
The aim of this section is to provide a summary of model results and scenario results and to discuss the model capability to answer the hypotheses and the model derived answers. A detailed description of the model setup and calibration/validation can be found in report 6 and detailed results of the scenarios are described in report 8.

2 Description of the 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, sediment transport and water quality (reports 4, 5 and 6 in Table 1.1).

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 section 1.2). 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 this report (chapter 3 and 4);
c) and d) in report 5 and this report (chapter 3 and 4);
e) in report 6 and this report (chapter 6);

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.

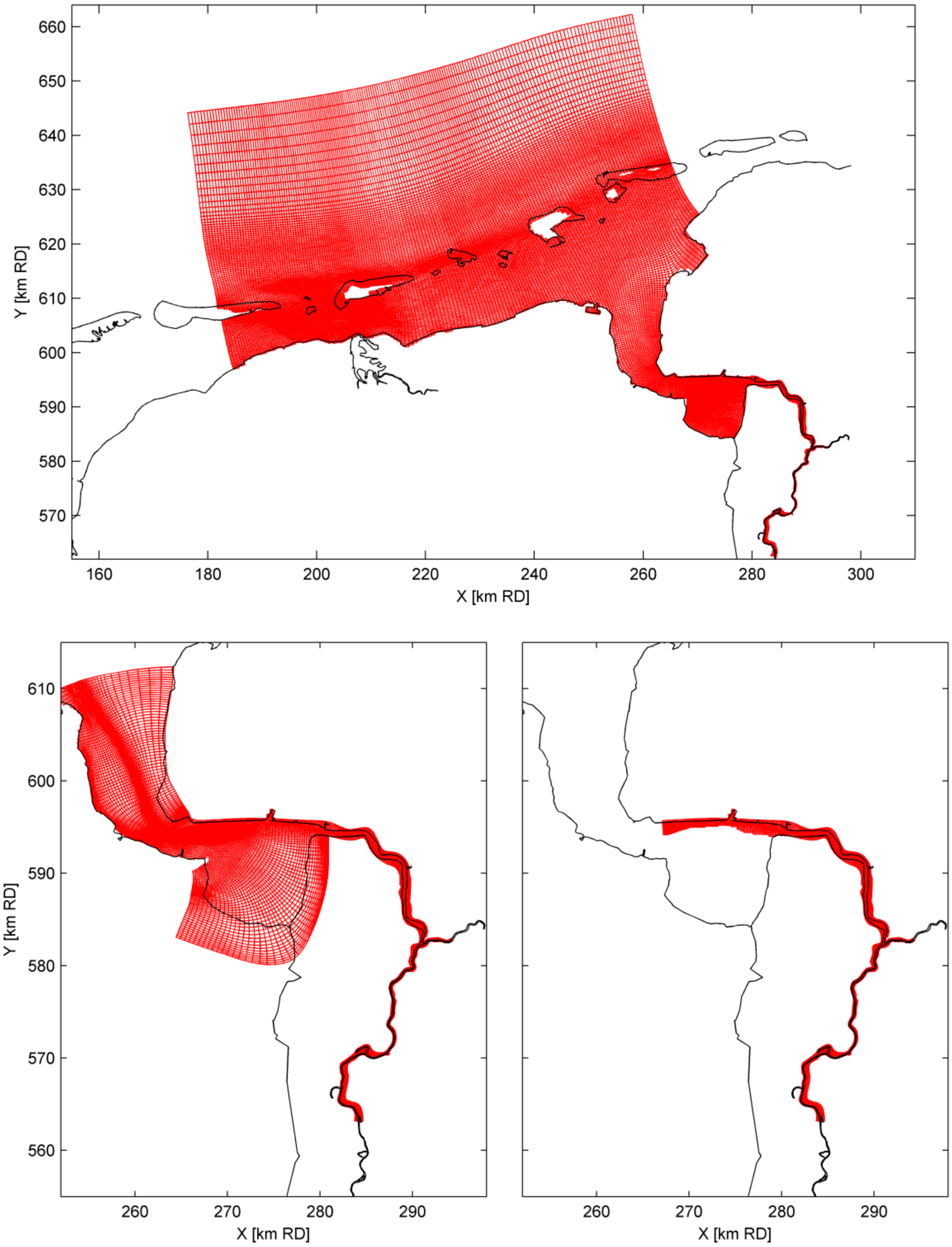

Figure 2.1 Computation grid of the WED model (top), the ERD model (lower left), and the ER model (lower right).

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.

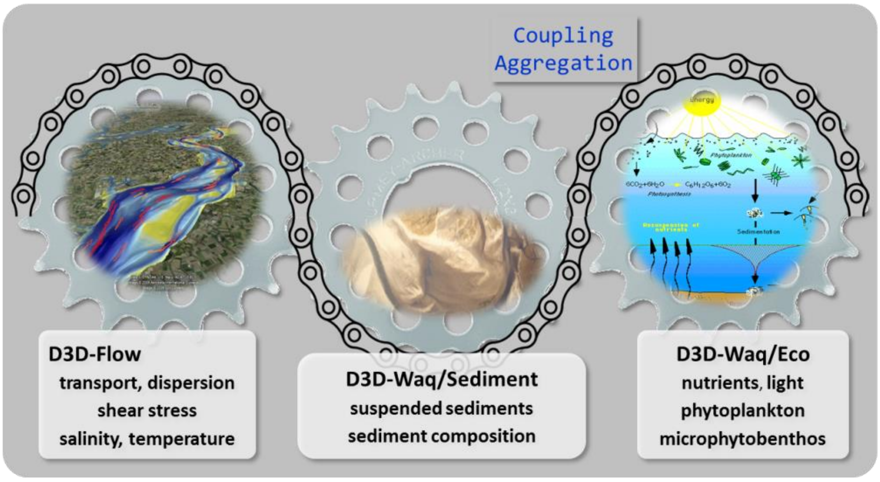

Figure 2.2 General set up of a linear effect-chain model.

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 changes in the Ems Estuary in the past decades but also to estimate the effect of proposed measures to improve the turbidity and primary production (Report 11).

The WED **hydrodynamic model** (described in report 4) simulates tides, salinity-driven flow and wind-driven flow, forced at the open boundaries by river flow and water levels (tides and storm-induced setup) and at the water surface by a time-varying wind. Boundary conditions are setup for the year 2012 (the reference conditions of the model) and 2013. A SWAN wave model is setup to simulate wave-induced bed shear stresses. The model has been compared against a large number of water level and salinity observation stations, and two velocity observation stations. Hydrodynamic historic scenarios with the WED model are set up by changing the bed topography of the model (using realistic observations for 1985 or closing the ports for a more theoretical scenario). With unchanged boundary conditions, such a historic scenario will reveal effects of topography on hydrodynamics (and the sediment and/or water quality modules).

The WED **sediment transport model** (described in report 5) computes the transport of fine sediment (mud). 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, unfeasible 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 (this is not the case for the lower Ems River, for which the ER and ERD models discussed hereafter were developed). And thirdly, in Delft3D-WAQ sediment transport processes are available (the buffering of fine sediment, using the so-called buffer model developed by van Kessel et al. (2011) which are important for description of estuarine sediment dynamics (see also section 3.4).

This buffer model has a two-layer bed module, where fine sediment is stored permanently or temporally in a low-dynamic lower layer of in a dynamic upper layer. Dredging and disposal is integrally modelled (sediment depositing in ports is regularly dredged and disposed on disposal locations through a dredging routine). A sediment model requires a finite time period to reach dynamic equilibrium (where changes in the sediment concentration vary over the tidal period and year but are not determined by initial conditions). Dynamic equilibrium is obtained by running the model for several consecutive years, until model realisations per year become similar. Dynamic equilibrium needs to be re-established for each historic scenario. The model has been compared against snapshot suspended sediment concentration observations collected throughout the estuary and the year, two long-term suspended sediment measurement stations at the estuary mouth, port siltation, and the spatial distribution of mud.

The **water quality/primary production model** (described in report 6) builds on the generic and open source software Delft3D Water Quality (http://oss.deltares.nl/). Transport and dispersion of water and substances builds on the WED hydrodynamic model mentioned above. Suspended sediment concentrations, important to calculate light availability for primary production, builds on the WED sediment transport model. The water quality/primary production model simulates light extinction considering extinction by dissolved organic substances, phytoplankton, dead particular material, inorganic particulate material and a background extinction. Generic formulations and coefficients were chosen to maintain consistency with similar models for other water systems. Primary production, phytoplankton biomass, and chlorophyll-a were simulated using the GEM-BLOOM module (Blauw et al., 2008; Los & Wijsman, 2007). Nutrient cycles are simulated using generic formulations, including layered sediment with early diagenesis of organic material, and sediment-water exchange of nutrients (Smits & Van Beek, 2013).
The water quality/primary production model was first calibrated with regard to observed light extinction by modifying the modelled suspended sediment. Once extinction was simulated correctly, pelagic primary production was simulated reasonable to well using generic descriptions of primary production and chlorophyll-a development. The model was calibrated against MWTL data for 2012, and validated against monitoring data that were collected as part of this project (Report 9), and MWTL data for 2013.

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

The exchange of sediment between the lower Ems River and the Ems Estuary may be important for the sediment dynamics in the Ems Estuary (and therefore part of the hypotheses formulated in report 2). It is known that the lower Ems River became significantly more turbid in the last decades (e.g. de Jonge et al., 2014), and presently the lower Ems River is a hyper-concentrated system with very limited ecological value. In order to better understand the potential impact of changes in the lower Ems River on the Ems Estuary, models have also been developed which specially aim at describing the tidal and sediment dynamics in the lower Ems River (the Ems River (ER) and Ems River Dollard (ERD) models).

The ecological state of the lower Ems River is not part of the current study, and therefore no water quality models are developed for this area.

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 ERD model is not used in this study.

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. The historic topography and hydraulic roughness has been setup for four years in report 4 (1945, 1965, 1985, and 2005), which will be used in this report to analyse historic trends.

3 Changes in the lower Ems River

This chapter describes the impact of changes in the lower Ems River on the suspended sediment dynamics within the lower Ems River and on the hydrodynamics and sediment dynamics of the Ems estuary (hypothesis 3 and 9 related to **suspended sediment dynamics** and **hydrodynamics**).

3.1 Introduction

The present-day lower Ems River (see Figure 3.1) is characterized by thick and mobile mud suspension up to 200 kg/m^3 (Papenmeier et al., 2013) which migrates up and down the estuary with the tide over several 10's of km. At low river flow high sediment concentrations are measured up to Herbrum, where a weir in the river has been constructed (Talke et al., 2009). The suspended sediment concentration has been increasing for decades (de Jonge et al., 2014) and the river probably became hyper-turbid somewhere in the 1990's, but the exact timing of the fluid mud appearance is difficult to establish because of limited data availability.

The appearance of fluid mud was accompanied by a decreasing hydraulic drag in the estuary, inferred from an analysis of long-term water level observations with an analytical model (Winterwerp and Wang, 2013; Winterwerp et al., 2013). Recent semi-analytical model studies relate the up-estuary shift of the Estuarine Turbidity Maximum (ETM) to changes in tidal asymmetry (Chernetsky et al., 2010), the length of the lower Ems River (Schuttelaars et al., 2013) and deepening (de Jonge et al., 2014). These semi-analytical models lack the bathymetric complexities, sufficiently detailed hydrodynamics and the non-linear sediment transport processes. Therefore, process-based numerical transport models should be applied to describe the non-linear behaviour. Accumulation of sediment in the lower Ems River may lead to lower suspended sediment concentrations in the Ems estuary (since the river acts as a net sediment sink), although sediment flushing during high discharge events may have the opposite effect. The aim of this chapter is to improve understanding of

1) The mechanisms responsible for the increase in turbidity in the lower Ems River
2) The impact of net accumulation in, and seasonal flushing of sediments from the lower Ems River on the sediment concentration in the Ems estuary.
3) The effect of deepening on tides in the Ems estuary (and resulting sediment dynamics there).

These questions are part of hypotheses 3 and 9:

3) *Sediment trapping in the Lower Ems River (the tidally influenced part of the river Ems) should lead to a reduction of the total sediment mass in the Ems estuary. This is partly compensated or reversed through flushing at high river discharge events. This exchange of sediments between the Ems estuary and Lower Ems River is strongly influenced by the Geisedam.*
9) *The deepening and realignment of the lower Ems River has so much influenced the tides in the Ems Estuary that (1) the Ems Estuary is importing more fine sediments and (2) the Lower Ems River is importing more fine sediments.*

Analysis of the exchange between the lower Ems River and the Ems estuary is complex because there is no single model that simulates the processes in the Ems River and in the Ems Estuary simultaneously. The large time and spatial scales required for modelling the Ems Estuary (simulation of a large domain over multiple years) conflict with requirements for the lower Ems River (requiring a higher horizontal and vertical resolution, as well as full coupling between the flow, sediment transport and morphology). This is described in report 5 (Table 1.1). As an alternative, we evaluate changes in the Ems River with a separate model (the ER model). The effect of the Ems River as a sediment sink is investigated with the WED model by extracting sediment from the entrance of the lower Ems River. The effect of sediment flushing from the lower Ems River into the Ems Estuary is prescribed as an additional source in the WED model. Although this is not realistic (the Ems River is a sink, and not a source of sediment), it does provide important information on (1) the spatial extent of the influence of the lower Ems River on the (fine) sediment dynamics in the Ems Estuary (especially the available amounts), and (2) the period of the year when the influence by the lower Ems River is more or less important.

The impact of the Geisedam on the exchange of sediments between the Ems estuary and the lower Ems River is not analysed. Increased insight in the functioning of the Geisedam (since the hypotheses where formulated) learned that the Geisedam has so much influenced morphological developments in the area (report 3) that studying the effect of the Geisedam alone (by e.g. removing the structure in the simulations) has no physical meaning, as long as the dam-induced morphological changes remain in the bed topography. These dam-induced morphological changes are not known and any assumptions therein are speculative.

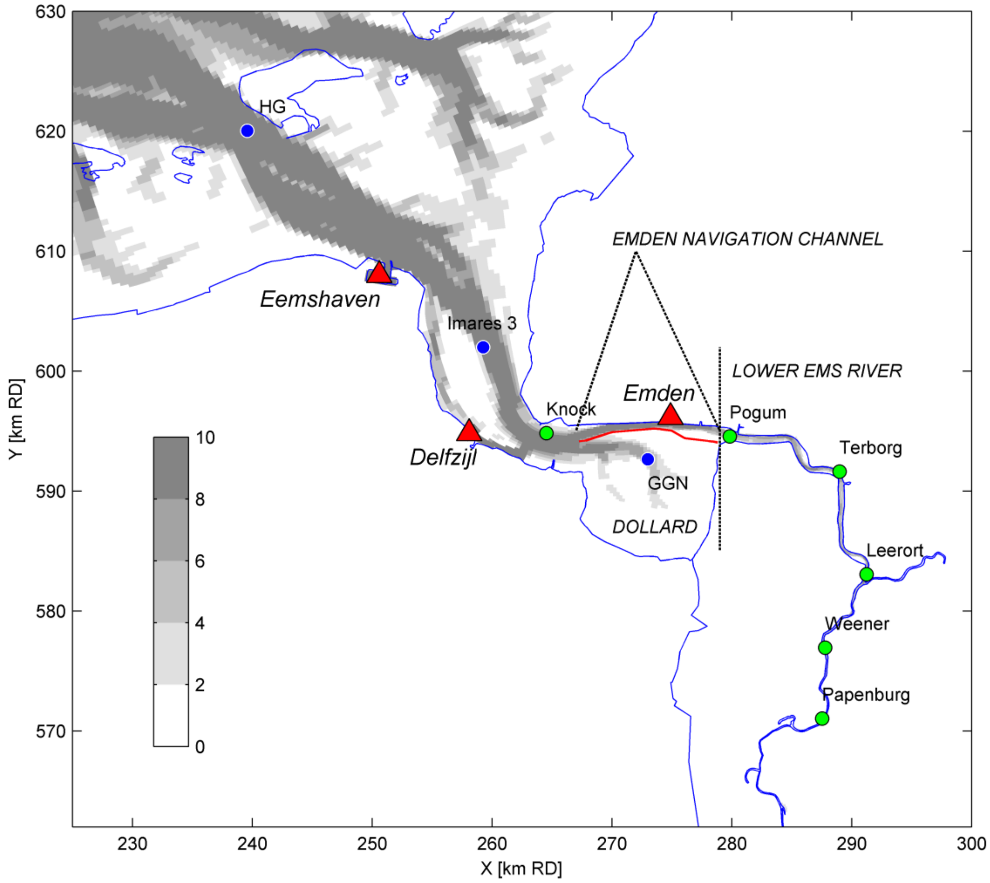

Figure 3.1 Map with model bathymetry (only depth between 0 and 10 m shown to highlight the difference between tidal channels and flats) of the Ems Estuary, including the main ports (Eemshaven, Delfzijl, and Emden, denoted with red triangles) and observation points used in this chapter. The sediment concentration stations (Imares3, HG (= Huibertgat) and GGN (= Groote Gat Noord)) are in blue. Stations in the lower Ems River, with data supplied by the NLWKN, are green. The Emden navigation channel connects the Lower Ems River (up-estuary of Pogum) with the Ems Estuary near Knock. The Emden navigation channel is separated from the Dollard by the Geisedam (red line).

The effect of deepening (hypothesis 3) on sediment transport processes within the lower Ems River is elaborated in section 3.2. The impact of these changes on the turbidity in the Ems estuary (hypothesis 3) and the effect of deepening of the Ems River on tides in the Ems Estuary (hypothesis 9) will be estimated in section 3.3. The accuracy of the applied models will be discussed in section 3.4; results are summarised and related to the hypotheses in section 3.5.

3.2 Impact on the lower Ems River

In this section the impact of historical changes in the lower Ems River on the sediment dynamics in the lower Ems River itself is quantified. It explains how deepening, tidal amplification and sediment transport are inter-related and what this implies for restoration of the river. The present-day sediment transport mechanisms are discussed in section 3.2.1, using the sediment transport model and observations. The change in these transport mechanisms over time are subsequently addressed in section 3.2.2. The impact of these results on the present-day state of the lower Ems River, and implications for restoration, are addressed in section 3.2.3.

3.2.1 Present-day sediment transport mechanisms

Sediment is transported into the lower Ems River, and subsequently re-distributed, by a combination of estuarine circulation, 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). Several studies stated that sediment is probably flushed out of the lower Ems River by river discharge (Postma, 1981; Spingat and Oumeraci, 2000; de Jonge et al., 2014). The relative importance of tidal asymmetry and river discharge on suspended sediment transport can be quantified in detail with the numerical model developed in report 4 and 5. We will first analyze the 2005 model runs to quantify the present-day sediment transport mechanisms, and subsequently analyze historic model scenarios to understand which mechanisms were critical to the observed increase in suspended sediment concentration in the lower Ems River.

Any asymmetry in the hydrodynamics (spatially or temporarily) will generate residual transport of fine sediment, as long as the sediment particles have a finite settling velocity and critical shear stress for erosion (van Maren and Winterwerp, 2013). An asymmetry in flow velocity can be induced by residual flow and by tidal asymmetry. Tidal asymmetry is a persistent, tide-generated difference in ebb and flood velocities, which can manifest itself in different maximum flow velocities (and consequently different durations of ebb and flood) but can also have the form of a difference in slack tide duration (with equal ebb and flood velocities).

In the Ems River, the main source of tidal asymmetry is the interaction of M_2 with its principal overtide M_4 (report 4) and consequently this type of tidal asymmetry is determined by the phase lag in the depth-averaged flow velocity of these two constituents: $\theta_u = 2\phi_{u_{M2}} - \phi_{u_{M4}}$. For θ_u = -90 to 90^o, the peak flood flow velocity is larger than the peak ebb flow velocity (with maximum asymmetry at θ_u = 0^o); see e.g. Friedrichs and Aubrey (1988). Since fine sediment transport typically scales with u^3 to u^4, larger peak flood flow velocities lead to landward transport. For θ_u = 0 to 180^o, the duration of HW slack is longer than that of LW slack. Sediment transported landward during flood therefore has a longer period to settle at slack tide, than sediment transported seaward during ebb, resulting in net landward transport. The computed velocity phase differences θ_u decrease from ~100^o (Knock) to ~0^o (Papenburg), much in line with the observations by Chernetsky et al. (2010), see Figure 3.2.

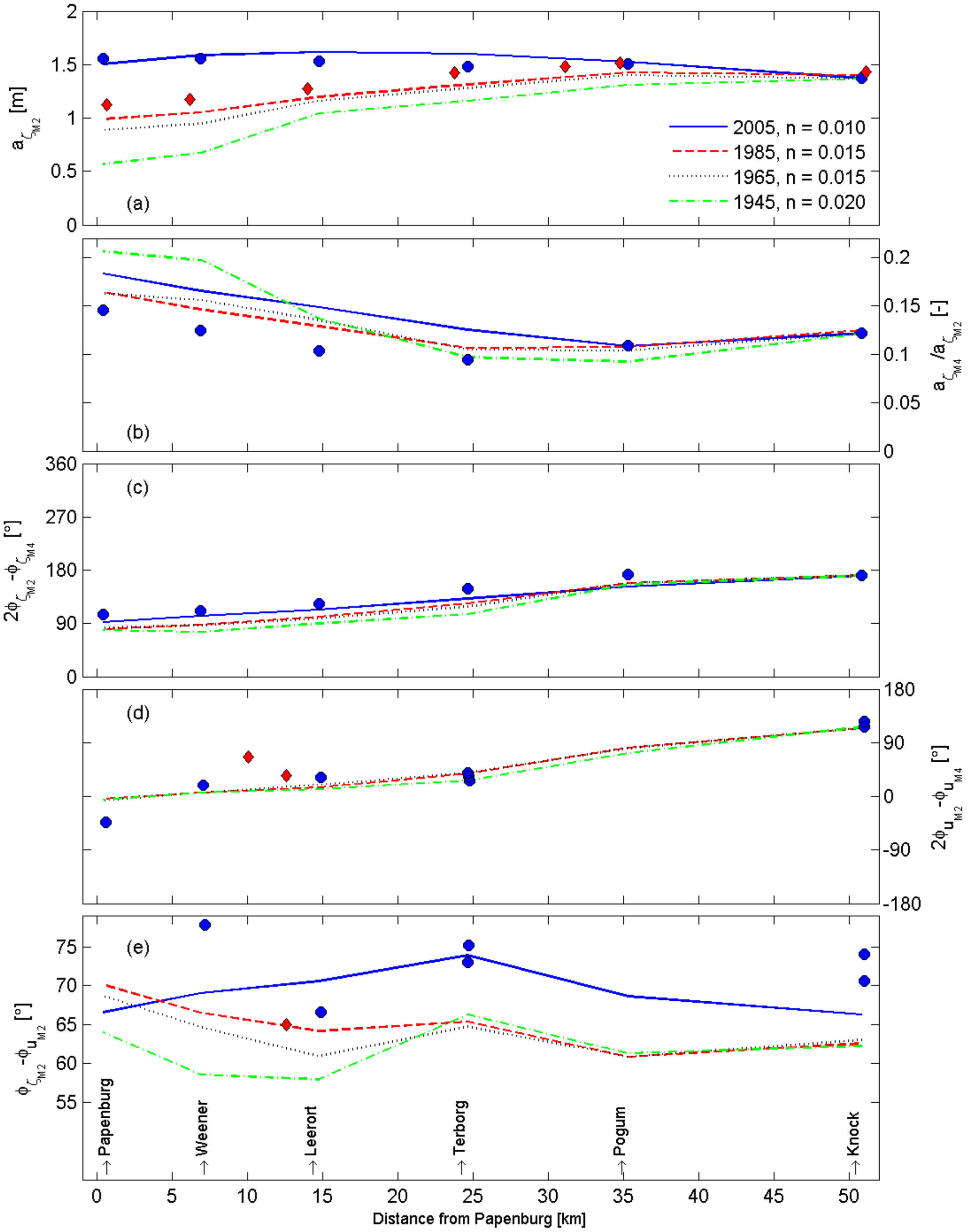

Figure 3.2 *Panel (a): waterlevel amplitude of* M_2 $a_{\zeta_{M2}}$ *in 1945, 1965, 1985, and 2005 (with 2005 observations from available data (blue dots) and observations in 1980 from Chernetsky et al., 2010 (red diamonds)). Panel (b): amplitude ratio of* M_4 *to* M_2 $a_{\zeta_{M4}}/a_{\zeta_{M2}}$ *(with 2005 observations in blue dots). Panel (c) and (d): phase difference between* M_2 *and* M_4 *for waterlevels (* $2\phi_{\xi_{M2}} - \phi_{\zeta_{M4}}$ *) and depth-averaged flow velocity* $2\phi_{u_{M2}} - \phi_{u_{M4}}$*, with data on* $2\phi_{u_{M2}} - \phi_{u_{M4}}$ *from Chernetsky (2010). Panel (e): phase difference between water levels and depth-averaged flow velocity* $\phi_{\xi_{M2}} - \phi_{u_{M2}}$*, with data from Chernetsky (2010).*

The corresponding change in waterlevel asymmetry $\theta_\zeta = 2\phi_{\xi_{M2}} - \phi_{\zeta_{M4}}$ is approximately a shift from 180^o at Pogum to 90^o at Papenburg (from the lower left to the upper right panel in Figure 3.3). However, the exact relation between the type of asymmetry (determined by θ_u) and θ_ζ depends on the phase difference between water levels and flow velocity $\phi_{\xi_{M2}} - \phi_{u_{M2}}$. In the lower Ems River, this phase difference is typically 65 to 75^o (Figure 3.2). For such a phase difference, HW slack tide dominates from θ_ζ = 70 to 250^o (maximum at θ_ζ = 160^o) and flood flow asymmetry tide dominates from θ_ζ = -20 to 160^o (maximum at θ_ζ = 70^o). The computed water level phase differences θ_ζ decrease from ~170^o (Knock) to ~90^o (Papenburg), supported by the observational data (see report 4 for details). Therefore the tides evolve from HW slack-tide dominant at the entrance (Pogum) to flood-dominant up-estuary (Papenburg).

This evolution from HW slack water asymmetry to flood flow asymmetry can also be observed in measured and modelled Suspended Sediment Concentration (SSC). The LW slack tide period at Pogum and Terborg is so short that the flood concentration peak immediately follows the ebb concentration peak (Figure 3.4), and little or no sediment settles. The HW slack period is much longer and sediment transported up-estuary has time to settle on the bed. Such a mechanism effectively transports sediment up-estuary (Dronkers, 1986), possibly the main mechanism behind the large up-estuary transport illustrated in Figure 3.5. The model does not exactly reproduce the measured SSC levels, but the asymmetries are very similar (especially in Pogum). These asymmetries strongly influence the residual sediment transport, and with Pogum at the entrance of the Ems River, the sediment flux into the river is reproduced by the model. Further upstream (Leerort and Papenburg) the sediment concentration becomes more asymmetric, with higher sediment concentrations during the flood than during the ebb, characteristic for tides with a peak flood flow asymmetry (see report 5 for details).

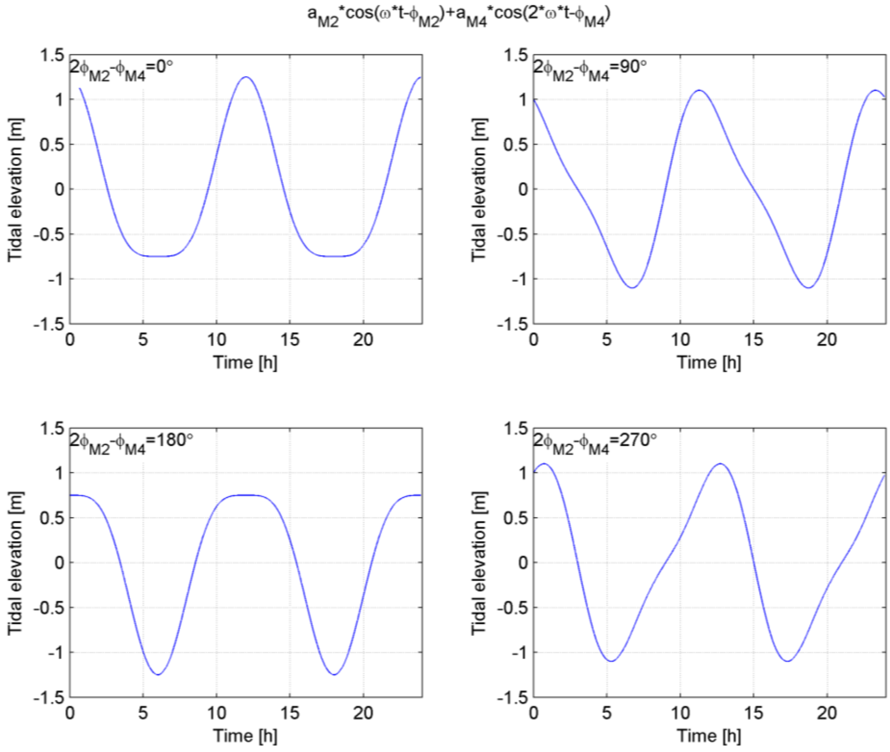

Figure 3.3 Four end members of tidal asymmetry in water levels resulting from the M_2 and M_4 tidal constituents for different values of $\theta=2\varphi_{M2}-\varphi_{M4}$

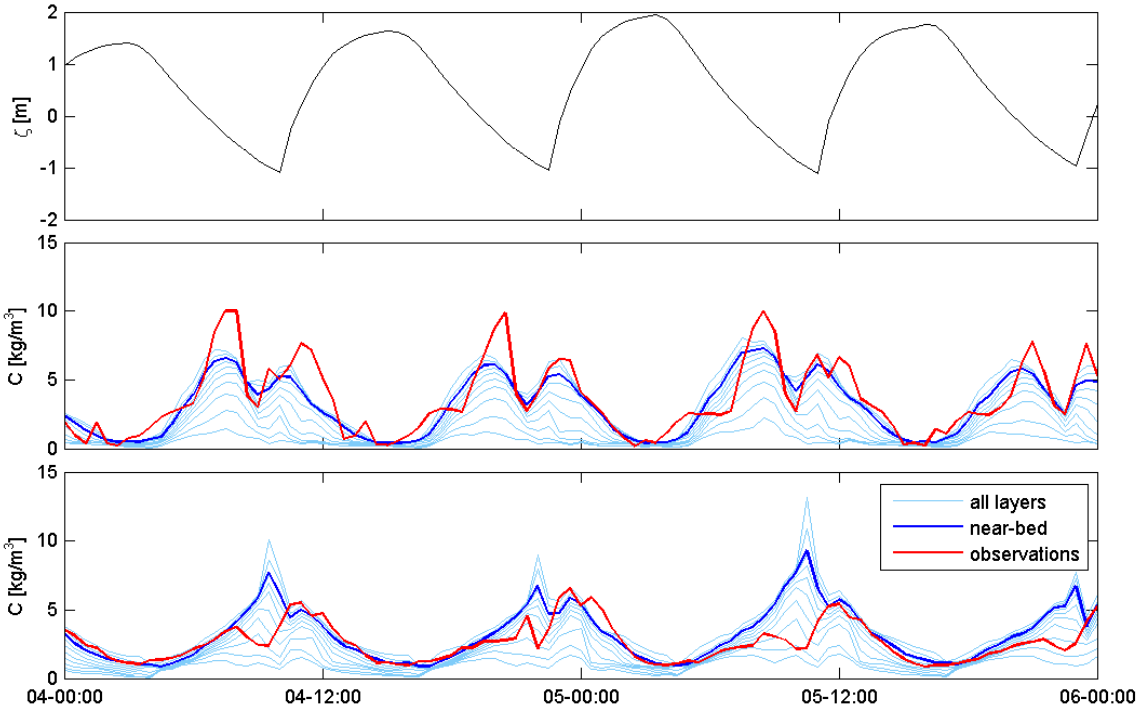

*Figure 3.4 Top panel: computed waterlevel at Pogum for reference.
Second and third panel: observed (red line) and computed sediment concentration on 4-5 December 2005 at Pogum (2nd panel) and Terborg (3rd panel). The dark blue line represents the computed average sediment concentration in the lower 10 to 30% of the water column that best approximates the location of the sensor. The light blue lines depict the computed sediment concentration per layer, indicating the vertical variation in SSC.*

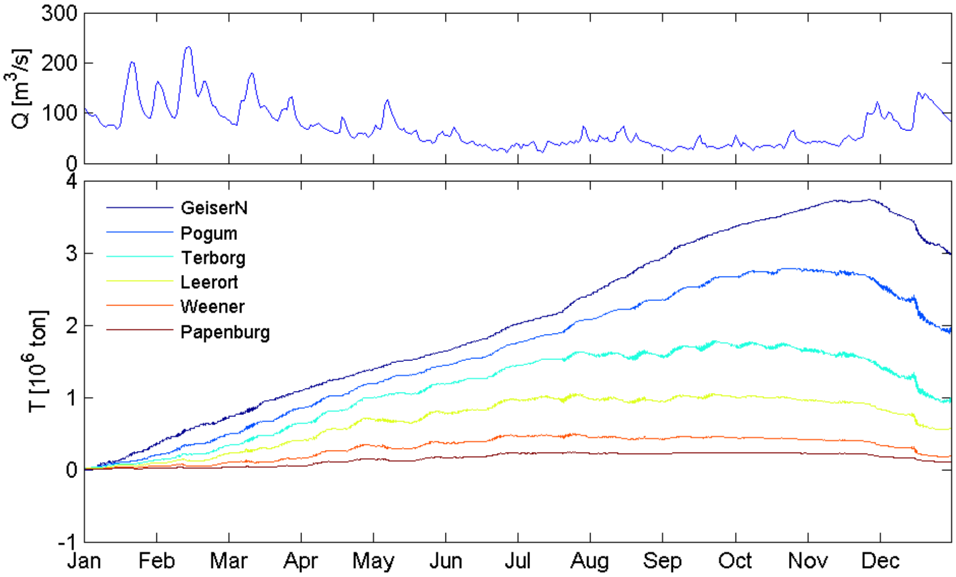

Figure 3.5 Cumulative sediment transport into the Lower Ems River; the cross-section GeiserN is close to the model seaward boundary.

A measure for the degree of asymmetry is $a_{\zeta_{M4}} / a_{\zeta_{M2}}$, the water level amplitude ratio of M_2 and M_4, which increases in up-estuary direction. Even though the model reproduces $a_{\zeta_{M2}}$ reasonably, the increase in $a_{\zeta_{M4}} / a_{\zeta_{M2}}$ (and therefore $a_{\zeta_{M4}}$) upstream of Terborg is overestimated (report 4). So even though the transition from HW slack tide to flood-dominant tides (determined by θ) is well captured, the model overestimates the degree of the flood-dominant tidal asymmetry.

The suspended sediment concentration is determined by the net effect of two mechanisms. One mechanism is driven by slack tide asymmetry and peak flow asymmetry and results in an up-estuary sediment transport. The other mechanism is driven by river discharge and results in a down-estuary transport of sediment by flushing (Spingat and Oumeraci, 2000). Flushing occurs during large discharge events where the river-induced flow velocity is so large that the majority of water (and possibly sediment) is flushed out of the lower Ems River within several weeks. The effect of flushing can be evaluated with the relationships between the river discharge Q and the bed shear stress τ_b (see Figure 3.6). The net effect of both opposing mechanism is illustrated in Figure 3.5: sediment is transported up-estuary during the largest part of the year but transported down-estuary during large discharge events. At low river discharge, the bed shear stress τ_b is larger during flood than during ebb throughout the lower Ems River (Figure 3.6).

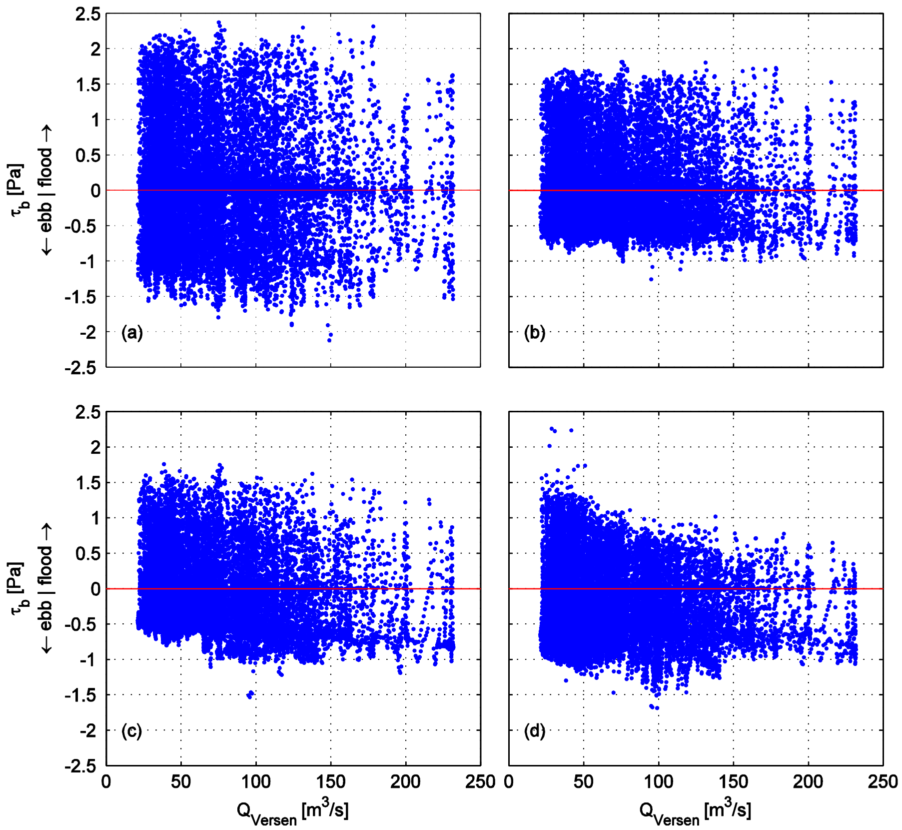

Figure 3.6 Computed bed shear stress τ_b as a function of river discharge at Pogum (a), Terborg (b), Weener (c) and Papenburg (d). A positive τ_b is in the flood direction, a negative τ_b is in the ebb direction.

With increasing river discharge, τ_b is reduced during the flood. This ‘flood-reduction’ of τ_b depends on the channel cross-section, and therefore increases in up-estuary direction. At Papenburg, τ_b peaks during ebb exceed τ_b peaks during flood at river discharges larger than 70 m^3/s. Since also the duration of ebb is larger than the duration of flood, sediment will be transported down-estuary from Papenburg at higher river discharges - see the sediment transport in December in Figure 3.5. At the more down-estuary stations τ_b remains larger during flood. Hence, even during fairly large river discharges, tidal asymmetry will generate an up-estuary sediment transport balanced by a river-discharge generated down-estuary transport.

As a result of the transport mechanisms discussed above, sediment accumulates in the upper reaches of the lower Ems River during low discharge conditions (resulting in high sediment concentrations, see Leerort in Figure 3.9) and is flushed seaward during larger discharge (resulting in highest concentrations near the river mouth during large discharges, see Pogum in Figure 3.9). In the next section, we will evaluate how sediment importing and exporting mechanism have changed in the past decades.

3.2.2 Historic scenarios

In report 4 a number of historic bathymetry scenarios were developed, based on qualitative interventions given in Table 3.1. Based on this information and the 2005 bathymetry, historic bathymetries for 1945, 1965 and 1985 were reconstructed using the thalweg depth (is the deepest part of the river) in combination with high water levels. To avoid a uniform, flat bed level, the 2005 bathymetry has been raised. In this way, small variations in the bathymetry (like deeper parts in outer bends) were preserved (see Figure 3.7). These scenarios were executed for a number of hydraulic roughness values that were compared to observed high and low water levels (see for instance station Papenburg in Figure 3.8). The year 2005 was extensively calibrated and required a low Manning’s *n* (0.01, typical for a muddy system) whereas 1965 was best approximated with *n* = 0.015. The roughness in 1945 should probably be higher than 0.015, and for 1985 in-between 0.01 and 0.015. This is in line with an observed transition (Krebs and Weilbeer, 2008) from a sand-dominated system (with typically large values for Manning’s *n*) to a mud-dominated system.

Table 3.1 Chronology of fairway deepening and other interventions in the lower Ems River, from Schoemans (2013), based on Herrling and Niemeyer, 2008, Krebs & Weilbeer, 2008, and pers. comm. Krebs (2013). MHW is Mean High Water and CD is Chart Datum.

Year	*Intervention*	*Historic scenario*			
		1945	*1965*	*1985*	*2005*
Before 1939	Emden fairway below -6 m CD				
1932-1939	Pogum-Leerort 5.5 m below MHW, Leerort-Papenburg 4.2 m below MHW				
1939-1942	Emden fairway at -7 m CD				
1942-1948	No maintenance dredging: Emden fairway at –5.8 m CD				
1957	Emden fairway at -8 m CD				
1961-1962	Leerort-Papenburg 5 m below MHW.				
1965	Emden fairway at -8.5 m CD				
1983-1986	Emden-Papenburg 5.7 m below MHW				
1984-1985	Straightening of bends, reducing the river length with 1 km.				
1991-1994	Emden-Papenburg 7.3 m below MHW				
2001-2002	Construction of storm surge barrier (near Pogum)				

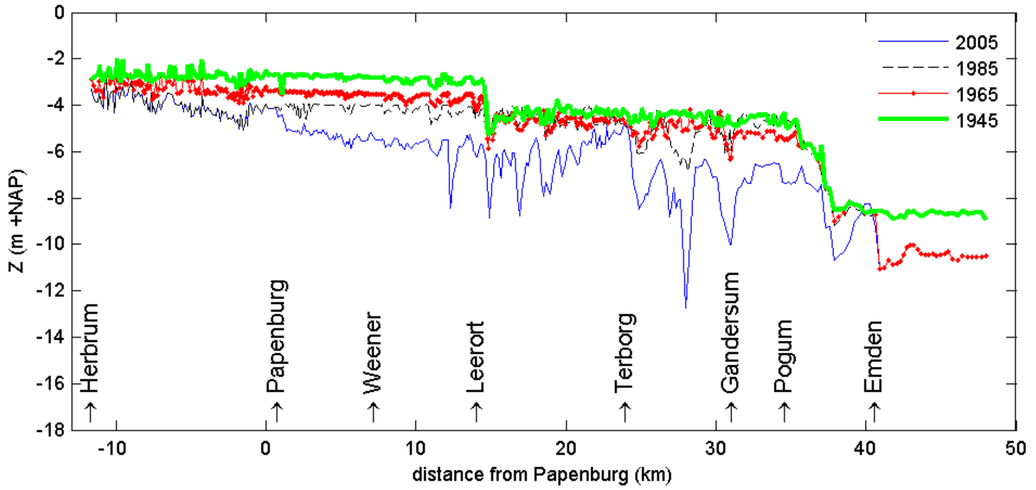

Figure 3.7 ER model depth along the thalweg of the Lower Ems River from Herbrum to the seaward model boundary at Knock. The bed level has remained unchanged in the Emden Fairway in since 1965 (red overlaps black and blue lines).

The sediment transport model setup for 2005 (see report 5 in Table 1.1) is subsequently applied to the calibrated hydrodynamic scenarios for the different years, developed in report 4. These simulations vary in bed level (Figure 3.7) and bottom roughness (Figure 3.8) and were calibrated using water levels (see report 4 in Table 1.1 for more details). The sediment concentration computed in the lower Ems River is several orders of magnitude lower for 1945-1985 compared to 2005 (see Pogum and Leerort in Figure 3.9). The model results show a large increase in sediment concentration between 1985 and 2005, which is supported by SSC observations (de Jonge, 2000) and a transition from a sandy bed to a muddy bed (Krebs and Weilbeer, 2008). Despite simplified sedimentological formulations, the model captures some of the mechanisms governing this transition, and therefore these mechanisms are analysed in more detail in the following section.

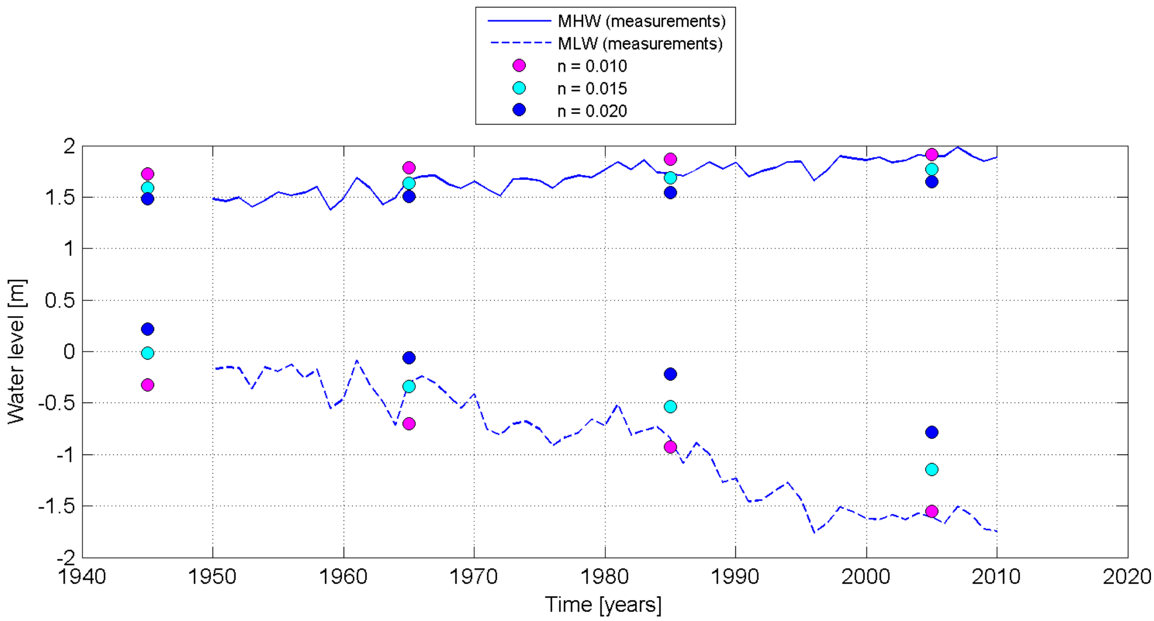

Figure 3.8 Observed and computed HW and LW at Papenburg. HW (LW) is defined as the yearly average of every high water (low water) per tidal cycle.

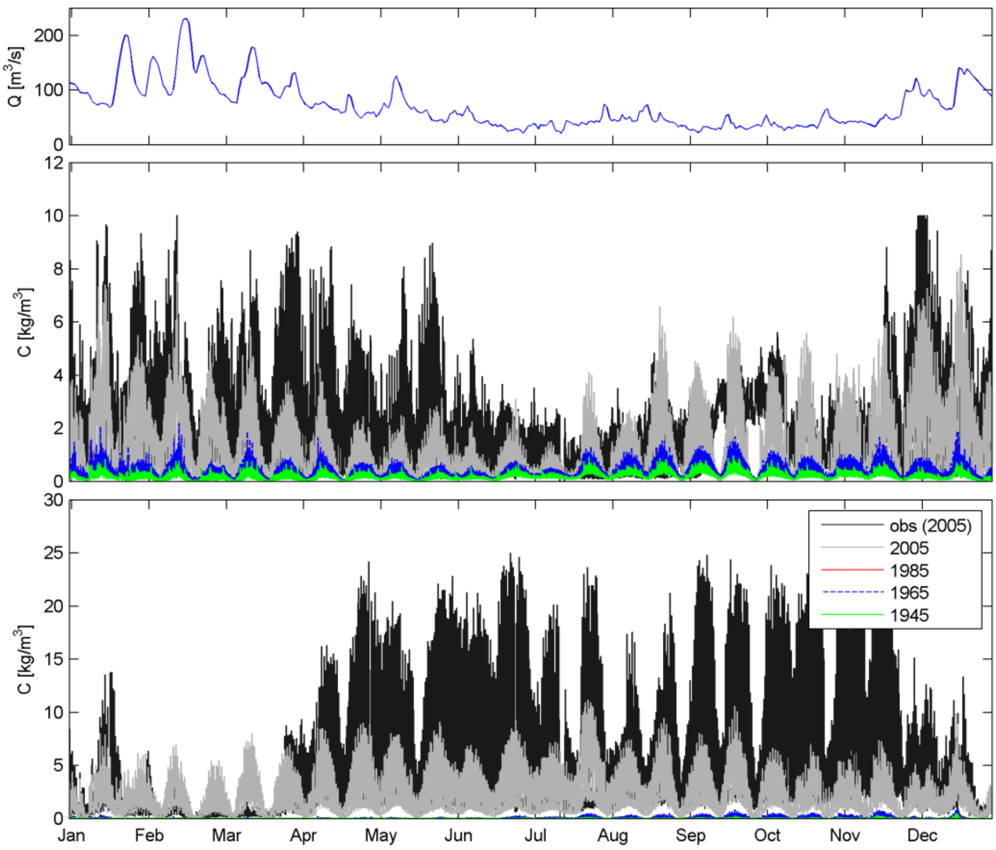

Figure 3.9 Observed discharge at Versen in 2005 (top panel), computed sediment concentration at Pogum (middle panel) and Leerort (bottom panel), for 1945 (green), 1965 (blue), 1985 (red), and 2005 (grey), with variable roughness (n = 0.020, 0.015, 0.015, and 0.010, resp.) based on the hydrodynamic calibration (report 4). Suspended sediment concentration observations (2005) are in black. The 1985 model results are very similar to 1965 and therefore largely hidden.

Surprisingly, the computed asymmetry in θ_ζ and θ_u changed little over time (panel 3 and 4 in Figure 3.2). This is in line with the observations presented by Chernetsky et al. (2010) from 1980, also showing a minor change compared to 2005. All historic scenarios remain flood-tide dominant or HW slack dominant, both importing sediments. The computed degree of asymmetry $a_{\zeta_{M4}}/a_{\zeta_{M2}}$ is lower in 1965 and 1985, but larger in 1945. So even though the tides strongly amplified in the past decades, the degree and type of tidal asymmetry remained fairly constant. Despite constant asymmetry parameters $a_{\zeta_{M4}}/a_{\zeta_{M2}}$ and θ, the gross sediment transport rate did increase because the amplitudes of M_2 and M_4 increased over time. The existing difference (due to tidal asymmetry) between the total sediment transport during the flood and during the ebb has therefore also become larger. As a result, the net up-estuary tidal transport has increased with increasing tidal amplitude.

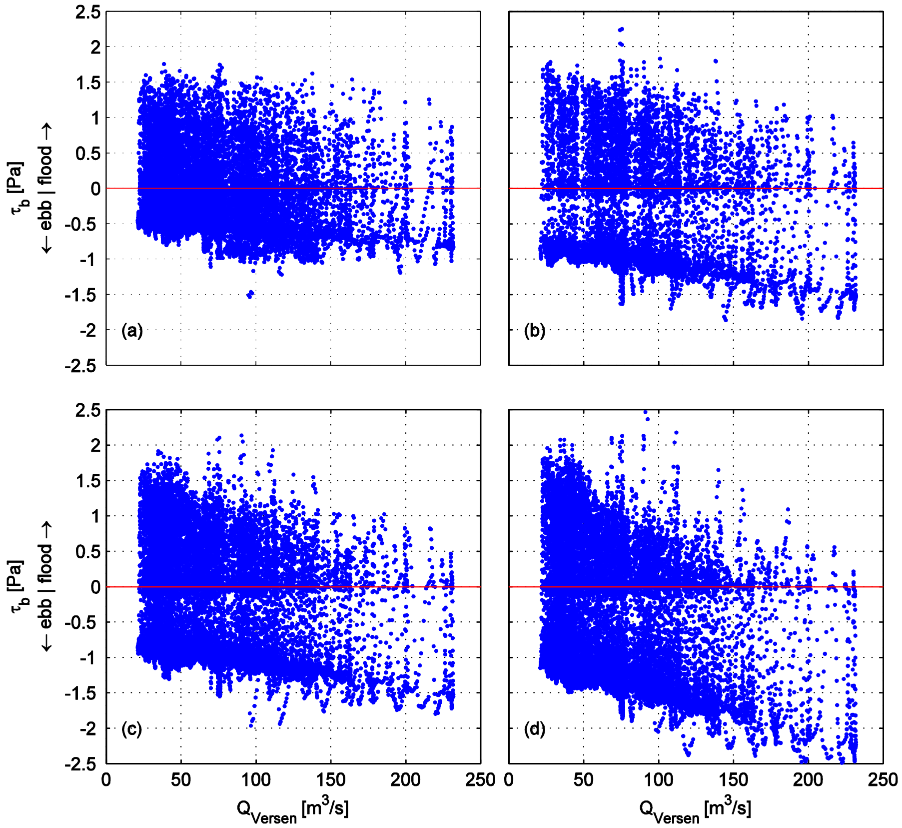

Figure 3.10 Ebb and flood bed shear stress τ_b at Weener as a function of discharge, in 2005 (Manning's n = 0.010, a), in 1985 (Manning's n = 0.015, b), in 1965 (Manning's n = 0.015, c), and in 1945 (Manning's n = 0.02, d). A positive τ_b is in the flood direction, a negative τ_b is in the ebb direction.

Changes in river flushing were much more pronounced than changes in tidal asymmetry. Therefore, in In addition to increasing sediment import in time, the computed export of sediment by river flushing decreased. In 2005, τ_b was always larger during the flood throughout the year (except for *Q* > 70 m^3/s at Papenburg, see Figure 3.6). The changing relation between *Q* and τ_b is exemplified at station Weener (Figure 3.10). In 2005, flood peaks in τ_b at station Weener are always larger than during ebb. However, ebb peaks in τ_b were larger during the ebb (compared to the flood) for river dischargers of ~120 m^3/s in 1965-1985. In 1945, this transition even occurs at a river discharge of ~70 m^3/s. This excludes the effect of the longer ebb duration (as discussed previously) further strengthening the effect of the discharge. Hence, the modeled increase in suspended sediment concentration (in 2005) results from a decrease in river flushing in addition to an increase in tide-induced up-estuary transport.

The historic scenarios differ in bathymetry, but also in hydraulic roughness. In order to distinguish their individual effect, the sediment concentrations are also computed for constant roughness values. A low bed roughness (*n* = 0.010 s/m$^{1/3}$; upper panel in Figure 3.11) results in high sediment concentrations for all historic bathymetries. Note that this is a numerical test case: the hydrodynamics of these model runs are (except for 2005) in disagreement with water level observations (see report 4). With moderate bed roughness (*n* = 0.015 s/m$^{1/3}$; lower panel in Figure 3.11), the sediment concentration is only high in 2005. These two observations have two important implications:

1) The 1990's deepening of the lower Eems river increased the up-estuary sediment transport to such a degree that even with a hydraulically rough bed, large quantities of sediment are imported. This sediment leads to lower hydraulic drag, and hence more import.
2) A return to the pre-1990 bed level will not lead to the pre-1990 water levels as long as the bed remains hydraulically smooth: a combination of a shallow channel but low bed roughness still imports sediment.

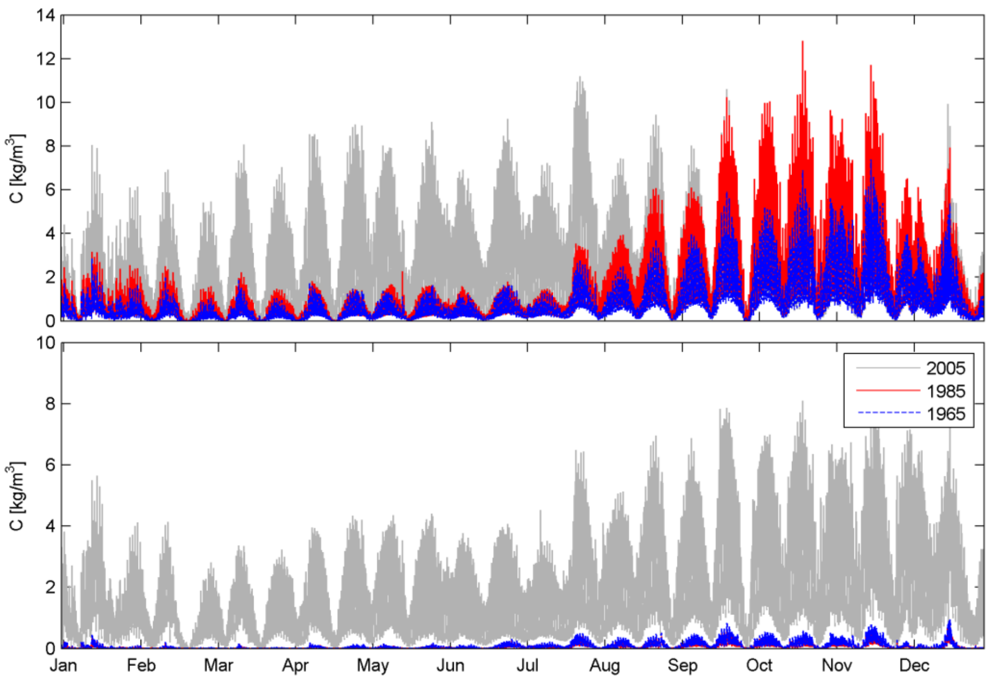

Figure 3.11 Computed sediment concentration at Leerort in 1965 (blue dashed), 1985 (red), and 2005 (grey), using n = 0.010 (top panel) and 0.015 (bottom panel).

The turbidity maximum (ETM) in the lower Ems River differs from many other estuaries by its up-estuary locations, extending all the way into the fresh water region. This was explained by Talke et al. (2009) by sediment-induced density currents, transporting sediment further up-estuary than only salinity-induced residual circulation could do. A sediment-induced density coupling is included in our ER model, mimicking a feedback mechanism between sediment concentration gradients, turbulence and hydrodynamics (e.g. Winterwerp, 2001). Tidal asymmetry in mixing (Jay and Musiak, 1994; Scully and Friedrichs, 2003) and flocculation were postulated by Winterwerp (2011) to be important mechanisms for up-estuary sediment transport. Tidal mixing asymmetry leads to stronger mixing during one phase of the tide resulting in relatively more transport near-surface flow (where the flow velocity is largest). The vertical distribution of the suspended sediment concentration in our model can be inferred from Figure 3.4. In case of evenly spaced sediment concentrations, the profile is mixed. Although the vertical profile appears to be slightly better mixed during the flood, the difference is not very large. Therefore asymmetries in vertical mixing have a small impact on the modeled up-estuary transport during the conditions such as in Figure 3.4. The asymmetry in bed shear stress changes substantially throughout the river and as a function of river discharge (Figure 3.6), and therefore asymmetry in vertical mixing may be important during other periods in time. This is part of on-going research.

3.2.3 A new stable state

Winterwerp and Wang (2013) identified a feedback mechanism between tidal deformation (an increase in tidal range and propagation speed of the tidal wave, resulting from channel deepening and reclamation of intertidal areas), sediment import (leading to increasing suspended sediment concentrations) and hydraulic drag (decreasing as a result of increasing suspended sediment concentrations and strengthening tidal deformation) – see Figure 3.12. Because of this positive feedback mechanism, deepening or other engineering interventions may set into motion an evolution in which the tides become progressively more asymmetric, continuously more sediment is imported, and the hydraulic drag becomes increasingly lower.

The model results suggest that only the deepening in the 1990's (part of the 2005 bathymetry and phase 1 in Figure 3.12) sufficiently influences hydrodynamics (phase 2) to import large quantities of fine sediment (phase 3, see Figure 3.9). Such an increasing import leads to reduced hydraulic roughness (phase 4). A reduced hydraulic roughness then further enhances the tidal amplification (step 2, see Figure 3.12) which again strengthens sediment import and raises the sediment concentration (step 3: see Figure 3.11). This feedback mechanism between geometry, sediment import and hydraulic roughness does not exist for the main exporting process, identified as riverine flushing. Export by river flushing decreases immediately with larger depth, but is only limitedly influenced by the hydraulic roughness. Therefore, river flushing does not contribute to the positive feedback mechanism depicted in Figure 3.12.

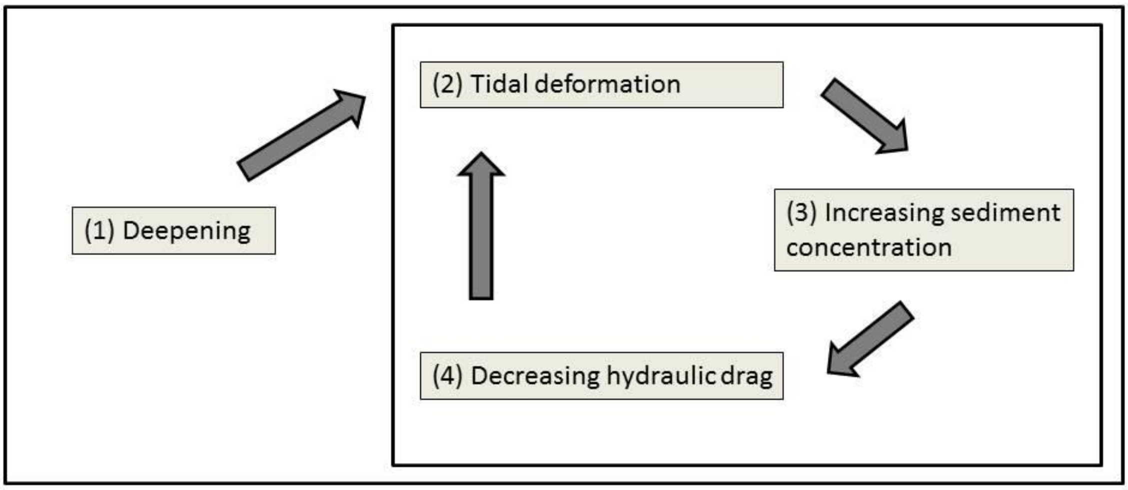

Figure 3.12 Estuarine response to channel deepening, in which tidal dynamics initially respond to the geometrical changes, but sets in motion a positive feedback mechanism in which increasing sediment import and resulting decrease in hydraulic drag lead to progressively larger tidal deformation.

The model results also suggest (Figure 3.11) that for low roughness conditions, the suspended sediment concentration in the lower Ems River is always high (independent of the geometry). Stopping maintenance dredging would lead to lower water depths (possibly similar to a bed level before the 1990's), but since the deposited sediment would be primarily mud, the hydraulic drag remains low and the sediment import and sediment concentrations large. When the river channel is filled in with mud, and not with sand, a return to the pre-1990 depth would not lead to the low sediment concentrations occurring during that period. As previously concluded by Winterwerp et al. (2013), an alternative, hyper-turbid state has developed, which is very stable and self-maintaining.

3.3 Impact on the Ems Estuary

In this section the impact of historical changes in the lower Ems River on the sediment dynamics in the Ems estuary is estimated. It addresses (i) the impact of the deepening of the lower Ems River on the tides in the Ems estuary, (ii) the effect the lower Ems River on the estuary because it acts as a sediment sink, and (iii) the impact of flushing of sediment from the lower Ems River into the estuary.

3.3.1 Hydrodynamics

The effect of deepening of the lower Ems River on tidal propagation (and resulting sediment dynamics) in the Ems Estuary can be largely estimated from observations in tidal amplification throughout the Ems Estuary (Figure 3.13). The entrance of the lower Ems River is close to Knock. At Knock, the constant increase in tidal amplitude is very similar to the increase further down-estuary (Eemshaven, Emshorn). Since the tidal volume rapidly increases down-estuary of Knock, the increase in tidal amplitude observed throughout the estuary is probably not or only slightly related to the lower Ems River.

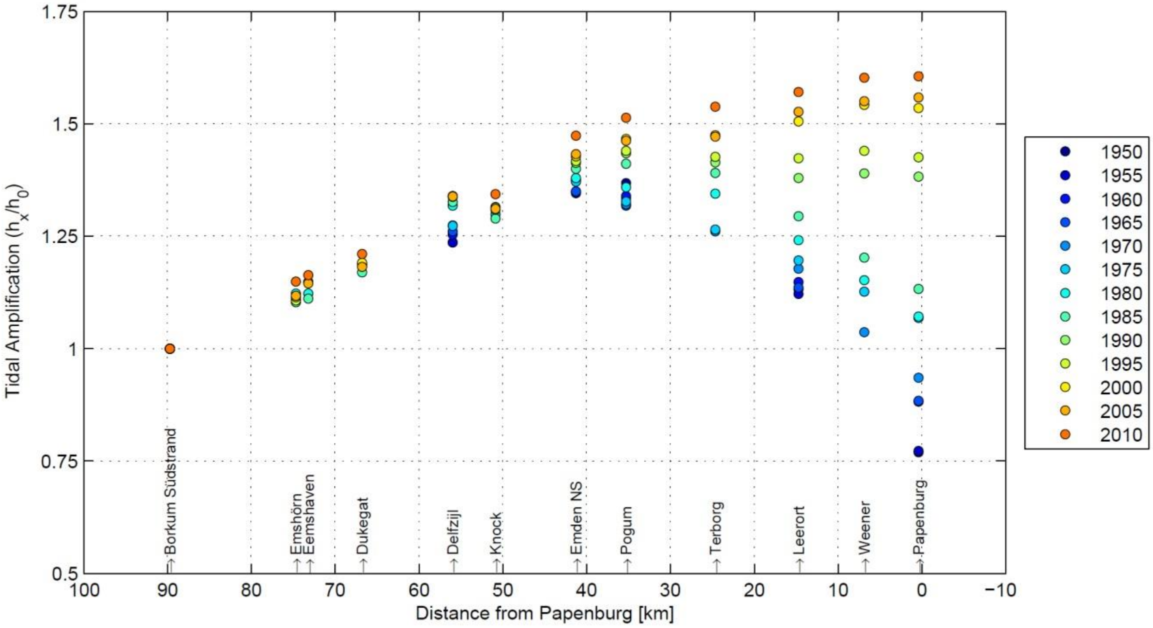

Figure 3.13 Tidal amplification hx/h0 in the Ems estuary, defined as the tidal range hx relative to the tidal range at the most seaward station (Borkum Südstrand; h0), from Borkum Südstrand (Ems-km 89) to Papenburg (Ems-km 0). The entrance of the lower Ems River is close to Knock. Figure is taken from report 3.

The impact of the lower Ems River on the estuary can be further evaluated by comparing the simulated tidal volumes in the lower Ems River and the Ems Estuary for 1945 and 2005. The peak tidal discharge in 2005 at the mouth of the lower Ems River (Pogum) as computed with the ER model is typically 5000 m^3/s during spring tides. This peak discharge was 40% lower for the computation representative for 1945 (also using the ER model). The peak tidal discharge in the Ems Estuary at the mouth of the lower Ems River (transect from Knock to the entrance of the port of Delfzijl) is 30.000 m^3/s (computed with the WED model for 2005). Consequently, the tidal discharge from the Ems River constitutes approximately 15% (5000 out of 30.000 m^3/s) of the present-day tidal discharge in the Ems Estuary near Knock.

The estimated increase in tidal discharge as a result of deepening of the lower Ems River is 2000 m^3/s since 1945 (40% of 5000 m^3/s). This is 6% of the present-day peak tidal discharge in the Ems Estuary near Knock. However, also in the Ems Estuary the tidal discharge must have been lower around 1945 because of the smaller tidal range (Figure 3.13); the impact of the lower Ems River was therefore slightly less than 6%. The tidal discharge in the Ems estuary rapidly increases in the seaward direction: the peak tidal discharge through Huibertgat is ~100.000 m^3/s (simulation with WED model). Therefore the effect of deepening of the lower Ems River on the gross tidal discharge decreases in the seaward direction, reduced to only 2% at Huibertgat (2000 out of 100.000 m^3/s).

An increase in the tidal discharge in the Ems Estuary of 2 to 6% influences tide-induced flow velocities and possibly sediment transport. Fine sediment transport rates cannot be directly related to local flow velocities because the transport of fines is often supply-limited and not erosion-rate limited. An increase at Huibertgat of 2% does therefore not necessarily lead to an increased sediment transport rate. However, it is likely that the increase in gross sediment fluxes is at least comparable to the increase in water volumes (in case of constant sediment concentration, sediment transport scales linearly with the discharge; i.e. 2% at Huibertat). The horizontal resolution of the WED model in its present form is too low to reproduce the effect of deepening of the lower Ems River on tidal propagation (see report 4). Therefore this effect cannot be simulated with sufficient confidence. Nevertheless, based on the impact on hydrodynamics, it is likely that deepening of the lower Ems River increased the gross sediment fluxes from the Wadden Sea into the Ems estuary with at least a few percent.

3.3.2 Sediment dynamics

Approximately one million ton of sediment is annually dredged from the lower Ems River (so excluding the port of Emden and the Emden fairway) and disposed on land since the 1990's (Krebs and Weilbeer, 2008). Therefore the lower Ems River is a sediment sink. The effect of this sink can only partially be investigated with the WED model, because the accumulation in the lower Ems River is insufficiently reproduced by the WED model. The WED model underestimated import because hydrodynamics and sediment dynamics in the lower Ems River and the Emden fairway are still poorly understood, but also require a model resolution which cannot be achieved with a long-term large-scale model such as the WED model (see section 5.6 in report 5 for details). In order to still approximate the impact of this sink on the Ems estuary, all sediment entering the approach channel to Emden and its port is extracted in the model (~0.5 million ton/year: see Figure 3.14). The effect of this extraction is a reduction in suspended sediment concentrations throughout the estuary (Figure 3.15).

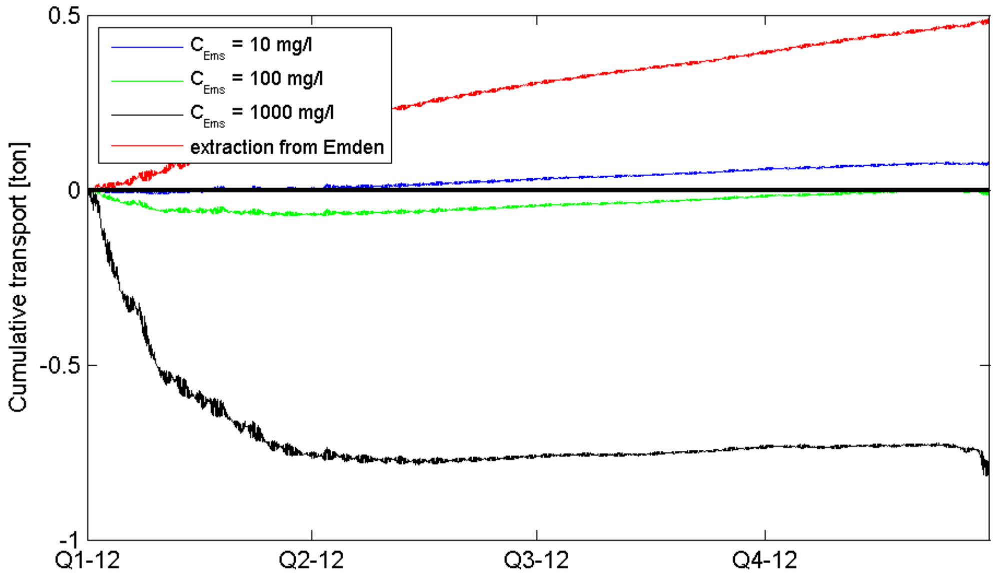

Figure 3.14 Cumulative sediment transport from the Ems Estuary into the Emden navigation channel (red, extracting sediment deposited in the port and navigation channel) and from the Emden navigation channel into the Ems River, for a sediment concentration of 10, 100 and 1000 mg/l in the Ems River.

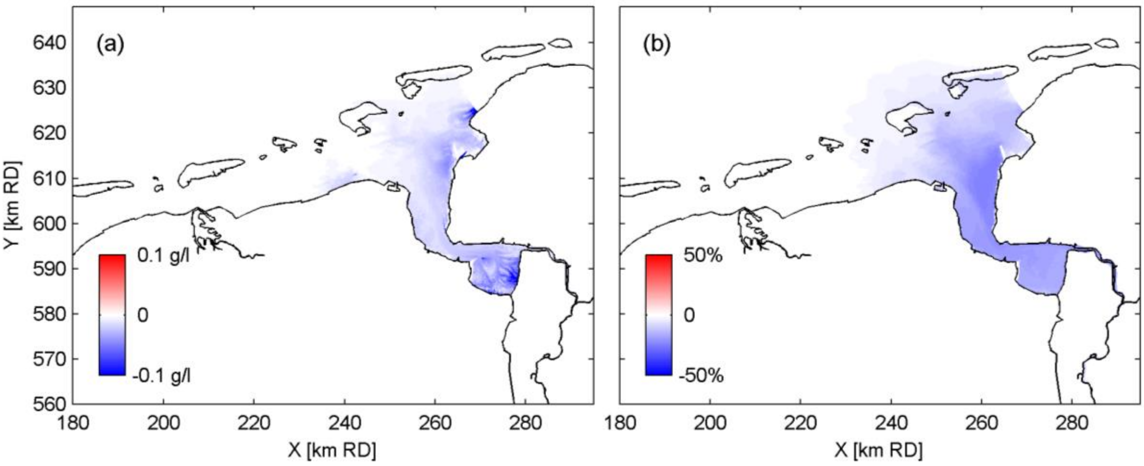

Figure 3.15 Absolute (a, in g/l) and relative (b, in %) increase in yearly averaged near-surface suspended sediment concentration by extracting 0.5 million ton/year from Emden navigation channel.

During high discharge events, sediment is expected to be flushed from the lower Ems River into the Emden fairway (Spingat and Oumeraci (2000), see also Figure 3.5) and some of this sediment from there into the Ems estuary. However, there are several reasons why it is likely that the amount of sediment flushed into the Ems Estuary is limited. First, even though sediment is flushed seaward, a large amount of this sediment probably accumulates between Pogum and Terborg (based on data and model results, see section 3.2.1). Secondly, sediment rapidly returns to the Ems River following large discharges, suggesting most sediment remains upstream of Knock and is not flushed into the Ems estuary. And thirdly, the largest dredging amounts is required in the Emden fairway during large river discharge conditions (pers. Comm. Dr. Weilbeer, BAW) suggest that sediment that is transported seaward of Pogum is trapped in the Emden fairway but that flushing into the Ems Estuary itself is limited. Still, in order to approximate the maximal area which may be influenced by flushing of sediment from the Ems River, the lower Ems River is modelled as a sediment source (instead of the sediment sink it is in reality).

The lower Ems River contains ~78 million m^3 of water. An average sediment concentration estimated at 2 g/l, yields a suspended sediment mass of about 0.16 million ton. Fluid mud is present in the most upstream ~30 km. An upper bound estimate for the sediment mass in the fluid mud layer in the Ems is obtained by estimating the fluid mud sediment concentration (~100 g/l) and thickness (~1m) with a river width of ~200 m, resulting in 0.6 million ton. The total sediment mass in the lower Ems River is therefore approximately 0.76 million ton.

The impact of the complete flushing sediment is approximated by adding a source term in the lower Ems River (even though in reality the Ems River is a net sediment sink). This source term is generated by setting the sediment concentration in the river discharge to 10, 100, and 1000 mg/l. Ten mg/l is insufficient to generate a net flux into the lower Ems Estuary (as in the baseline model), see Figure 3.14. A sediment concentration of 100 mg/l leads to a sediment flux from the lower Ems River into the Ems Estuary of 0.1 million ton during winter (high discharge), which is transported back into the lower Ems River during summer (low discharge). A sediment concentration of 1000 mg/l leads to permanent transport of from the lower Ems River into the Ems estuary (0.8 million ton of sediment, mostly in January and February). Since this sediment mass is comparable to the sediment mass in the lower Ems River (estimated above at 0.76 million ton), the 1000 mg/l scenario represents the short term of complete flushing. This scenario is an upper bound for the effect of the lower Ems River on

the short term. In reality, the effect of flushing on the Ems Estuary will be much weaker because
1) Only a fraction of sediment present in the lower Ems River will be flushed seaward
2) All sediment flushed seaward during large discharge events will be transported back into the estuary during periods of low discharge.

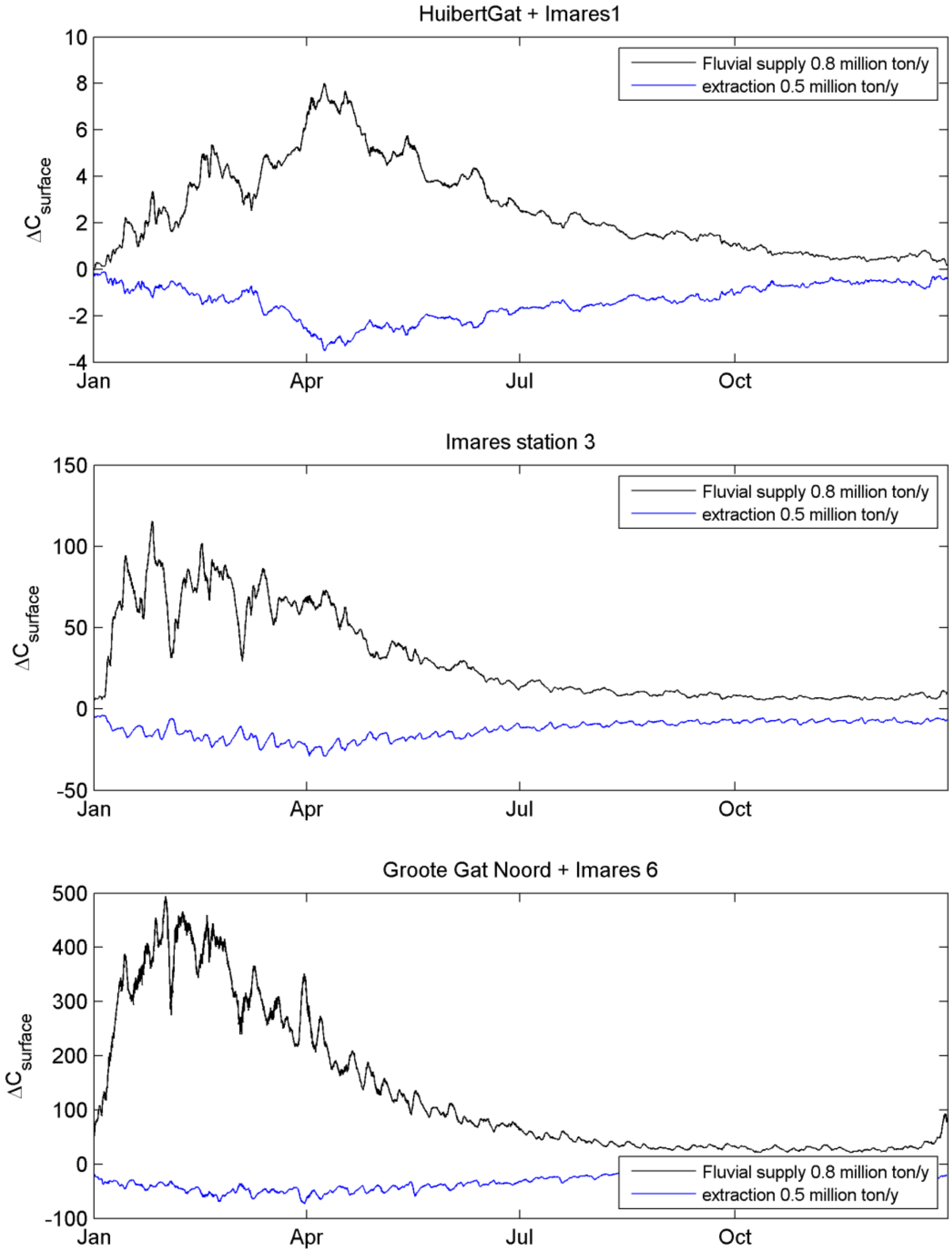

Figure 3.16 Change in near-surface sediment concentration (in mg/l, relative to the reference simulation) with an additional sediment supply from the lower Ems River (1000 mg/l, resulting in an additional source of 0.8 million ton/year; see Figure 3.14) and with extraction from the port of Emden and approach channels (0.5 million ton/year). The sediment concentration is smoothed with a 24-hour moving average. See Figure 3.1 for location of stations.

Since we mainly aim to investigate the impact of such an event on the potential and temporal increase in sediment concentrations in the lower Ems River, we only evaluate model results in the time domain. Furthermore, the scenario is too far off reality (the Ems River is a sink, not a source of sediments) to evaluate the impact on yearly averaged suspended sediment concentrations.

For all stations in the Ems Estuary, the large sediment loads from the lower Ems River only limitedly influence the sediment concentrations in the second half of the year (Figure 3.16). This is in line with expectations, since the Ems River is importing sediment in this tide-dominated period. The relatively minor effect of the Lower Ems River on summer concentrations also means that the modelled underestimation of SSC in the middle of the estuary in summer (see report 5) is probably not related to the lower Ems River. A second important model observation is that even a very large sediment load from the lower Ems River has little effect on Huibertgat station: the yearly averaged sediment concentration increases 3-4 mg/l. The impact of a (hypothetical) large sediment load from the Ems River on the Dollard (station Groote Gat) is very large.

3.4 Model applicability

This section gives a brief description of the model applicability in terms of hydrodynamics and suspended sediment dynamics for testing hypotheses 3 and 9. A more elaborate description of model applicability can be found in reports 4 and 5 (see Table 1.1).

3.4.1 The ER model

The ER model is used to quantify the mechanisms responsible for the increase in the past decades of concentrations from several 100 mg/l to 10’s of g/l in the lower Ems River. The target variables (Harezlak et al., 2014) to assess the accuracy of the sediment transport model were defined as the suspended sediment concentration and the residual transport (report 5). In the downstream section of the lower Ems River (near Pogum) the available data suggests that the model reproduces the main sediment transport patterns, such as the intra-tidal variation in suspended sediment concentration (Figure 3.4) and the seasonal and spring-neap variation (see report 5). The most important mechanism transporting sediment upstream is tidal asymmetry. The agreement between observed and computed hydrodynamics (Figure 3.2) and the intra-tidal variation in suspended sediment concentration (Figure 3.4) show the main characteristics of tidal asymmetry is represented in the model. The main mechanism transporting sediment downstream is river discharge, which is straightforward to model. The ER model is therefore considered to be a sufficiently realistic tool to explore the mechanisms responsible for the evolution of the sediment dynamics in the lower Ems River.

3.4.2 The WED model

The exchange between the lower Ems River and the Ems Estuary is challenging to reproduce since for both individual systems modelling approaches are used that require different process formulations (see report 5 for details) as well as horizontal and vertical resolution. The transport mechanisms within the lower Ems River can be modelled with the ER model. However this model cannot be applied on the scale of the Ems Estuary due to very large computational time and dominant processes there (wave resuspension, sediment buffering), which have been implemented in the WED model. Without the sediment-induced density coupling (modelled with the ER model) the WED model cannot reproduce the observed large siltation rates in the Emden navigation channel. These large siltation rates in this specific area may be additionally related to processes such as consolidation and flocculation which are insufficiently understood, requiring further research and detailed observations.

Probably, the sediment concentration in the Ems estuary is influenced by the lower Ems River through two mechanisms with opposite effect:

(1) During most of the year, large quantities of sediment are transported into the lower Ems River, where it is extracted from the system, leading to a decrease in SSC in the Ems Estuary
(2) Horizontal diffusion of suspended sediments by tidal currents will lead to higher sediment concentrations in the Ems estuary because the concentrations in the lower Ems River have increased. This will be most prominent during periods of large river discharge, when turbid water in the lower Ems River is transported in the seaward direction.

Both these aspects cannot be realistically reproduced with the WED model. The effect of the Ems River acting as sediment sink, and as a temporal source of sediment (sediment flushing), is investigated with scenarios. The temporal impact of flushing on the suspended sediment dynamics has been evaluated by adding a large amount of sediment (0.8 million ton/year) to the model. The effect of extraction from the lower Ems River is approximated by removing sediment from the Emden Port and fairway. Both scenarios are only limitedly realistic, and the results should be carefully interpreted. They do suggest that the any increase in suspended sediment concentration of the lower Ems River on the Ems estuary is fairly local. The exchange between the two systems is very complex, and therefore more research specifically focussing in the coupling of the lower Ems River and the Ems estuary is needed.

3.5 Conclusions

3.5.1 Summary of model results

The ER model reproduces the low-turbid state and the hyper-turbid state of the estuary, by only changing the bathymetry and calibrating the hydraulic roughness against existing water level observations. The model suggests that the differences between the low-turbid and the hyper-turbid conditions are caused by tidal amplification (despite constant phase lag differences or the relative strength of overtides) and decreasing riverine flushing. Furthermore it is observed that the modelled transition may have already occurred for ‘sand-bed’ hydraulic drag following the deepening of the tidal river in the early nineties. The transition provided a crucial change in the system, followed by a rapid increase in turbidity. The associated reduction in hydraulic drag further increased the sediment import capacity of the system, and hence the sediment concentration. The effect of hydraulic roughness is so large that a return to a pre-dredging depth is insufficient to significantly reduce sediment import and associated suspended sediment levels in the estuary. This implies that not only the bed level needs to be raised but also the large quantities of mud need to be removed in order to restore the system to its pre-dredging conditions.

Deepening of the lower Ems River increased the peak tidal discharge with ~40% in the lower Ems River, ~6% in the Ems estuary near Knock, and ~2% at the mouth of the estuary (Huibertgat). The effect of the lower Ems River on tidal discharge is hence small. The effect of this increase in tidal discharge depends on the importance of the tidal discharge for sediment transport (compared to, for instance, salinity-driven flows). If salinity-driven flow is very important for the suspended sediment dynamics, then an increase in the tidal discharge of several % does not significantly influence estuarine suspended sediment transport. As will be elaborated in more detail in chapter 4, the residual sediment transport in the WED model is strongly influenced by salinity-driven flows. An increase of the tidal discharge of only several % is therefore estimated to have an even smaller effect on residual sediment transport.

The large siltation rates in the lower Ems River (0.75 – 1 million ton/year) lead to a reduction in SSC in the Ems estuary. During high discharge conditions, an unknown quantity of sediment is flushed from the lower Ems River into the Ems estuary. The hypothetical maximum seaward spreading of this sediment pulse is computed by adding an additional source term in the WED model. Even though this approach strongly overestimates the effect of the lower Ems River (because in reality the lower Ems River acts as a net sink, rather than a source), the computed increase in suspended sediment concentration near station Huibertgat (10-20% over a short period) as result of this large sediment pulse is much less than the observed (and permanent) increase at Huibertgat (from 10 to 25 mg/l, or 150%). This suggests that changes in SSC at Huibertgat are not governed by the SSC in the lower Ems River.

3.5.2 Hypotheses

Hypothesis 3 (*Sediment trapping in the Lower Ems River should lead to a reduction of the total sediment mass in the Ems Estuary. This is partly compensated or reversed through flushing at high river discharge events. This exchange of sediments between the Ems Estuary and Lower Ems River is strongly influenced by the Geisedam*) cannot be answered with sufficient confidence. Extracting sediment from the entrance of the lower Ems River leads to a large reduction in suspended sediment concentration in the Ems estuary. On the other hand, the higher sediment concentrations in the lower Ems River will also influence the Ems estuary due to diffusion of sediment by tidal currents (especially during large discharge events). Which of these two opposing effects is stronger, has not been ascertained. The effect of the Geisedam has not been investigated because of uncertainties in the effect of the Geisedam on the morphology.

Hypothesis 9 (*the deepening and realignment of the lower Ems River has so much influenced the tides in the Ems Estuary that (1) the Ems Estuary is importing more fine sediments, and (2) the Lower Ems River is importing more fine sediments*) cannot be answered with sufficient accuracy, but is probably not true. The tidal discharge in the Ems Estuary increased with 2 to 6% (depending on the location in the estuary) from the 1940’s to 2005. This will enhance import of fine sediment, but whether it has led to a significant increase in suspended sediment concentrations remains unclear, depending a.o. on the role of tides relative to estuarine circulation and sediment sinks. Especially the role of estuarine circulation on residual sediment transport is probably large (see Chapter 4), possibly rendering the effect of a small increase in gross-tide-induced transports insignificant for residual sediment transport. Note that this is not true for the Ems River itself: here deepening has led to a strong increase in sediment import.

4 Changes in the Ems Estuary

This chapter describes the effect of changes that have occurred in the Ems Estuary (mainly related to channel deepening and dredging and disposal strategies) on the estuarine suspended sediment concentration (hypothesis 4, 5, 7, and 8 related to **suspended sediment dynamics** and **hydrodynamics**).

4.1 Introduction

The Ems estuary (see Figure 4.1) has been heavily modified in the past decades to centuries. Land reclamations carried out in the past 500 years have greatly reduced the intertidal area. Human interferences in the past 50 years are dominated by shipping requirements. Three ports and a large shipyard exist in the estuary, requiring regular deepening and permanent maintenance dredging of the access channel.

The tidal channels in the Ems Estuary used to be organized as distinct ebb- and flood channels (van Veen, 1950). Some of these channels (especially in the middle reaches) have been transformed into a single-channel system. Channel deepening affects tidal propagation, typically increasing the tidal range (the difference between high and low water); increasing tidal range frequently leads to higher turbidity levels (Uncles, 2002). Deepening and especially port construction leads to more maintenance dredging and subsequent sediment dispersal. These activities may have significantly influenced the average turbidity levels (de Jonge, 1983, 2000). This is investigated in this chapter, in which we will relate changes in bathymetry, port construction, and dredging in more detail. The formulated hypotheses related to changes in the Ems estuary are:

4) *The sediment concentration in the Ems Estuary has increased because of a loss of tidal flats, leading to (1) modified tides and (2) less sediment sinks.*

5) *The sediment dynamics in the Dollard area have marginally changed, so the Groote Gat station (where the sediment concentration does increase) is not representative for the Dollard area.*

7) *The sediment concentration in the Ems Estuary has increased due to dredging and dumping because of*
    a. *recirculation processes*
    b. *fining of the sediment bed.*

8) *Long-term natural and anthropogenic changes in the intertidal areas and the tidal channels of the Ems Estuary have sufficiently modified the tidal propagation to significantly influence sediment dynamics.*

The effect of dredging and disposal (hypothesis 7) will be evaluated in section 4.2. The effect of morphological changes (tidal channels and flats; hypotheses 4 and 8) on suspended sediment concentration is analysed in section 4.3. The accuracy of the model is evaluated in 0. The results are summarised and related to the hypotheses (including hypothesis 5) in section 4.5.

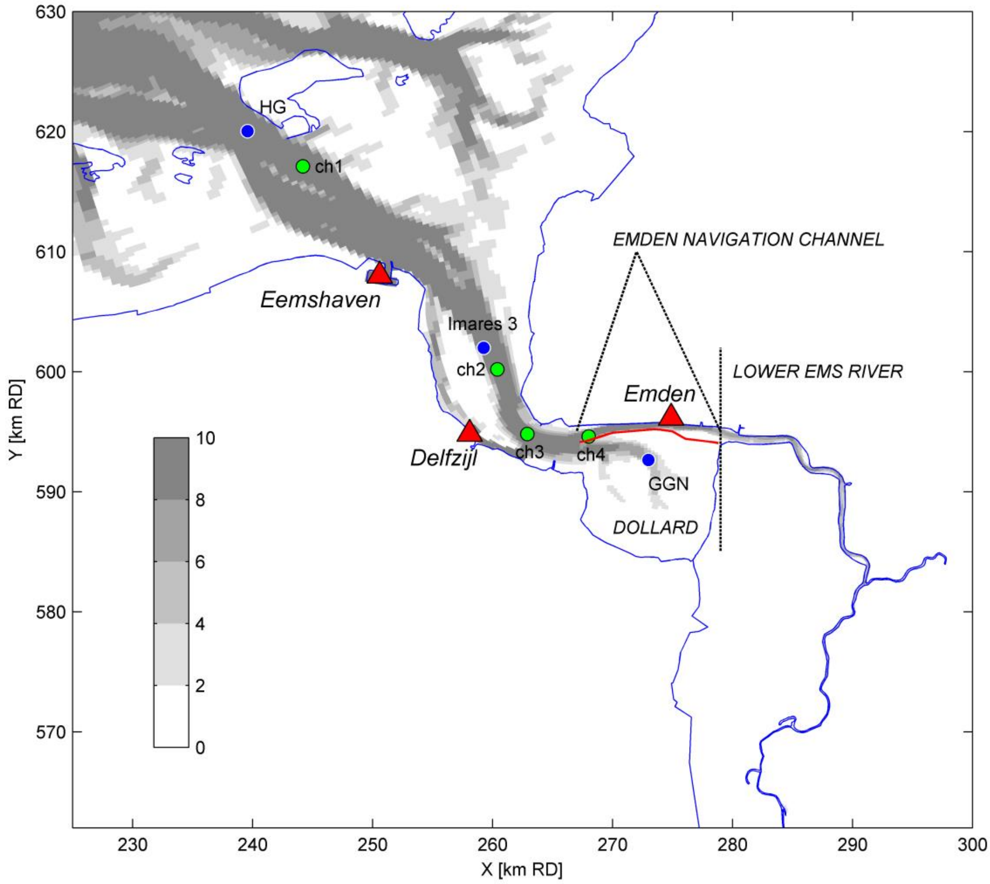

Figure 4.1 Map with model bathymetry (only depth between 0 and 10 m shown to highlight the difference between tidal channels and flats) of the Ems Estuary, including the main ports (Eemshaven, Delfzijl, and Emden) and observation points used in this chapter. The sediment concentration stations (HG = Huibertgat and GGN = Groote Gat Noord) are in blue. The green observation points (ch1 – ch 4) are used to compute residual flow velocity profiles. The Emden navigation channel connects the Lower Ems River with the Ems Estuary near ch4. The Emden navigation channel is separated from the Dollard by the Geisedam (red line).

4.2 Dredging, disposal and extraction of sediment

The amount of sediment dredged in the Ems estuary used to be around 15 million m^3/year in the seventies, but decreased to ~10 million m^3/year nowadays (Figure 4.2). This change is mainly due to a decrease in sediment extraction from the port and fairway of Emden, which averaged 5.1 million m^3/year from 1960 – 1994. Since 1994, the fluid mud in the port of Emden is regularly re-aerated and navigable for ships, and as a result dredging was no longer necessary. The dry bulk density of dredged sediment is typically 500 kg/m^3, and therefore the total dredging effort presently is 5 million ton/year. In this Chapter, we quantify the effect of dredging on the ambient turbidity and the effect of the historic extraction on ambient turbidity.

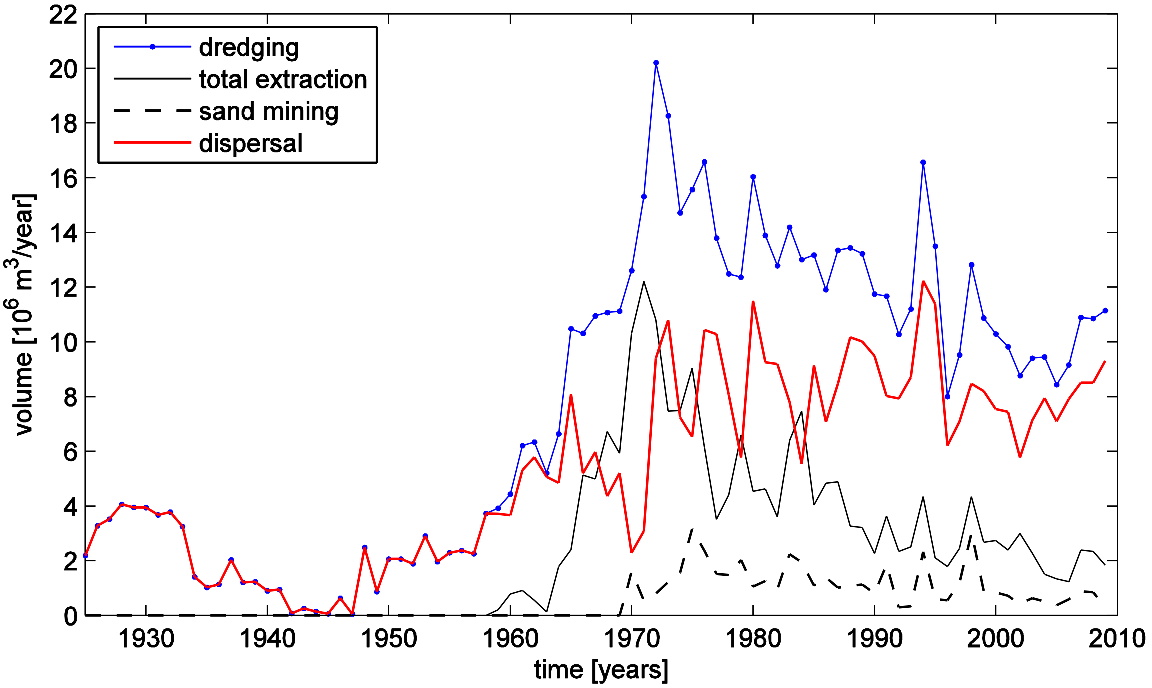

Figure 4.2 Dredging volumes since 1925. Dredging volumes before 1960 are derived from from de Jonge (1983) and are excluding sand mining. Dredging volumes after 1960 is from Mulder (2013) for the Ems Estuary (including sand mining) and from Krebs (2006) in the lower Ems River (until 2006; after 2006 a constant value of 1.5 million m^3 is used). Total extraction (sediment dredged and brought onland) 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 (disposal) is the difference between dredging and total extraction.

For this purpose different dredging and disposal scenarios have been set up. At different periods, dredging occurs in the main harbours (Ems, Delfzijl and Emden) and in the Emden fairway. Disposal takes place in the Ems estuary and Dollard. Some sediment is extracted from the system and brought to overland deposits. Dredging, disposal and extraction volumes are mainly based on information from Mulder (2013): see Figure 4.2. Dredging sediment which is subsequently disposed remains within the system, whereas extracted sediment is effectively taken out the system (and brought on land).

To test the effect of dredging, the reference WED model (with present-day ports, including dredging and disposal, see report 5 for details) is executed for three dredging and disposal scenarios (see Table 4.1).

- Without disposal from the port and approach channel of Emden (scenario 1), sediment is extracted and brought on land
- Without disposal (scenario 2), sediment is extracted from all ports (Eemshaven, Delfzijl, and Emden) and brought onland
- Without ports (scenario 3), hence no deposition in ports, but also without dredging and disposal.

These scenarios each consist of a one-year run which is cyclically repeated (for several years) until the simulation is in morphological equilibrium. At morphological equilibrium, the computed sediment concentration (which varies throughout the year in response to tides, waves, wind, and river flow) is the same for consecutive years. The computed difference between scenarios therefore provides the long-term effect of these scenarios.

Table 4.1 Model scenarios related to dredging

Scenario	Ports	Extraction	Bathymetry	Density effects
Reference	Yes	No	2005	Baroclinic
Scenario 1	Yes	Port of Emden	2005	Baroclinic
Scenario 2	Yes	All ports	2005	Baroclinic
Scenario 3	No	No	2005	Baroclinic

Extracting sediment from the port of Emden and its approach channel (scenario 1, Figure 4.3) leads to a small reduction in the outer reaches (Huibertgat, ΔC < 10 mg/l, Figure 4.6) increasing to ~50 mg/l halfway (Imares 3, Figure 4.6) to more than 100 mg/l in the Dollard (Groote Gat, Figure 4.6). The near-surface concentration in the Dollard is up to 600 mg/l (report 5), implying a reduction of 20%. However, it was also concluded that the model strongly underestimates deposition rates in the port of Emden and its approach channel (report 5). Historically, as much as 2.5 million ton was extracted on an annual basis and in scenario 1 (Figure 4.3) only 0.5 million ton/year is extracted. The model therefore underestimates the effect of the port of Emden on suspended sediment concentrations in the Ems Estuary. To compensate the low effect of the port of Emden, the model is also executed with extraction from all ports (scenario 2, totalling a mass of 1.75 million ton, see report 5), leading to a reduction in suspended sediment concentration about 2 times larger (Figure 4.4). Note that for this scenario the amount of extraction is realistic, but the location is not realistic.

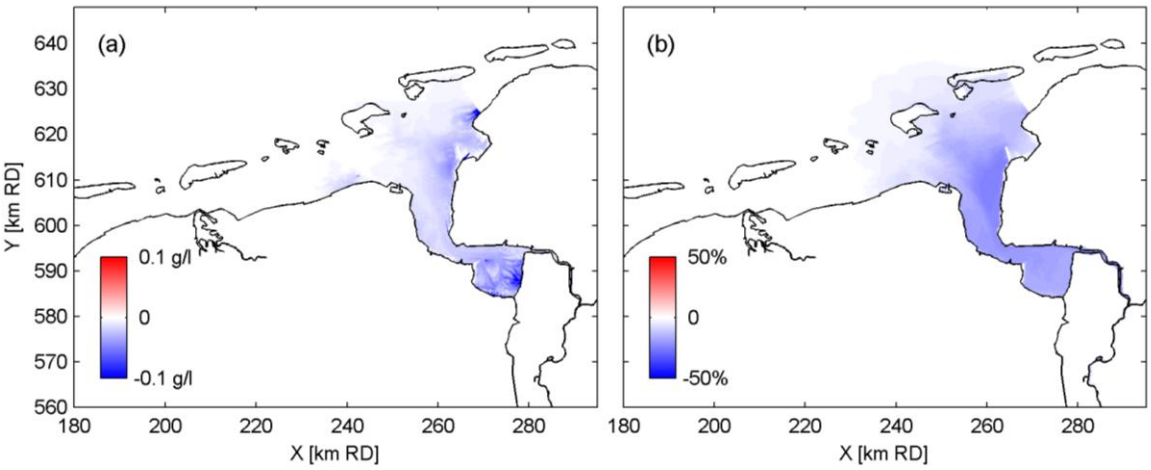

Figure 4.3 Absolute (a, in g/l) and relative (b, in %) increase in yearly averaged near-surface suspended sediment concentration resulting from sediment extraction from the port of Emden and approach channel (scenario 1 - reference)

The conclusion that extraction is important, does not automatically imply that maintenance dredging itself leads to higher suspended sediment concentrations. During extraction, system is removed from the estuary, which leads (by definition) to a reduction in suspended sediment concentration. Maintenance dredging and disposal is a process in which sediment is removed from one part of the estuary (the port) and disposed elsewhere (on the disposal grounds). This will lead to a change in the suspended sediment distribution, but not automatically to a change in average estuarine suspended sediment concentration.

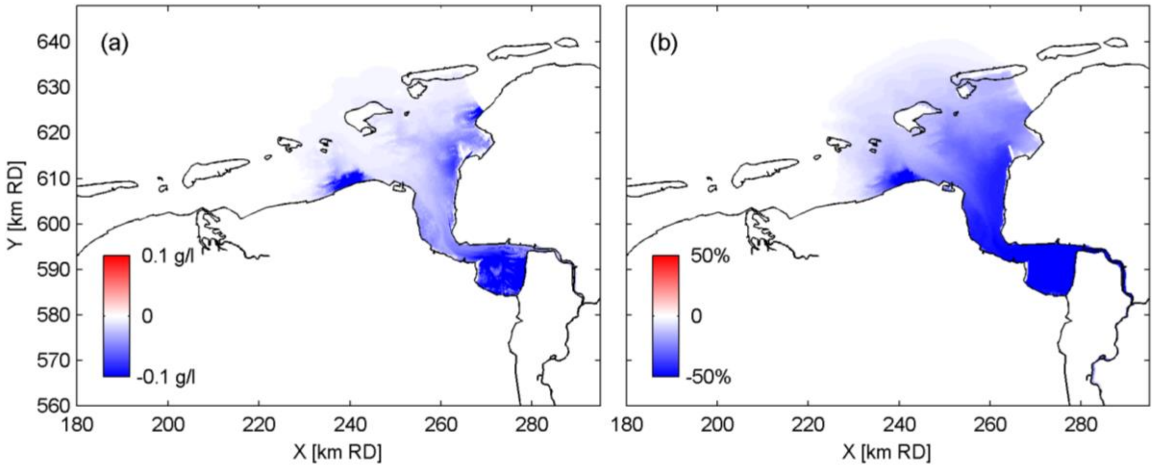

Figure 4.4 Absolute (a, in g/l) and relative (b, in %) increase in yearly averaged near-surface suspended sediment concentration resulting from sediment extraction from all ports (scenario 2 - reference)

The most realistic way to evaluate the effect of dredging from ports (excluding their approach channels) and subsequent disposal is by comparing the model including ports, dredging and disposal (the reference simulation) with a model excluding ports (and therefore also without deposition in ports): scenario 3 (Figure 4.5). The effect of ports on turbidity is more a change in the patterns of suspended sediment concentration, rather than a pronounced estuary-wide increase or decrease (such as scenarios 1 and 2). In the outer estuary, the concentrations increase when the ports are closed, but the inner estuary (notably the Dollard) becomes less turbid. This can be explained by the large sediment accumulation rates in the ports, extracting sediment from the estuary and hence lowering the suspended sediment concentration in a large part of the estuary (comparable with scenario 2). This sediment concentration is larger near the disposal grounds. The effect of three main ports themselves and their maintenance (dredging and disposal) on the suspended sediment concentration is therefore (only) a redistribution of sediment with an increase in suspended sediment concentration in the vicinity of disposal sites, but to a decreasing sediment concentration further away from the disposal sites.

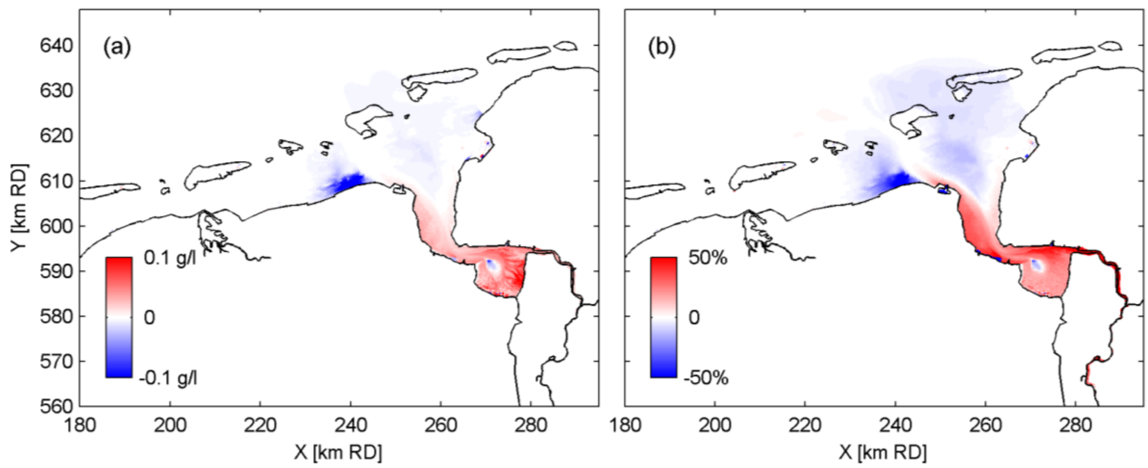

Figure 4.5 Absolute (a, in g/l) and relative (b, in %) increase in yearly averaged near-surface suspended sediment concentration resulting from closure of the ports (scenario 3 - reference)

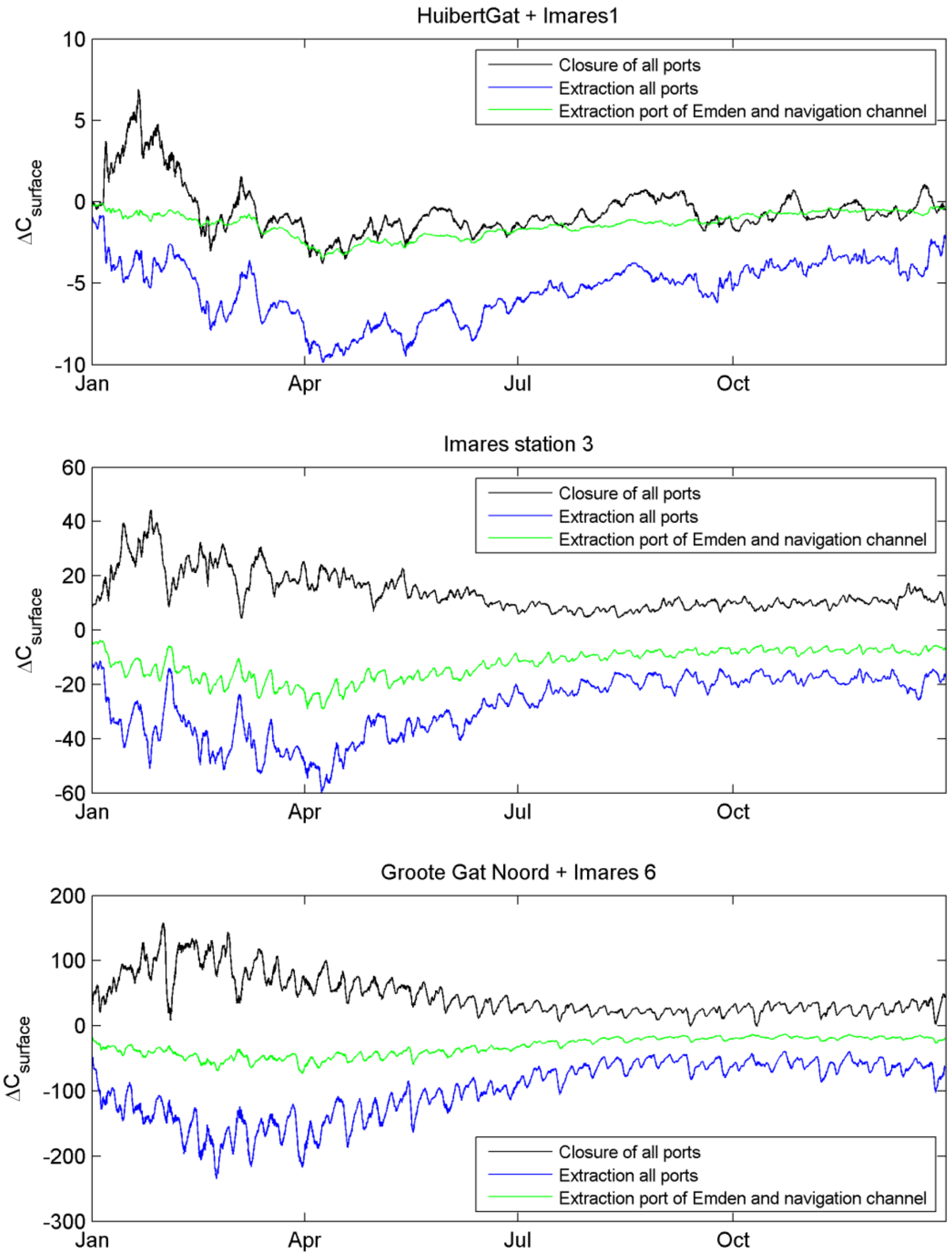

Figure 4.6 Increase in near-surface sediment concentration ΔC. 'Closure of all ports' is Scenario 3 – Reference; 'Extraction all ports' is Scenario 2 – Reference; 'Extraction port of Emden' is Scenario 1 – Reference. The sediment concentration is smoothed with a 24-hour moving average.

4.3 Morphological changes

4.3.1 Introduction

The morphology of the Ems Estuary has changed over a wide range of temporal and spatial scales. In the past centuries, a large part of the tidal flats in the Ems Estuary (particularly in the Dollard) have been reclaimed (reducing the combined supra and intertidal area from 290 to 160 km^2). At least partly in response to these reclamations (Gerritsen, 1952), parts of the estuary transformed from double-channel system with distinct ebb and flood channels into a single-channel system. However, there is insufficient quantitative information available to quantify the effect of these large-scale changes in morphology numerically with the WED model. Any effect these changes may have had, would have taken place decades to centuries ago. Since we aim to explain the effect of changes in SSC in the past decades, the effect of the tidal flats on tidal dynamics will be addressed semi-quantitatively in section 4.3.2.

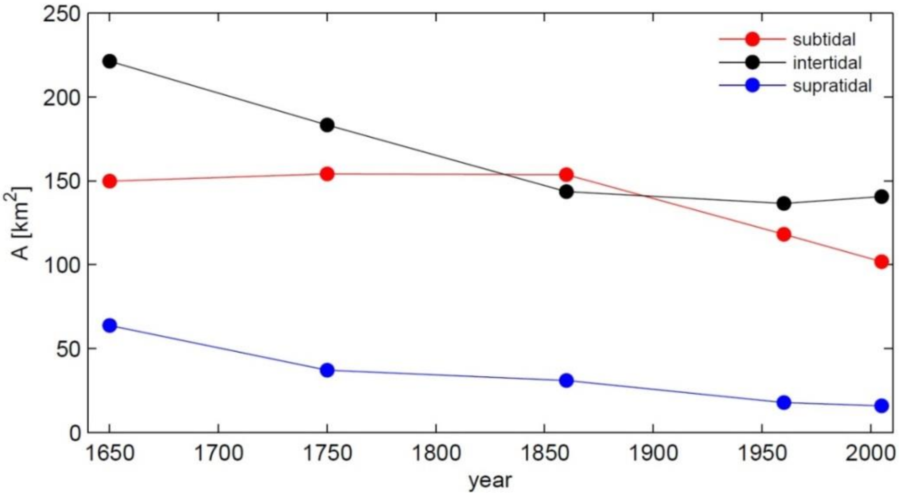

Figure 4.7 Surface area of subtidal (H<MLW), intertidal (MLW<H<MHW), and supratidal (H>MHW) areas in the Ems estuary, based on Herrling and Niemeyer (2007).

The most important man-made morphological changes in the last decades are related to deepening of the main channels (Oostfriesche Gaatje, Randzelgat and Doekegat, see Figure 1.1 for location of channels). A former ebb channel, the Bocht van Watum, is rapidly accreting (Figure 4.8). It is not clear to what extent the deepening of the main channel is caused by capital dredging works or by a transition from a 2-channel system to a single channel system (where the main channels deepens and the Bocht van Watum becomes shallower). The effect of morphological changes from 1985 to 2005 on suspended sediment dynamics is quantified by executing the WED model for 1985 as and for 2005, and compare the computed suspended sediment dynamics for both these periods (section 4.3.3).

4.3.2 Loss of intertidal flats

Fine sediments accumulate in intertidal areas. Since intertidal areas generally keep pace with sea-level rise, they provide a net sink of sediment. A reduction of the intertidal area therefore decreases sediment extraction from the estuarine system. Especially before 1860, the intertidal area of the Ems estuary was substantially larger than nowadays (see Figure 4.7), mainly because the Dollard was about two times larger than present. Around 1860, the reduction in intertidal areas stopped whereas the extend of the supra-tidal areas (mainly salt marshes) decreased.

The present-day average accumulation rate of fine sediments in the Dollard basin varies between 1 and 2 mm/year, but is locally as high as 8 mm/year (de Haas and Eisma, 1993). Since 1650, the size of the intra and supra-tidal area has decreased with about 130 km^2 (Figure 4.7). These areas have become land, and therefore the accumulation rates were larger than present-day accumulation rates. Assuming accumulation rates of 2-4 mm/year and a dry bed density in-between 600 and 1000 kg/m^3, suggests present-day net accumulation rates are 0.15 to 0.5 million ton/year lower compared to the year 1650. Assuming a constant supply from the Wadden Sea, a reduction in sediment sinks should lead to an increase in suspended sediment concentrations. The cumulative sediment mass deposited over the past 300 year (assuming linearly decreasing intertidal areas) is (0.15 to

0.50 million) x 300 year / 2 = 22.5 to 75 million ton. This is comparable to the total amount of sediment extracted from the system between 1960 and 1994 (Figure 4.2). Recent findings by Albert Oost (pers. comm.) suggest that the sediment sink in the Dollard was much larger, up to several million ton/year. The Dollard may have provided an annual sink as large as the extraction from the port of Emden (Figure 4.2) – this requires further research.

Water storage on tidal flats influences tidal asymmetry in the channels. In general, the tidal channels of short estuaries with extensive tidal flat areas tend to be more ebb-dominant (Friedrichs and Aubrey, 1988) than estuaries without extensive tidal flats. The Dollard basin, with a large intertidal area (relative to the subtidal area) is ebb-dominant (Ridderinkhof et al., 2000). The tidal flat areas in the Ems Estuary used to be larger (Figure 4.7), and therefore it seems likely that the present-day flood-dominant estuary used to be less flood-dominant or even ebb-dominant.

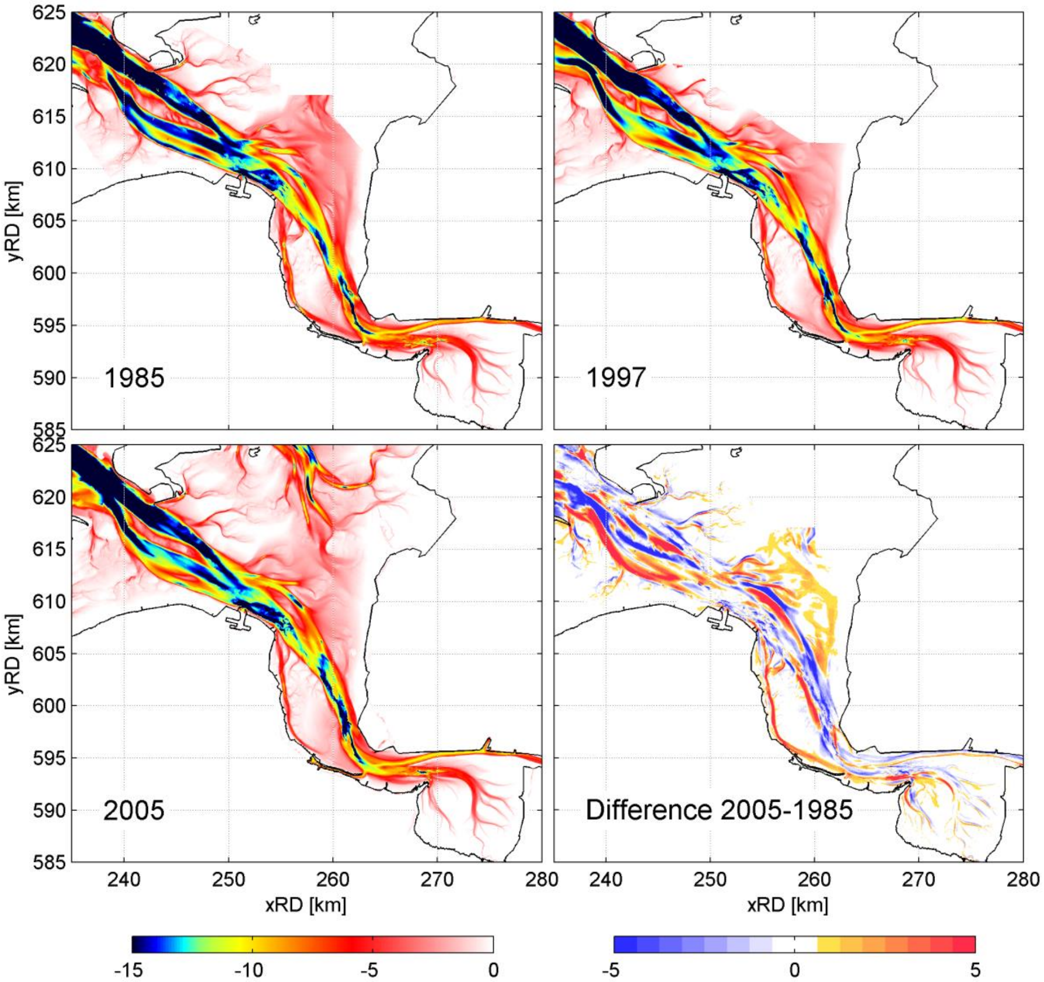

Figure 4.8 Bathymetry in the Ems estuary in 1985, 1997, and 2005 (soundings by the Dutch ministry of public works, in m below the reference level NAP), and the difference between 1985 and 2005 (in m).

4.3.3 Deepening of main channels

The effect of channel deepening is analysed by executing the model with a 1985 bathymetry instead of the bathymetry from 2005, for 2 dredging scenarios (scenario 4, see Table 4.2):

1) With dredging and dispersal as today (i.e. no extraction): this will provide information on the effect of changes in bathymetry on the suspended sediment distribution. This is scenario 4.

2) With dredging and dispersal as in 1985 (i.e. with extraction from Emden). This will provide the most realistic impact of changes from 1985 to 2005 on the suspended sediment distribution. This is scenario 5.

The year 1985 is chosen because for this year the oldest reliable bathymetry data set is available.

Table 4.2 Model scenarios related to channel deepening

Scenario	Ports	Extraction	Bathymetry	Density effects
Reference	Yes	No	2005	Baroclinic
Scenario 4	Yes	No	1985	Baroclinic
Scenario 5	Yes	Port of Emden	1985	Baroclinic
Scenario 6	Yes	No	2005	Barotropic

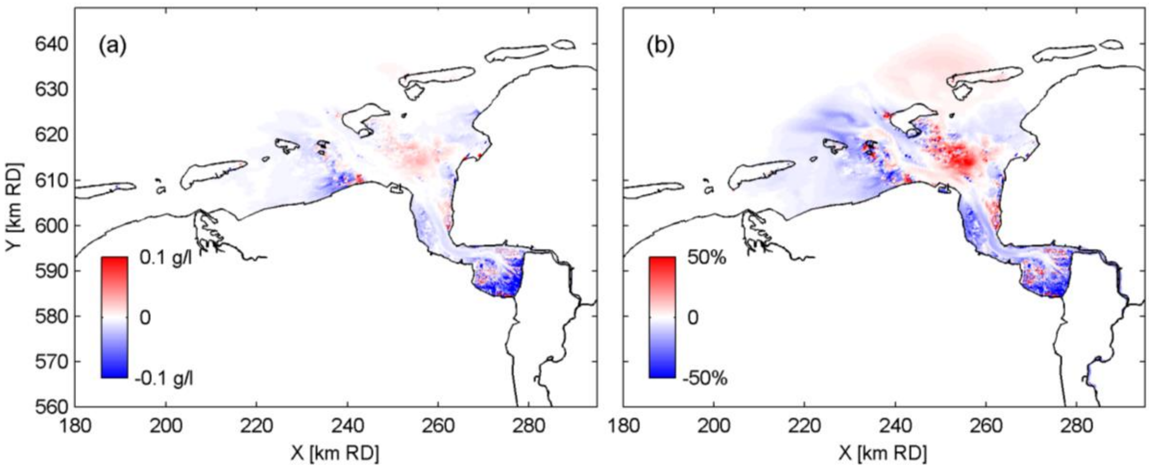

Figure 4.9 Absolute (a, in g/l) and relative (b, in %) increase in yearly averaged suspended sediment concentration using the 1985 bathymetry (scenario 4-reference)

Executing the sediment transport model with the 1985 bathymetry leads to lower suspended sediment concentrations in the Ems Estuary compared to 2005, particularly on the tidal flats in the Dollard (Figure 4.9). The decrease in the sediment concentration is largest in the shallow parts of the Dollard (several tens of percent). In the channels of the Ems estuary (including the Dollard), the decrease in the sediment concentration is smaller (typically around 10%, see Figure 4.9). The effect of the bathymetry also varies over the year (Figure 4.11). In the first half of the year the sediment decrease is small (Groote Gat) or may even increase (Huibertgat). In the second half of the year, the sediment concentration decreases in all stations.

In 1985, sediment was still extracted from the port of Emden (Figure 4.2). The reduction in suspended sediment concentration becomes larger when, using this same 1985 bathymetry, sediment is extracted from the port and approaches of Emden (Figure 4.10). This scenario is therefore most representative for the change from 1985 to 2005. Comparing both scenarios, the effect of extraction is larger than the effect of the morphological changes (most evident in Figure 4.11).

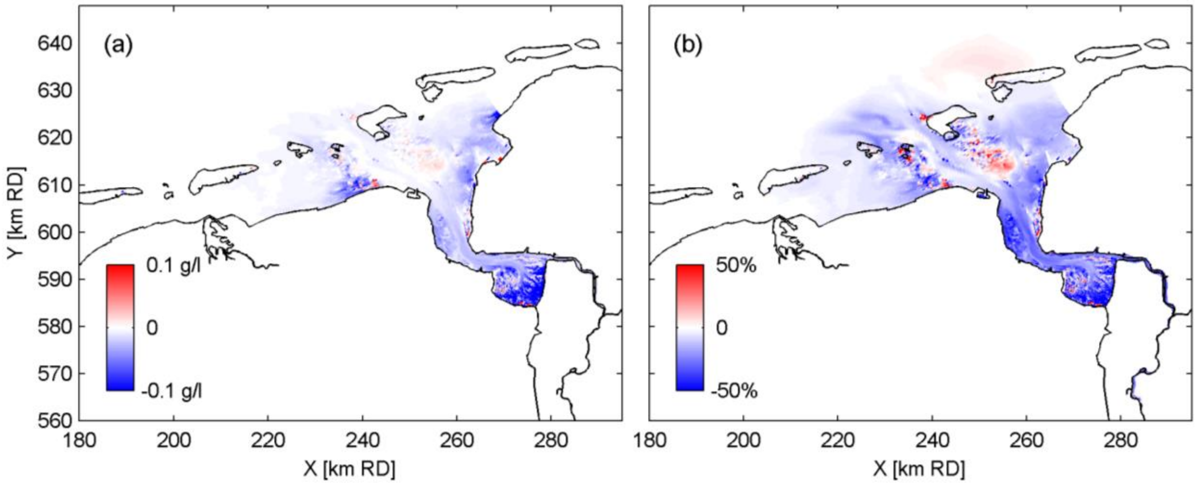

Figure 4.10 Absolute (a, in g/l) and relative (b, in %) increase in yearly averaged suspended sediment concentration using the 1985 bathymetry and extracting sediment rom the port of Emden (scenario 5-reference)

The modelled tidal propagation in the Ems estuary did not significantly change between 1985 and 2005 (using the 1985 and 2005 bathymetry, see report 4). Therefore the large computed difference in SSC between 1985 and 2005 (scenario 4, see Figure 4.9) may be the result of salinity-induced estuarine circulation. It is well known that salinity-induced density currents lead to up-estuary transport of sediment (e.g. Meade, 1969, Uncles et al., 1985). Estuarine circulation is a residual flow component (superimposed on the oscillating tidal currents) which develops in the presence of a horizontal salinity gradient and increases in strength with larger water depth and larger salinity gradients. The surface flow velocity is directed towards the area of higher salinity, and the near-bed velocity is directed towards the freshwater source. Since the near-bed sediment concentration is higher than the near-surface sediment concentration (see report 5), estuarine circulation generates up-estuary sediment transport

The impact of estuarine circulation is analysed by running the model in barotropic mode (without salinity-induced effects), and compare this with the baroclinic reference simulation (with salinity effects). In these simulations, the only constituent influencing density is salinity. In barotropic mode, the sediment concentration in the Ems estuary is much lower (Figure 4.12), demonstrating the importance of estuarine circulation for up-estuary sediment transport. The sediment concentration is only higher in barotropic mode at Huibertgat during resuspension events (Figure 4.11) since in baroclinic mode, the resuspended sediment is transported up-estuary whereas the sediment remains in the outer estuary without estuarine circulation (see also report 5).

This observation is supported by residual flow velocity profiles (Figure 4.13). In barotropic mode, the residual flow velocity is low and shows a logarithmic vertical profile with currents in the seaward direction. In contrast, for both 1985 and 2005 (in baroclinic mode) simulation, the residual flow velocity near the bed is directed up-estuary. However, the magnitude of the near-bed flow residual flow velocity is about two times larger in 2005 compared to 1985 (Figure 4.13). The magnitude of the residual flow velocity *u* at vertical position *z* scales with the cubed water depth *h* according to Hansen and Rattray (1965):

$$u_z \equiv h^3 \left(1 - 9\left(\frac{z}{h}\right)^2 + 8\left(\frac{z}{h}\right)^3 \right)$$

As a result of this strong depth-dependence, deepening of tidal channels leads to strengthening of the residual current. Typical changes of the tidal channels in-between 1985 and 2005 are deepening of 2-4 m of the Oostfriesche Gaatje (a ~10 m deep channel, see Figure 4.8). For a 10 m deep channel, deepening by 2 to 4 metres leads to a 1.7 to 2.7 -fold increase in salinity-induced residual flow (assuming the horizontal salinity gradient is unaffected by deepening). The computed increase in estuarine circulation is therefore in line with Hansen and Rattray's analytical residual flow velocity profile.

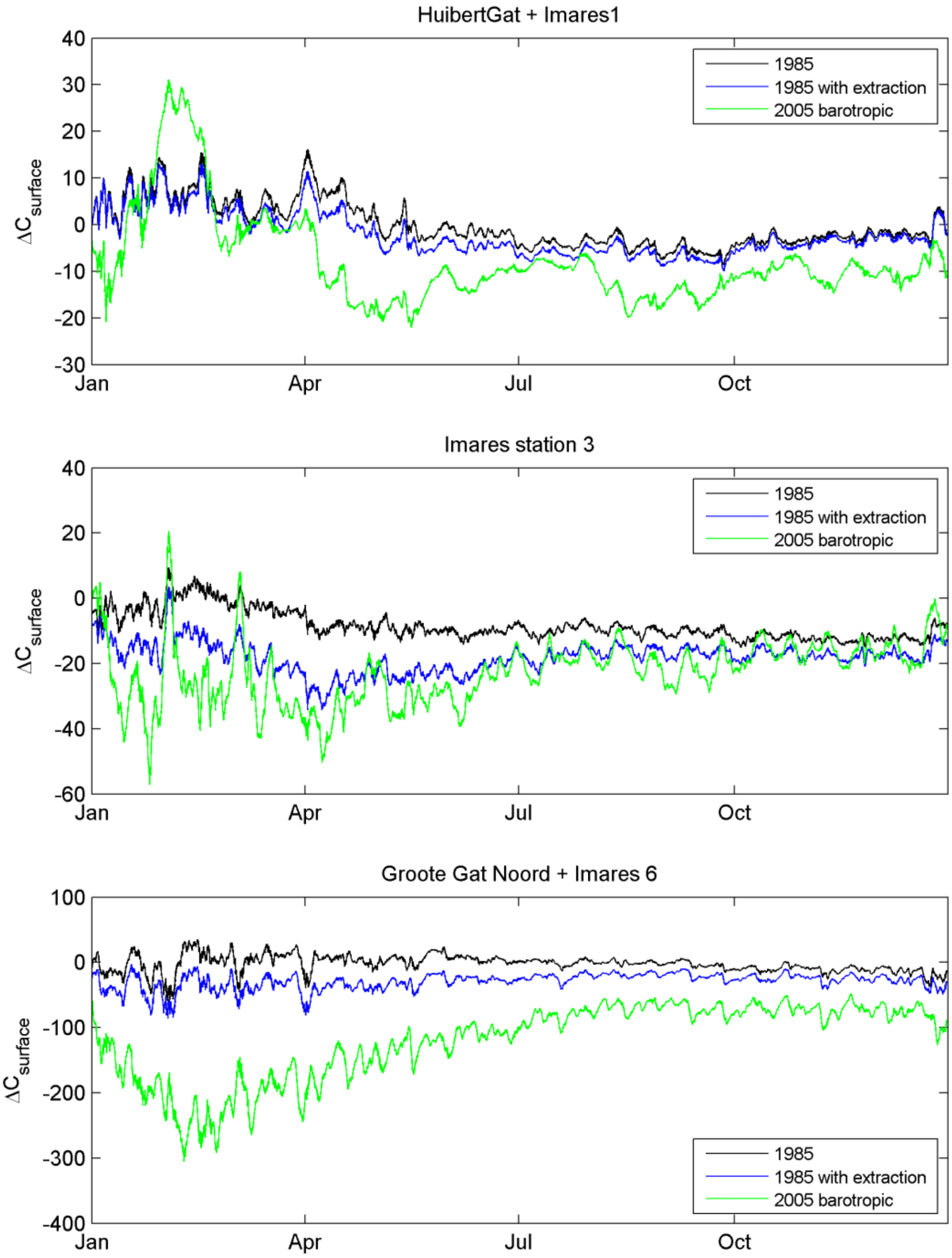

Figure 4.11 Increase in sediment concentration ΔC. '1985' is Scenario 4 – Reference; '1985 with extraction' is Scenario 5 – Reference; '2005 barotropic' is Scenario 6 – Reference. The sediment concentration is smoothed with a 24-hour moving average.

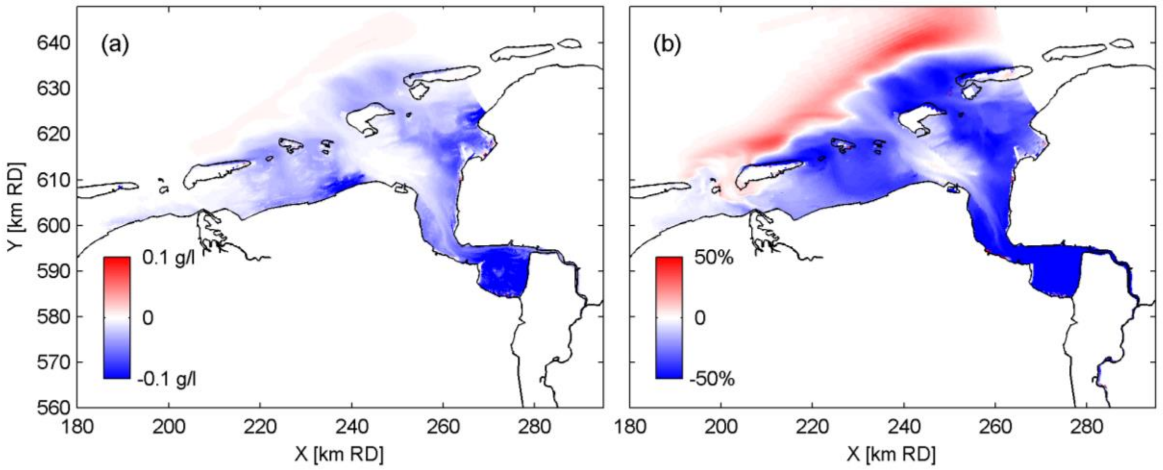

Figure 4.12 Absolute (a, in g/l) and relative (b, in %) increase in yearly averaged suspended sediment concentration resulting from switching off salinity effects (scenario 6 - reference)

It is therefore concluded that the deepening of the tidal channels (Oostfriesche Gaatje, Doekegat) and other morphologic changes in the estuary in the period 1985 to 2005 has strengthened salinity-induced estuarine circulation patterns, which increased the suspended sediment concentrations in the estuary up to several 10%.

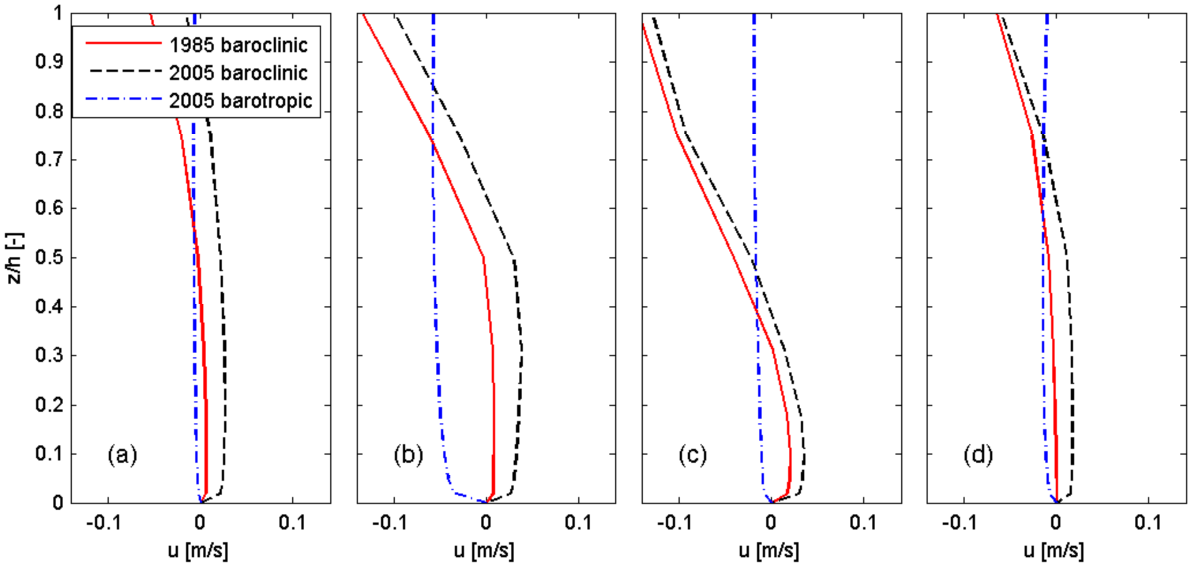

Figure 4.13 Residual flow velocity profiles, with positive values directed up-estuary, computed at GSP2 (a), ch1 (b), ch2 (c), and ch3 (3) for 1985 and 2005 (baroclinic mode) and 2005 (barotropic mode, i.e. no density effects). The averaging period is January through March, the period during which the fresh water discharge is largest. See Figure 4.1 for the location of stations. The water depth is dimensionless, defined as the vertical position z divided by the water depth h, allowing time-averaging of the velocity profiles.

4.4 Model applicability

4.4.1 Dredging, disposal, and extraction

The effect of dredging on suspended sediment concentration is determined by the amount of sediment disposed, and how rapidly this sediment disperses. Therefore the computed effect of dredging and disposal on suspended sediment concentrations is mainly determined by

- Deposition rates in the ports (and subsequent disposal)
- Residual transport rates and sediment sinks

The port deposition rates and residual sediment transport rates have both been defined as target variables (see Harezlak et al., 2014) to quantify the accuracy of the sediment transport model (report 5). The accuracy of the model to reproduce these target variables is briefly summarised below (see report 5 for details).

Deposition rates

Siltation in the ports of Delfzijl and Eemshaven were in agreement with observations, but siltation in the Emden Port and its approach channel was underestimated with 1 million ton/year. As a result, the model underestimates the effect of dredging from the Emden area (disposal and extraction).

For disposal, this has been partly compensated by modifying the disposal strategies from the port of Delfzijl. In Delfzijl, ~80% of sediment is agitated where it flows out of the port as a density current (and thereby re-enters the estuary). In the model, all sediment settling in the port is disposed on the dumping grounds in the Dollard. This has a more pronounced effect of turbidity then agitation dredging (sediment enters the estuary at the entrance of the port of Delfzijl, not in the Dollard, through agitation dredging). This increased turbidity partly compensates the underestimation of the disposal flux from the Emden area. A consequence is the effect of the port of Delfzijl on turbidity is probably overestimated.

The effect of extraction from the Emden area on turbidity is underestimated when the model underestimates the deposition flux in this area. Therefore an additional model scenario has been executed in which sediment is extracted from all ports combined (in addition to a scenario in which sediment is only extracted from the Emden area. Extraction from all ports provides a better approximation of the total extracted sediment mass that was historically extracted from the port of Emden.

Residual transport

The model underestimates net sediment sinks (such as the lower Ems River and the Bocht van Watum, see report 5). The sediment mass annually accumulating in the main sinks (the Bocht van Watum and lower Ems River) is estimated to be about 1.5 million ton. Transport to the ports account for an additional transport: about 1.6 million ton is annually dredged from the fairway to the port of Emden, 1.3 million accumulates in the ports of Delfzijl and Eemshaven (but since half is resuspended by airset about 0.6 million contributes to the residual transport). This gives a total of 3.7 million ton. In the model, 1.9 million ton is annually depositing in the ports, implying that the residual transport is underestimated with 50%.

4.4.2 Channel deepening

In our model, channel deepening strongly influences the suspended sediment concentration through estuarine circulation. The most important uncertainties related to channel deepening are therefore related to

- The magnitude of the residual circulation (how realistic is the computed change in estuarine circulation)
- The impact of residual circulation on suspended sediment transport (how important is estuarine circulation for overall sediment transport, compared to tidal transport)

These uncertainties are evaluated in more detail below.

The residual flow velocity often is a small net difference between large gross ebb and flood flow velocities that makes the residual sensitive for small errors in the gross values. However, the computed change in residual flow velocity is in line with the frequently-used Hansen and Rattray (1965) analytical solution. The modelled residual flow velocity is difficult to compare with observations, because also observed residual flow velocity profiles are inaccurate in case of small residuals compared to gross values, the residual has a strong spatial variation, influenced by topographic details that are not part of the model, and few observations exist.

It is even more important to verify how important the estuarine circulation is for total suspended sediment transport. The model suggests that up-estuary transport is strongly dependant on estuarine circulation (demonstrated by the low sediment concentrations in the Dollard for the barotropic simulations). There is no data available to support or oppose the modelled large influence of residual flow on residual transports. However, the computed hydrodynamic and sediment transport results are physically realistic, and provide an explanation for observed changes in suspended sediment concentration.

4.5 Conclusions

4.5.1 Summary

In the past centuries, loss of tidal flats through large-scale land reclamations probably made the tides in the Ems estuary more flood-dominant whereas simultaneously less sediment was extracted from the system. Both lead to an increase in suspended sediment concentration.

Deepening of tidal channels will strengthen estuarine circulation patterns and contribute to enhanced suspended sediment concentrations, especially in the Dollard. Until ~1990, sediment concentrations were lowered by large-scale sediment extraction from the port of Emden. Ending this practice has led to larger suspended sediment concentrations after 1990.

Compared to the effect of extraction, the impact of the presence of ports (including maintenance dredging and dispersal) is small. Comparing the present-day situation (with ports and dredging and disposal) to a scenario without ports (and hence no dredging and disposal) reveals that constructing ports (1) reduces the turbidity levels close to the ports and (2) increases the turbidity near the disposal sites. Averaged over the estuary, the impact of dredging and disposal is not very large (and smaller than the impact of channel deepening or sediment extraction). These changes cannot be directly compared to the impact of the loss of the tidal flats, because these have not been quantified with the model.

4.5.2 Hypotheses

Hypothesis 4 (*The sediment concentration in the Ems Estuary has increased because of a loss of tidal flats, leading to (1) modified tides and (2) less sediment sinks)* is probably true over longer timescales (centuries) but not on the timescales on which this study focusses (decades). This hypothesis is addressed with data, not with the model. In the presence of extensive tidal flats (such as historically in the Ems estuary), tides are generally more ebb-dominant. However, there is insufficient historical data available to quantify and verify the impact of changes of the tidal flats with the applied models. The loss of intertidal areas has reduced the natural sediment sink in the system with 0.15 to 0.5 million ton/year. This reduced sediment sink has very likely contributed to an increase in suspended sediment concentrations.

Hypothesis 5 *(the sediment dynamics in the Dollard area have marginally changed, so the Groote Gat station (where the sediment concentration does increase) is not representative for the Dollard area)* can be tested by analysing the spatial distribution of computed sediment concentration changes for the various model scenarios in this chapter. Unfortunately, the various scenarios generate contrasting spatial distribution of changes in SSC. The computed effect of ending sediment extraction shows a spatially uniform increase in SSC throughout the Dollard (Figure 4.3 and Figure 4.4). The presence of ports results in a reduction of SSC in large parts of the estuary, but an increase near disposal sites (Figure 4.5). The Groote Gat station is located fairly close to a disposal site, so the observed increase here (Figure 1.3) may be local (with SSC decreasing elsewhere, see Figure 4.5). The effect of deepening generates largest increase in SSC on the flats, rather than in the tidal channels (Figure 4.9). It is likely that the observed increase in SSC at Groote Gat results from a combination of mechanisms, and therefore on average the increase at Groote Gat station can be considered as representative for the Dollard. The hypothesis is rejected.

Hypothesis 7 *(The sediment concentration in the Ems Estuary has increased due to dredging and disposal because of (a) recirculation processes and (b) fining of the sediment bed)* is partly true. The effect of dredging and disposal is, compared to a situation without ports, mainly a spatial redistribution of sediments but has a limited impact on the suspended sediment concentration. The SSC merely increases near disposal sites, but decreases elsewhere. However, the change in the extraction strategy from the port of Emden ended the reduction in suspended sediment concentration that it provided up to 1994. The ending of sediment extraction is probably an important mechanism for the observed increase in suspended sediment concentrations. Part b) of the hypothesis has not been addressed because this effect is too difficult to distinguish from other processes, in the model and in available data (when an area becomes more muddy, more dredging is needed, so it is difficult to distinguish the effect of additional fining as a result of dredging).

Hypothesis 8 (*Long-term natural and anthropogenic changes in the intertidal areas and the tidal channels of the Ems Estuary have sufficiently modified the tidal propagation to significantly influence sediment dynamics)* is probably true. The changes in the extent of the tidal flats (especially the infilling of the Dollard in the past centuries) must have influenced tidal propagation. Also the long-term change in tidal channels was large, and this must have affected the tidal dynamics. However, these effects cannot be numerically verified due to lack of sufficient detailed topographic, historic data (see also Hypothesis 4 above). The changes for which data is available (the past decades) are comparatively small, but have still had a large effect on sediment dynamics. The main mechanism for this change was a change in vertical residual circulation. Tidal propagation was only marginally affected.

5 Changes in the Wadden Sea and North Sea

This chapter describes the effect of external changes on the suspended sediment dynamics in the Ems Estuary (hypothesis 2 and 6 related to **suspended sediment dynamics** and **hydrodynamics**).

5.1 Introduction

In addition to changes that have occurred in the Ems Estuary or the lower Ems River (see Figure 5.1 for location), the turbidity in the Ems Estuary may also be influenced by external factors. The most prominent external factors are sediment supplied by the Wadden Sea and the North Sea and sea level rise. The morphological changes in the Wadden Sea, which may affect sediment supply to the Ems estuary are large, including closures of tidal basins and changes in land reclamation schemes (both leading to a large-scale loss of net sediment sinks as discussed in the previous chapter).

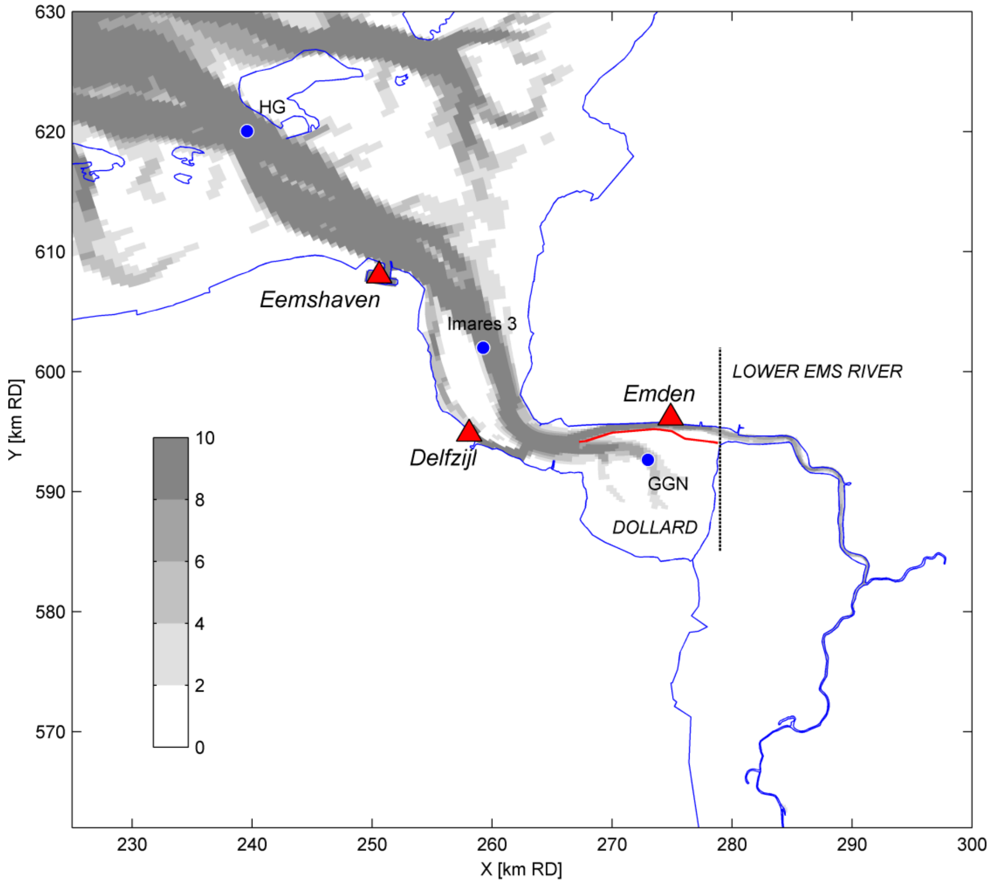

Figure 5.1 Map with model bathymetry (only depth between 0 and 10 m shown to highlight the difference between tidal channels and flats) of the Ems Estuary, including the main ports (Eemshaven, Delfzijl, and Emden) and observation points used in this chapter. The sediment concentration stations (HG = Huibertgat and GGN = Groote Gat Noord) are in blue.

There are indications that the suspended sediment concentration in the Wadden Sea is indeed increasing (see report 3 and this chapter). The sea level rise is both eustatic (global sealevel rise, which is often predicted to accelerate in the near-future) and local (resulting from subsidence due to gas extraction). These impacts have been summarized in two hypotheses:

(2) *The sediment dynamics in the Eastern Wadden Sea have remained constant despite changes in salt marsh works and biological factors. As long as the hydrodynamics in the Ems Estuary remain unchanged, so does the transport from the Eastern Wadden Sea into the Ems Estuary.*

(6) *Sea level rise does not change the sediment dynamics of the Ems estuary.*

The effect of variable sediment concentrations from the Wadden Sea and the North Sea on the Ems Estuary sediment dynamics will be quantitatively explored in section 5.2, whereas a more qualitative analysis of the effect of Sea Level Rise (SLR) is provided in section 5.3. The accuracy of the model is discussed in section 5.4 and results summarised in section 5.5.

5.2 Offshore sediment supply

5.2.1 Introduction

Some of the stations in the Wadden Sea show an increase in suspended sediment concentration very similar to those in the Ems estuary (Dantziggat, ZO Lauwers Oost, see Figure 1.3). It has not been investigated to what extent the increasing suspended sediment concentration observed at these stations is local or more extensive. Nevertheless, they do suggest that possibly the eastern parts of the Dutch Wadden Sea is also becoming more turbid. An important question then is whether a changing turbidity in the Ems estuary influences the Wadden Sea, vice versa, or whether the regions have evolved independently of each other. During non-storm conditions, the tidal inlets in the Wadden Sea behave as separate sediment cells, with net import resulting from settling lags and scour lags (van Straaten and Kuenen, 1957, Postma, 1961, 1967). During storm events, sediment resuspension creates a landward increasing concentration gradient that, combined with horizontal diffusion of sediment by tidal currents, generates seaward transport. However, during storm events the storm setup allows exchange of water and sediment over the tidal divides of the Dutch Wadden Sea (Wang et al., 2012). With storms predominantly from the SW to N, storm-induced residual flow and transport is in eastward direction. The above suggests that the Wadden Sea influences the sediment concentration in the Ems estuary, and not vice versa.

The historic morphological changes in the eastern part of the Dutch Wadden Sea that may have influenced the sediment concentration within the Wadden Sea are as follows: The increase at Dantziggat (the station with the largest increase in suspended sediment concentration in the past 20 years, see Figure 1.3) is probably related to the large amount of local dredging and sediment disposal required for a navigation channel. Surprisingly, the stations in-between Dantziggat and ZO Lauwers Oost (also revealing a pronounced and statistically significant increase in suspended sediment concentration) show a decrease in SSC. Interestingly, these two stations are located in a tidal inlet that was partly closed in 1969 (reclamation of the Lauwers Sea, reducing the areal extent of the tidal basin with 30%). The reduced tidal prism resulted in significant morphological changes, amongst others the deposition of large volumes of mud in the Zoutkamperlaag channel (Oost, 1995; Van Ledden et al., 2006, Elias et al., 2012). Large siltation rates lead to local reduction in suspended sediment, thereby lowering the suspended sediment concentration.

The closure of the Lauwers Sea may, however, also lead to an increase in suspended sediment concentrations elsewhere. To partly compensate the loss of the Lauwers Sea, the tidal divide shifted eastward (3-4 km between 1979 and 1987; Oost, 1995). If it is assumed that sediment is eroded up to a depth of one meter, a lateral shift of 3 km over a 5 km wide tidal divide (the approximate width of the migrating part of the tidal divide) ~15 million m^3 of sediment is remobilized. The tidal divides are largely composed of fine sediment and therefore a large amount of mud was released during this migration: probably 5-10 million ton (assuming a dry bed density of 500 kg/m^3). With prevailing eastward transport this would lead to increasing sediment concentration east of the inlet, possibly explaining the increased sediment concentration at station ZO Lauwers Oost (albeit with a finite timelag, see report 3 for details). ZO Lauwers Oost is located in-between the Lauwers Sea and the Ems estuary, and if the increase at ZO Lauwers Oost is indeed caused by the Lauwers Sea, its closure probably significantly influenced the Ems estuary as well.

An additional mechanism possibly influencing long-term turbidity is the wind climate. The frequency of storms is increasing since ~1960 in the North Sea (Weisse et al., 2005) and the northern shores of the Netherlands (especially close to the Ems estuary; Smits et al., 2005). The changes are part of long-term multi-decadal fluctuations in wind patterns, with significantly low storm occurrence in 1930 and 1970, and maxima around 1920, 1950, and 1990 (Schmidt and von Storch; 1993; Schmidt 2001). This may influence fine sediment resuspension in the Wadden Sea (and hence the sediment transport towards the Ems estuary), but also directly increase wave-induced resuspension (and therefore the sediment concentration) in the Ems estuary itself.

A change in sediment concentration on the offshore North Sea is considered unrealistic (and also not observed: see Figure 1.3). The sediment concentration in the nearshore zone of the North Sea may have increased (for instance, as a response to nourishments). However, most sediment is nourished along the Holland Coast, and there are no indications of increasing turbidity in the first downdrift tidal inlet there, the Marsdiep (Philippart et al., 2013). It is therefore unlikely that the sediment concentration in the North Sea has changed in the past decades.

5.2.2 Model scenarios

In order to quantify the effect of changes in sediment supply from the Wadden Sea (loss of intertidal areas / increased storm activity) or the North Sea (effect of storm activity / nourishments) on the Ems Estuary, the boundary conditions of the model are varied. The sediment concentration in the model reference settings is 20 mg/l in the North Sea and 100 mg/l in the Wadden Sea (see Table 5.1). The Wadden Sea sediment concentration reasonably corresponds to observations (see report 5) whereas 20 mg/l is larger than offshore stations in the North Sea reveal (report 3). However, the sediment concentration in the North Sea increases rapidly towards the shore and no data is available to quantify that gradient. Therefore a uniform value of 20 mg/l was selected to represent the sediment concentration in the North Sea.

If there has been a change in the sediment concentration at the offshore boundaries, it is most likely that the concentrations used to be lower (Figure 1.3). This is part of scenario 1-3: a lower North Sea sediment concentration, a lower Wadden Sea sediment concentration, and both lower. The factor 2 decrease is based on observations in stations such as ZOLO and Huibertgat, where the concentrations more than doubled in the past 20 years (see report 3). A fourth scenario is a higher Wadden Sea sediment concentration (Table 5.1). Only long-term data is available on the western side of the model domain. In absence of available long-term data on the eastern side, the changes in sediment concentration are applied on both the east and west boundary of the model. Additionally, the sediment concentration imposed on the eastern boundary also is of lesser importance given the predominant west to east transport direction in the Wadden Sea.

Table 5.1 Scenarios for the effect of the offshore boundary conditions

Scenario	Wadden Sea concentration [mg/l]	North Sea concentration [mg/l]
Reference	100	20
1	100	10
2	50	20
3	50	10
4	200	20

5.2.3 Model results

The reduction in the imposed boundary condition of the North Sea (scenario 1, Figure 5.2) has a larger impact on the modelled sediment concentration in the Ems estuary than the reduction of the Wadden Sea boundaries (scenario 2, Figure 5.3). The difference between these two scenarios is largest during summer, when the effect of the Wadden Sea boundary on the sediment concentration in the Ems Estuary is low (Figure 5.6). During summer, the wave-induced reworking of sediment and eastward transport is insufficient to transport large amounts of sediment from the Wadden Sea into the Ems Estuary. The North Sea boundary has a larger impact than the Wadden Sea boundary because (1) the water volume over the North Sea boundary is much larger (the Wadden Sea boundary is located on a tidal divide), (2) the Wadden Sea boundary is located relatively far away from the Ems Estuary (with a tidal divide, with relatively low alongshore transport rates, in-between the boundary and the Ems Estuary, and (3) higher concentrations in the North Sea also lead to larger concentrations in the Wadden Sea. Both lead to higher sediment concentrations in the Ems Estuary, but the exact contribution of the North Sea / Wadden Sea therefore depends on the model domain.

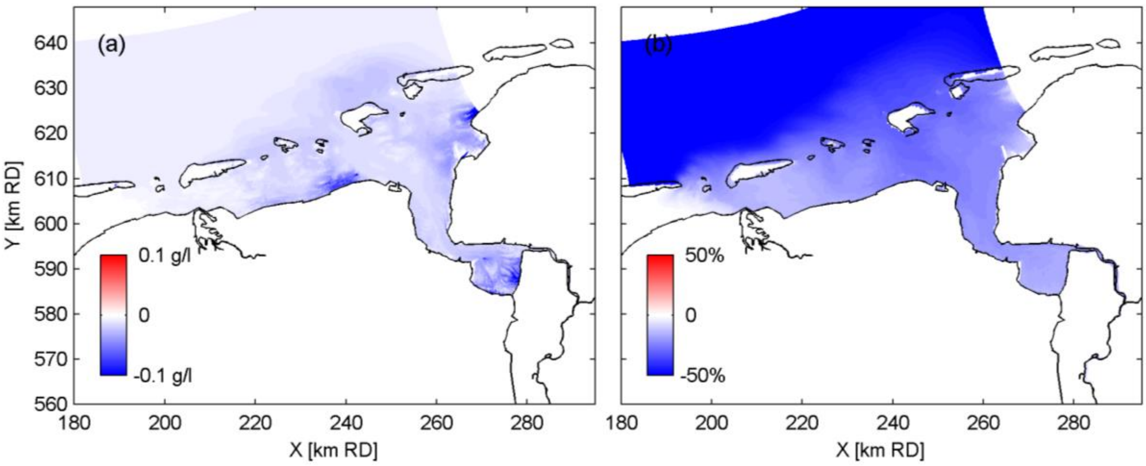

Figure 5.2 Absolute (a, in g/l) and relative (b, in %) increase in yearly averaged surface sediment concentration using a 2 times lower sediment concentration at the North Sea boundaries (scenario 1 - reference).

Reducing the sediment concentration on the boundaries of the Wadden Sea and the North Sea (scenario 3, Figure 5.4) leads to a reduction in SSC in the Ems estuary which is comparable with the sum of the Wadden Sea and North Sea contribution separately (Figure 5.2 plus Figure 5.3); see also Figure 5.6. This suggests that the modelled sediment concentration in the Ems Estuary is supply limited: the sediment concentration is strongly influenced by the amount of sediment available at the estuary mouth. This is further supported by scenario 4, in which the suspended sediment concentration at the Wadden Sea is a factor 2 larger (Figure 5.5), leading to a similar (but opposite) impact on sediment concentrations.

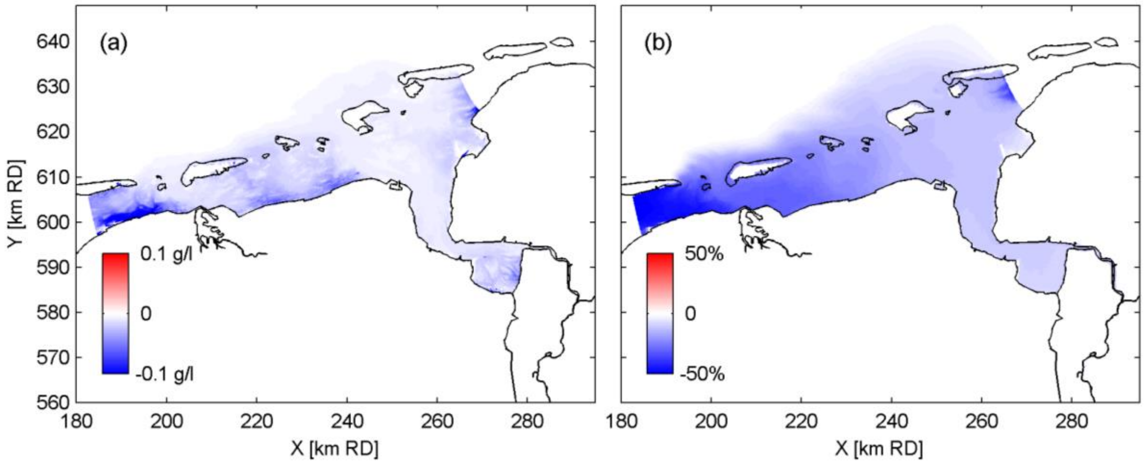

Figure 5.3 Absolute (a, in g/l) and relative (b, in %) increase in yearly averaged surface sediment concentration using a 2 times lower sediment concentration at the Wadden Sea boundaries (Scenario 2 - Reference).

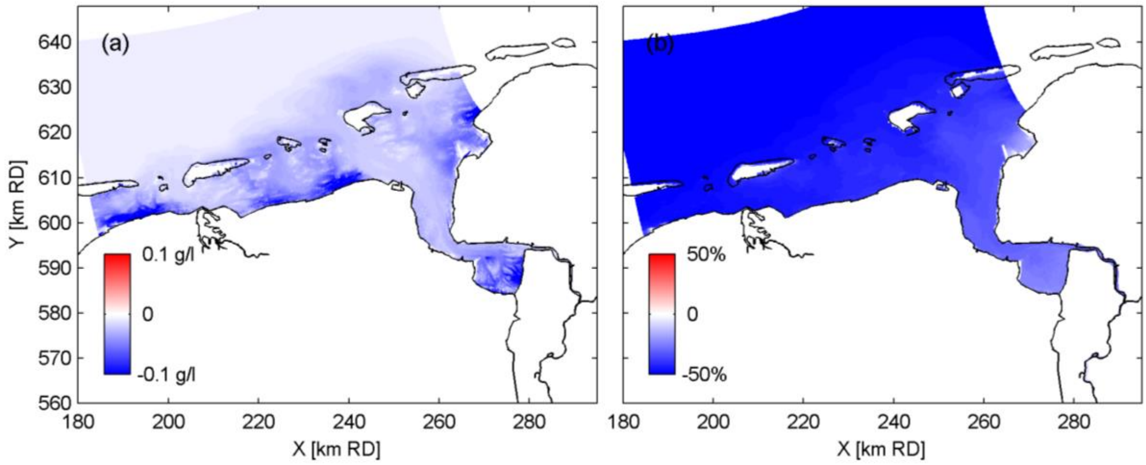

Figure 5.4 Absolute (a, in g/l) and relative (b, in %) increase in yearly averaged surface sediment concentration using a 2 times lower sediment concentration at the Wadden Sea and North Sea boundaries (Scenario 3 - Reference).

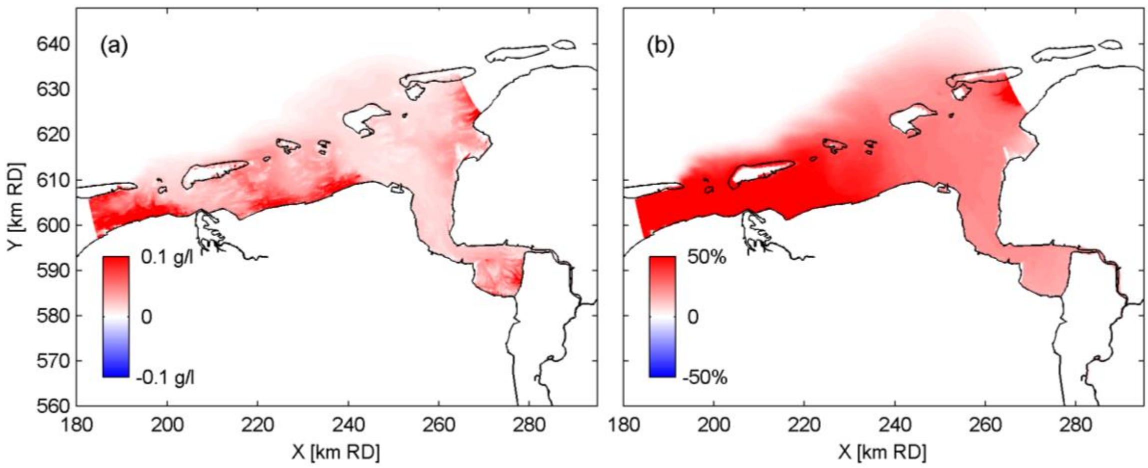

Figure 5.5 Absolute (a, in g/l) and relative (b, in %) increase in yearly averaged surface sediment concentration using a 2 times higher sediment concentration at the Wadden Sea boundaries (Scenario 4 - Reference).

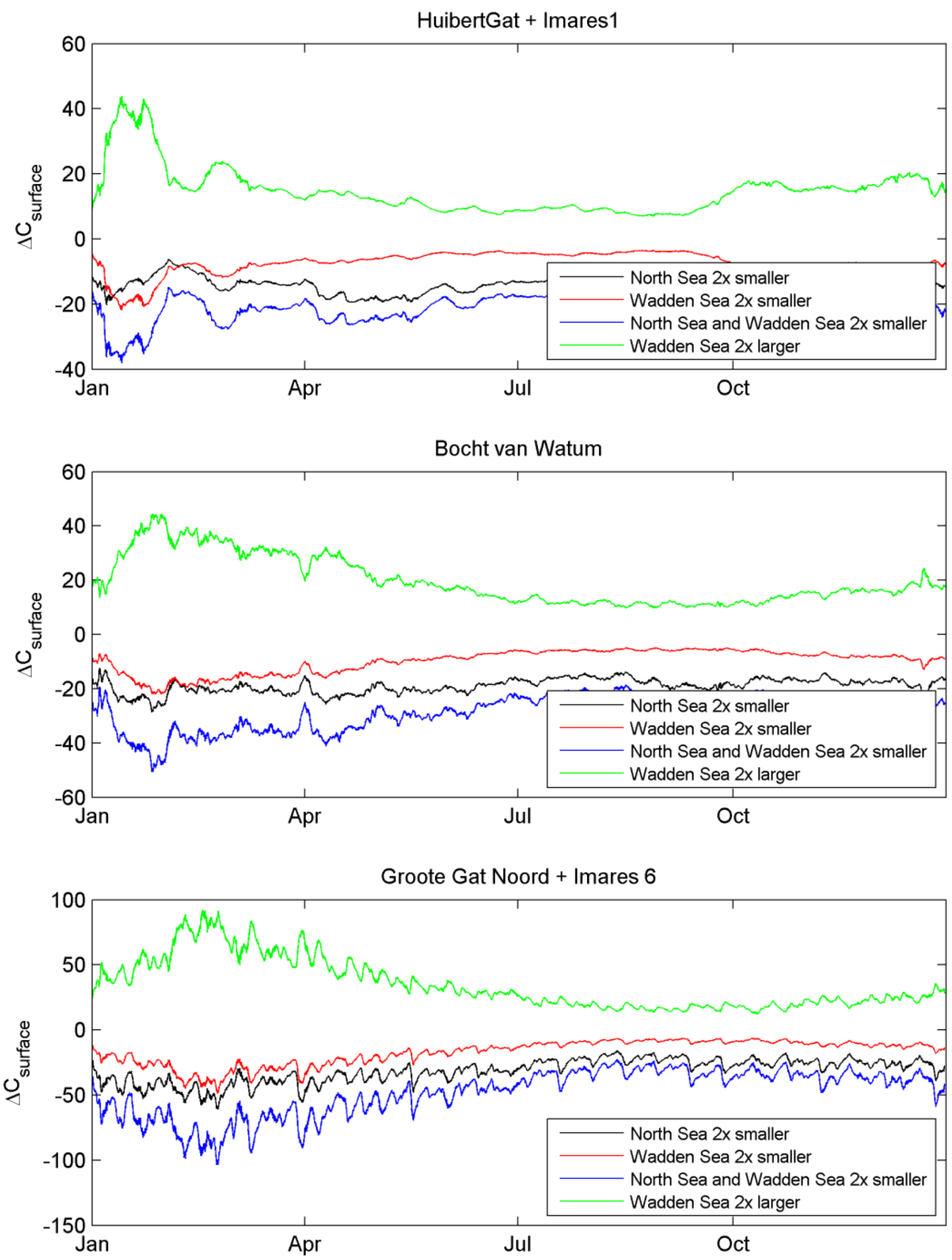

Figure 5.6 Increase in sediment concentration relative to the reference scenario in stations Huibertgat, Bocht van Watum, and Groote Gat (Scenario 1 to 4 – Reference).

The relative increase during last 20 years in observed suspended sediment concentration is largest at station Huibertgat, where the concentrations more than doubled in a period of 20 years (see Figure 1.3, but report 3 for details). The modelled impact of changes in the Wadden Sea and North Sea have a more pronounced impact on the sediment concentration in the outer estuary (near station Huibergat) compared to the impact resulting from changes in the Ems estuary or lower Ems River (Chapter 3 and 4). Despite the fairly crude assumptions in the Wadden Sea / North Sea simulations (related to the factor 2), these spatial trends suggests that the observed increase near Huibertgat is caused (at least partly) by external effects.

5.3 Sea level rise

Over long timescales, estuaries and lagoons fill in with sediments, transforming into terrestrial environments. This process is opposed by relative sea level rise and opposed by storm surges (such as the storm that created the Dollard in the 14th century). Relative sea level rise is composed of the eustatic (absolute) sea level rise (hereafter referred to as SLR) and land subsidence. The historical rate of SLR is 0.2 m / century, whereas land subsidence is spatially more variable. Relative SLR may have an influence on suspended sediment dynamics by influencing the hydrodynamics and by providing a sink of sediments. These effects will be reviewed here semi-quantitatively.

Compared to the rate of morphological change in the estuary (several meters in 20 years, see Figure 4.8) the relative change in water depth resulting from SLR (4 cm in the same period) is negligible. Any change in water depth resulting from SLR will be rapidly compensated by morphological adaptations in the tidal channels. The effect of eustatic SLR on hydrodynamics can therefore be assumed to be non-existent. More significant (although more local) is land subsidence resulting from gas extraction. Subsidence has been largest under the Bocht van Watum and Hond-Paap Island (Figure 5.7; see Figure 1.1 for locations): typically 15 to 20 cm. This is still small compared to the morphological adaptation speed of the tidal channels (several metres in the same period), and therefore also subsidence probably has limited impact on the hydrodynamics, in contrast to its influence on the availability of sediment sinks..

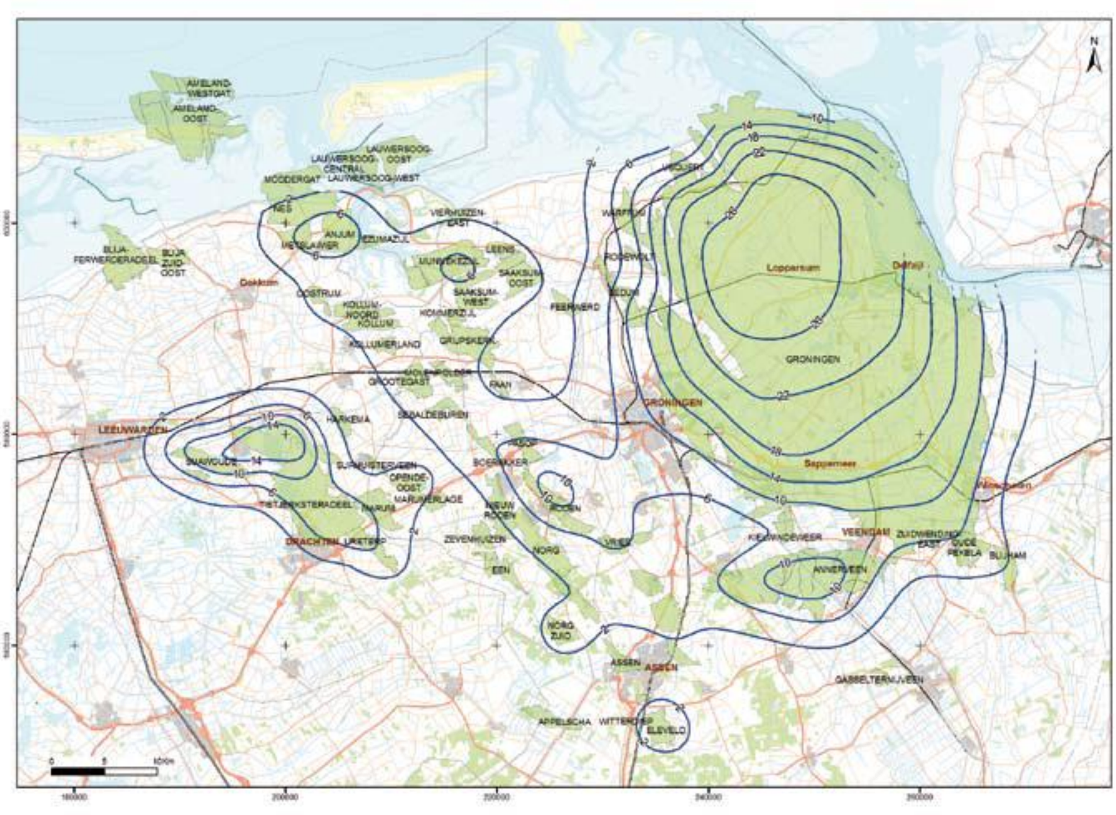

Figure 5.7 Land subsidence up to 2008 (in cm) resulting from gas extraction (NAM, 2010).

The combined intertidal and supratidal area in the Ems Estuary is 160 km^2 (see Figure 4.7). With a SLR of 2 mm/year, a volume of 0.32 million m^3/year needs to deposit annually on the flats and marshes to keep rise with SLR. In consolidated state, with a dry bulk density of 500 kg/m^3, this is equivalent to 0.16 million ton/year. This sediment mass is no longer resuspended, and therefore SLR may reduce the SSC in the Estuary. An acceleration of SLR, as foreseen with most climate scenarios, may then further reduce the SSC in the Ems Estuary relative to the autonomous development.

An additional sediment sink is provided by the rate of local subsidence (including subsidence resulting from gas extraction) times the area where fines may accumulate (tidal flats, shallow, sheltered areas), such as the shallow, relatively fine-grained Bocht van Watum and Hond-Paap island. This area (approximately 100 km^2) over which the average subsidence has been ~15 cm in the past 50 years, may have accumulated 0.3 million m^3/year (i.e. 0.15 million ton/y). In areas such as the Dollard, the subsidence rate is much smaller. Over the whole estuary, about 0.5 million m^3/year may be a realistic estimate for sediment deposition to compensate for subsidence. Assuming a mud content of with a density of 500 kg/m^3 (some of the deposited sediment will also be sand), this amounts to 0.25 million ton annually depositing to compensate for subsidence.

The combined effect of eustatic sea level rise and subsidence provides a net sediment sink, probably corresponding to approximately 0.4 million ton/year. Sediment extraction simulations executed in the previous chapter suggest that the effect of such an extraction may be very large (e.g. Figure 4.3). Therefore SLR may have a significant impact on (reducing the) estuarine suspended sediment concentration.

5.4 Model applicability

5.4.1 Offshore sediment supply

The response of the estuary to changes in offshore boundaries provides indicative information on which parts of the estuary are influenced by the Wadden Sea and the North Sea suspended sediment concentrations. The estuary is more influenced by the sediment concentration in the North Sea than in the Wadden Sea, but this may be partly related to the definition of the model domain. A change in North Sea SSC values is much less realistic than a change of SSC in the Wadden Sea (see Figure 1.3). In the Wadden Sea, increased turbidity levels have been observed (such as station ZO Lauwers Oost, where the turbidity has increased a factor 2 from 1990 to 2010), and several mechanism have been identified that may be responsible for such an increase (land reclamation strategies, closure of the Lauwerszee).

The numerical model can be used to determine trends (where does the sediment concentration change, and which forcing is probably more important), but is less suitable to quantitatively correlate trends in SSC to changes in the Wadden Sea boundaries or dredging strategies. Therefore the model can be applied to investigate if and where changes are likely to occur in response to interventions or to changes in boundary conditions. Of all modelled scenarios (in Chapter 3-5), the sediment concentration in the outer estuary only significantly increased as a result of changes in the Wadden / North Sea boundaries. These are strong indications that the observed increase at Huibertgat from 1990 – 2010 (see Figure 1.3 and report 3) is related to the offshore boundaries.

With respect to Huibertgat, however, it should be noted that long-term variations in sediment concentration exist which are difficult to explain. In the early 1980’s the observed sediment concentrations where much larger than present (report 3) while since 2011 the concentrations have become a factor 2 lower than the previous decade (report 5). Probably the observed sediment concentration here is also influenced by methodological issues (hence the accuracy of the data) or possibly large-scale (cyclic) morphological processes.

5.4.2 Sea level rise

Process-based numerical morphodynamic models may provide valuable insight in tidal flat sedimentation processes (van Maren and Winterwerp, 2013) as long as the spatial and vertical resolution is sufficiently high. Modelling equilibrium sedimentation rates on tidal flats with such a model is complicated. To reproduce equilibrium tidal flat profiles (and hence the growth of flats to keep pace with SLR) analytical tidal flat models such as used by Roberts et al. (2000), Pritchard et al. (2002), or Pritchard and Hogg (2003) are more appropriate. The numerical model applied in this study is morphostatic, i.e. without feedback mechanisms between the flow and the bed, and is not suitable to accurately model the response of the flats to SLR – this may be part of future research. Combining process-based numerical models with analytical profile models may provide a good approach; this could be part of further research.

5.5 Conclusions

5.5.1 Summary

The sediment concentrations in the Wadden Sea and in the North Sea strongly influence the suspended sediment concentration in the estuary. It is more likely that the sediment concentration in the Wadden Sea has changed (related to land reclamations and /or closure of the Lauwerszee) than in the North Sea (which is much larger and therefore less easily influenced by human interventions). Based on the trends computed with the numerical model (in this chapter but also chapter 3 and 4) an increase in the boundary conditions provides the most likely explanation for an increase in SSC in the outer reaches of the Ems Estuary. Such an increase is suggested by long-term observations of SSC at Huibertgat, although this data set should be interpreted with care because of methodological inconsistencies and morphological changes.

Sea level rise (SLR) creates space for sediments to deposit, thereby acting as a sink for the sediment. Such a sediment extraction will likely reduce the suspended sediment concentration.

5.5.2 Hypotheses

Hypothesis 2 *(The sediment dynamics in the Eastern Wadden Sea have remained constant despite changes in salt marsh works and biological factors. As long as the hydrodynamics in the Ems Estuary remain unchanged, so does the flux from the Eastern Wadden Sea into the Ems Estuary)* is rejected. There are indications that the sediment concentration in the Wadden Sea has increased (Figure 1.3), and mechanisms that may be responsible for such a change have been identified. An increase in the SSC in the Wadden Sea will lead to higher suspended sediment concentrations in the Ems Estuary.

Hypothesis 6 (*Sea level rise does not change the sediment dynamics of the Ems estuary)* is rejected. Sea level rise provides a sufficiently large sediment sink for large quantities of sediment to deposit, and therefore to a reduction in SSC in the estuary. The contribution of gas mining is probably equally important to eustatic SLR, although the relative SLR because of gas mining is finite and will decrease in time.

6 Implications of changing suspended sediment for primary production in the Ems estuary.

6.1 Introduction

The Ems estuary is characterized by strong gradients in physical and water quality parameters. The estuary is very turbid in the Dollard with high suspended matter concentrations (SPM) in the Dollard and low transparency and light availability (see previous sections). SPM concentrations decrease seawards and transparency and light penetration increase (Figure 6.1) (de Jonge and Brauer 2006). Nutrients coming from the Ems are highest in the Dollard and decline seawards (Figure 6.1) (van Beusekom and de Jonge 1998). Pelagic primary production in the Dollard is thus strongly light limited, while there is a gradual change towards nutrient limited primary production in the Wadden and North Sea during summer. The Ems Estuary is characterized by a large proportion of tidal flats, providing surface for microphytobenthos during dry periods with ample light availability. In the shallow areas, benthic primary production can be as important as pelagic primary production and controlling factors for benthic primary production are more ambiguous than for primary production.

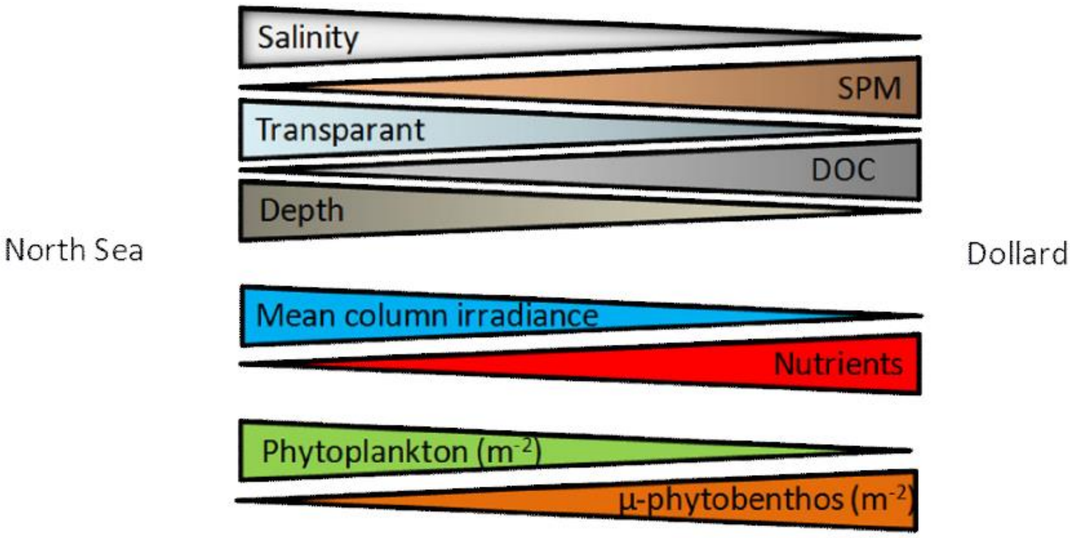

Figure 6.1 Simplified scheme indicating the direction of gradients of properties in the estuary. Vertical cross section of each symbol symbolises the magnitude of the parameter dependent of the location in the estuary (copy .of literature report, Spiteri et al. 2011).

In the 70s, benthic and pelagic primary production in the Ems estuary have been extensively studied and measured, mainly by F Colijn and V.N. de Jonge (e.g. Colijn 1982, Colijn 1983, De Jonge 1992, De Jonge et al. 1998). Most of their work and conclusions are still valid, since the gradients and limiting factors for primary production in the Ems Estuary have not changed drastically. However, actual concentrations have changed over the past decades, with a decrease in nutrient concentrations due to nutrient reduction measures and an increase in sediment concentrations (De Jonge and Brauer 2006, De Jonge et al. 2014). Especially phosphate concentrations from rivers have decreased, but there is still a summer release of phosphate from the sediment in the Dollard and middle reaches. Production and biomass of microphytobenthos were extensively measured and provided a strong dataset for many publications (e.g Colijn and De Jonge 1984, De Jonge and Colijn 1994). It was shown that benthic primary production can contribute significantly to pelagic chlorophyll-a, due to resuspension, occasionally up to 50% (De Jonge and Van Beusekom 1992). An assessment of total primary production of both phytoplankton and microphytobenthos based on this dataset showed that benthic production was a quarter of total production and even 70% in the Dollard. The controlling factors for benthic production include light availability, resuspension, nutrients, grazing and desiccation (Underwood, 2001). The annual average pelagic primary production in 1976-1980 ranged from 49 g C/m^2 in the Dollard to 263 g C/m^2 in the outer part of the Estuary (Colijn 1983).

In 2012 and 2013, IMARES has carried out pelagic primary production measurements (Brinkman et al. 2014, data report # 9). They found system average values of 120-125 g C/m^2/y, about 60% of the values in 1979-1980. The extrapolation of primary production measurements to system averages included the tidal area. This can be attributed to increased silt and decreased nutrients. Limiting factors for primary production are more difficult to measure than primary production and chlorophyll-a and are based on correlation and/or multiple regression (De Jong and Essink 1991), physiological state of algal cells (e.g. Riegman and Rowe 1994) and nutrient uptake experiments (Riegman et al. 1990). In the Wadden Sea recent studies reveal nutrient limitations (Loebl et al. 2009). Primary production models help to determine limiting factors for benthic and pelagic primary production in time and space based on prevailing environmental conditions.

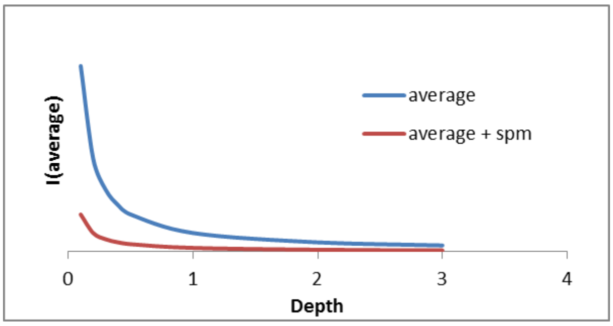

Figure 6.2 Average light availability dependent of depth for situation without and with SPM according to equation 1.

In general, light availability for pelagic primary production varies with turbidity and depth according to the depth integrated form of the Lambert-Beer equation:

$$I_{av} = \frac{I_{surf}}{K*Z} \qquad \text{(equation 1)}$$

Where I_{av} is the average irradiance in a completely mixed water column, I_{surf} is the irradiance at the surface, K is the extinction due to SPM, and Z is the water depth.

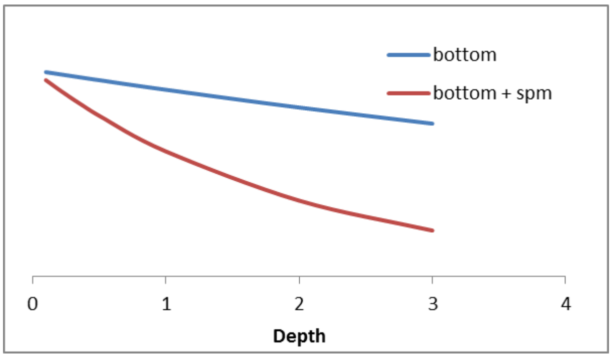

Figure 6.3 Light availability at the sediment-water interface dependent of depth for situation without and with SPM according to equation 2.

Average availability of light decreases proportionally to the product of water depth and K, resulting in low light availability in deep areas or in very turbid waters.

Light available for benthic primary production (at the bottom) equals:

$$I_{bot} = I_{surf} * e^{-K*Z} \qquad \text{(equation 2)}$$

Where I_{bot} is irradiance at the bottom. The light availability decreases proportional to the exponent of K*Z, meaning that the available area of suitable habitats for benthic primary production decreases rapidly upon either an increase in depth, or an increase in turbidity.

Understanding limiting factors for primary production, both for pelagic and benthic primary production is essential to predict the system response to measures on sediment reduction. The effect of changes in a nutrient and light limited system is presented graphically in Figure 6.4. In a light limited system an increase in silt will have a direct effect on the light or energy that is used for primary production.

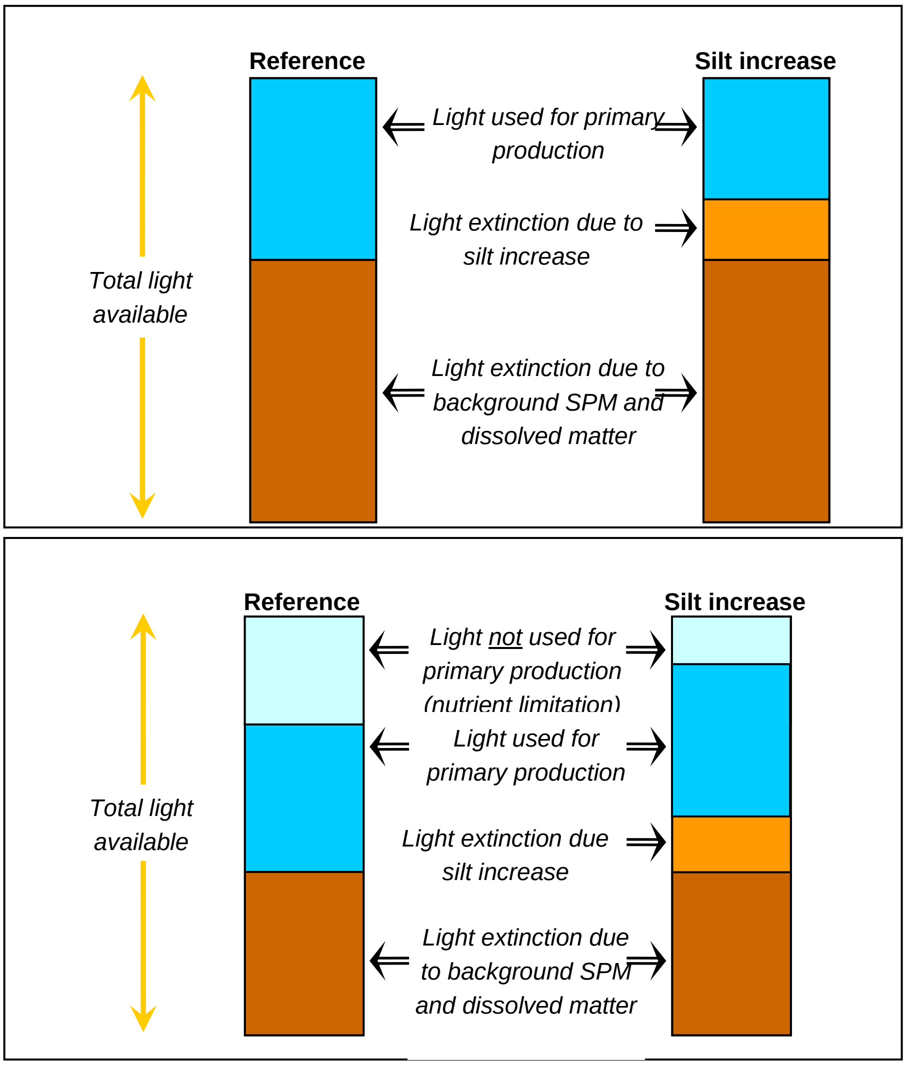

Figure 6.4 Top: In light limited areas all available light is used for primary production. An increase in silt will decrease primary production and vice versa. Below: In nutrient limited systems, not all light is used for primary production. A change in silt will not result in a change in primary production.

6.2 Hypotheses on the response of primary production on changes in suspended sediment and nutrients.

The aim of the primary production part was to study the effect of mud dynamics on primary production and water quality and to investigate solutions and measures to improve ecological quality. In the first phase, current system knowledge and knowledge gaps on the Ems estuary were identified (Spiteri et al., 2011). Based on that report, research hypotheses were formulated and a monitoring and modelling plan was made. The tools used to study these hypotheses were literature search, field monitoring, and modelling. In the second phase monitoring and model setup were conducted and in the third phase scenarios were carried out. This chapter aims to analyse the functioning of the Ems estuary ecosystem in terms of limiting factors for primary production, and the possible responses of the ecosystem to changes in turbidity and nutrient loads, using a calibrated and validated model chain. The following research hypotheses were defined:

1) ***Pelagic primary production is controlled by turbidity in the Estuary.***
2) ***Benthic primary production is mainly controlled by nutrients and resuspension.***
3) **Measures to reduce turbidity in the estuary will increase the primary production by phytoplankton and therefore contribute to higher carrying capacity for higher trophic levels.**
4) **The effect of decreased nutrient loads from land will reduce the benthic production, counteracting the effect of decreased turbidity in the estuary.**
5) **Changes in turbidity and nutrient availability will change algal composition.**
6) ***The three MWTL stations in the Ems Estuary are sufficiently representative in order to estimate the ecological status with regard to phytoplankton abundance.***

The model chain exists of the hydrodynamic model and sediment model to simulate suspended sediment concentrations in the water, described in chapter 2, and a (water quality and) primary production model. The models are linked in such a way that the primary production model uses output from the hydrodynamic model for transport, dispersion and freshwater discharges, and output from the sediment model to calculate the light extinction due to suspended particles. The set-up of the primary production model is described in detail in report 6 of this series reports.

The hypothesis can only be tested by modelling if there is enough confidence in the model results. In this case, it can be expected that the model predicts primary production and algal biomass well, and that it reacts realistically to changes in the forcing functions, notably suspended sediment concentration and river nutrient loads. Validation of the primary production model resulted in the following conclusions.

- The salinity gradient in the estuary was simulated well, although a precise validation was hampered by the difference between the data sets acquired by RWS and IMARES respectively.
- In order to reproduce light extinction measured by MWTL in the estuary for 2012, the suspended sediment concentration of the sediment model was reduced by a factor 2. For the validation year 2013, no such correction was needed.
- Once light extinction was calibrated well, average phytoplankton biomass, expressed as chlorophyll-a was predicted well. Variability was overestimated, so that chlorophyll-a is overestimated in summer and underestimated in winter.
- Average benthic algal biomass, expressed as chlorophyll-a prediction is in the right order of magnitude, but a precise validation is hampered by the assumed patchiness of benthic biomass, and the difficulty to match the scales of model and monitoring results.
- Average nutrient concentrations were predicted well. The seasonal variation was described reasonably, with a small time lag of concentrations as compared to measurements.
- Pelagic yearly primary production, aggregated on larger areas is predicted well. The variation of primary production along the estuarine gradient is estimated well, except for one area in the innermost part of the Dollard (IM08).
- Benthic primary production could not be validated because the benthic primary production measurements were not considered to be reliable.

- In general, when comparing the MWTL measurements with IMARES measurements, undertaken in the same years, there are good similarities, but also differences with respect to oxygen and salinity.

A detailed description of the model setup and calibration/validation can be found in report 6 and detailed results of the scenarios are described in report 8.

6.3 Approach

Hypotheses 1 and 2 were tested by an analysis of existing and new monitoring results, in combination with model results. Light availability and nutrient concentrations were measured in the field, giving an indication which factor might be limiting. In section 6.4, model results provide a spatial and temporal pattern of limiting factors for pelagic and benthic primary production.
Hypotheses 3, 4 and 5 have been tested by running different sensitivity runs with the calibrated water quality and primary production model. The sensitivity runs presented in this study consist of generalized reductions of suspended sediment concentrations and nutrient loads, and should only be used as a sensitivity analysis. Results are presented in chapter 6.6.
Hypothesis 6 has been tested by an analysis of monitoring results in combination with modelling. In this chapter, a comparison between water body integrated model output and the results of individual monitoring stations is presented (chapter 6.7).

6.4 Controlling factors for primary production

Light is the limiting factor for pelagic primary production in most of the estuary (literature study, report 1). This is caused by high suspended sediment concentrations, and therefore very low transparency of the water. Euphotic depth varies from 1 meter at the outer parts of the estuary to less than 0.1 m in the inner parts (report 1, chapter 4). So, it can be expected that net pelagic primary production is confined to shallow, intertidal areas. From field measurements, there are indications that nutrient limitation may occur, because annual summer chlorophyll-a correlates to phosphorus loads (De Jonge et al., 1998). Since nutrient concentrations are very high in the inner estuary, nutrients are most likely only limiting in the outer parts of the estuary (report 1, chapter 4). Benthic primary production is less dependent on the underwater light conditions, and thus suspended sediment. Benthic production takes place on intertidal areas during dry periods. Benthic chlorophyll-a seems more dependent on temperature than on nutrient loads (Report 1, chapter 4).

In this section, an analysis of model results is presented to further explore the effect of limiting factors on primary production. The results will be discussed in terms of possible system changes due to measures that aim to improve conditions in the estuary.

In summary the water quality model simulates physical and chemical processes, such as mixing, nutrient loads and boundaries well enough for the analysis done in this report. The processes involved in pelagic primary production and phytoplankton biomass are simulated well enough to use in this analysis. In a small shallow part of the Dollard, modelled chlorophyll-a was unnaturally high and this area will not be regarded further.
It is uncertain how well benthic primary production is simulated in the present analysis, due to uncertainties in measurements and therefore the validation (Chapter 2, this report, and report 6). Results of this analysis on benthic primary production should therefore be interpreted with care.

The main purpose of reviewing the limiting factors for primary production is to make assumptions of the effects of changes in the environment. From a model perspective, a limiting factor is defined as a process or concentration of nutrients and/or light, which limits the biomass of a certain algal group. Six potential limitations are distinguished which are not mutually exclusive.

- Light or energy limitation
- Nitrogen limitation
- Phosphorus limitation
- Silicate limitation – when silicate is limiting the growth of diatoms
- Growth limitation – when maximum growth rate is reached, but still light and nutrients are not depleted.
- Mortality limitation – when in spite of imposing the maximum mortality still some biomass remains. There is a high occurrence of this constraint in almost all parts of the Dollard. This is a reflection of the highly dynamic conditions with respect to SPM and depth due to tidal transport and mixing. Algal growth is followed by mortality due to suboptimal conditions while algae are transported through the estuary.

Growth limitation and mortality limitation are not shown in Figure 6.5, because these limitations are less important for the aim of this study, which is focussed on the effect of nutrients and light (limitation) on primary production.

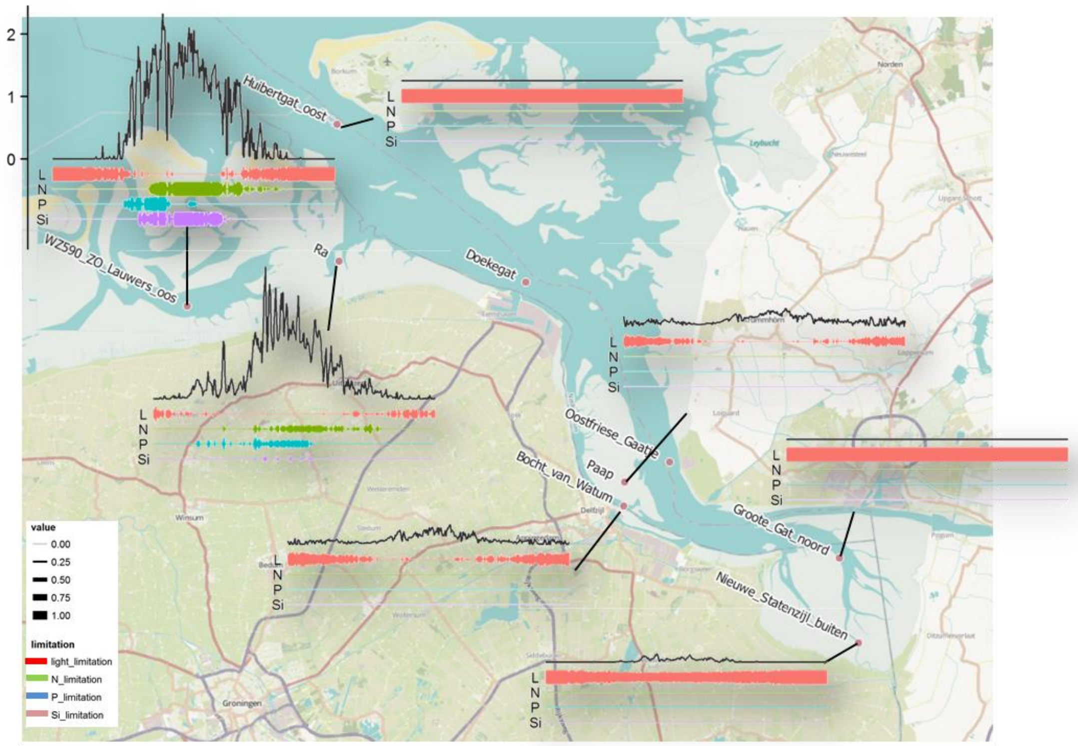

Figure 6.5 Part of the model domain with presentation of net primary production(gC/m2/d) (black line) and limiting factors modelled for the present situation. Coloured horizontal lines indicate the variation of limiting factors over the year. Limiting factors could occur for pelagic or benthic algae and the strength of limitation is indicated by the thickness of the coloured line. Scales are equal for all plots. L = light limitation (red), N = nitrogen limitation (green), P = phosphorous limitation (blue), Si = silica limitation (purple).

In the relatively deep channel stations (e.g. Huibertgat Oost, Doekegat, Oostfriese Gaatje and Groote Gat Noord) light limitation is by far the dominating limiting factor for pelagic primary production (Figure 6.5). At the same time, at these relatively deep locations, there is no calculated net primary production throughout the year. This can be explained by the high turbidity in combination with relatively deep waters. At a shallower station (Bocht van Watum and Paap), light is limiting in winter, but not during summer. Nutrients do not become an important limiting factor during summer and consequently, algae can grow with maximum growth rates during summer. Transport is constantly removing and diluting phytoplankton biomass, and this is the reason that net primary production is not higher at this station. At the shallowest station Nieuw-Statenzijl, algal biomass is limited by the high turbidity used to force the model in this part of the Dollard. The stations, Nieuw-Statenzijl and Ra have high net primary production because they are relatively shallow locations where mixing does not cause much dilution. At stations outside the Ems plume in the Wadden Sea (Ra and WZ590), algae become phosphorus-, and later also nitrogen- and silica-limited during summer (Figure 6.5). Net primary production is relatively high at these stations. This last factor is dependent on the depth of the station. Primary production is moderate at Bocht van Watum due to the relatively deep water column.

Summarizing, in the deeper parts of the Ems Estuary there is at present no net primary production possible, due to strong light limitation. In shallow parts in the Ems estuary, primary production is higher during summer, but nutrient limitation is not likely to occur. Outside the Ems plume, nutrient limitation occurs during summer.

In the model, benthic primary production occurs at shallow (intertidal) places, where light is ample available during dry periods. The model does not calculate light and/or nutrient-limitation per group, but model results shows that at some locations, phosphate and silicate concentrations become very low and therefore possibly limiting during summer (Figure 6.6). The low concentration is caused by consumption of both pelagic and benthic algae. It can be assumed that in such shallow segments, benthic algae have a large influence on concentrations of nutrients. So, phosphate and/or silicate limitation is possible, but since the calibration and validation of benthic primary production only resulted in an uncertain simulation of benthic production, these results should be interpreted with care. In nature, benthic diatoms are not often found to be limited by nutrients (Barranguet et al., 1998). Dense layers of benthic diatoms may occasionally be limited by the diffusion rate of carbon and/or oxygen from the water to the diatoms layer (Admiraal et al., 1982; Cook & Røy, 2006). Carbon is not modelled explicitly in the current application, and can therefore not act as a limiting factor for benthic diatoms.

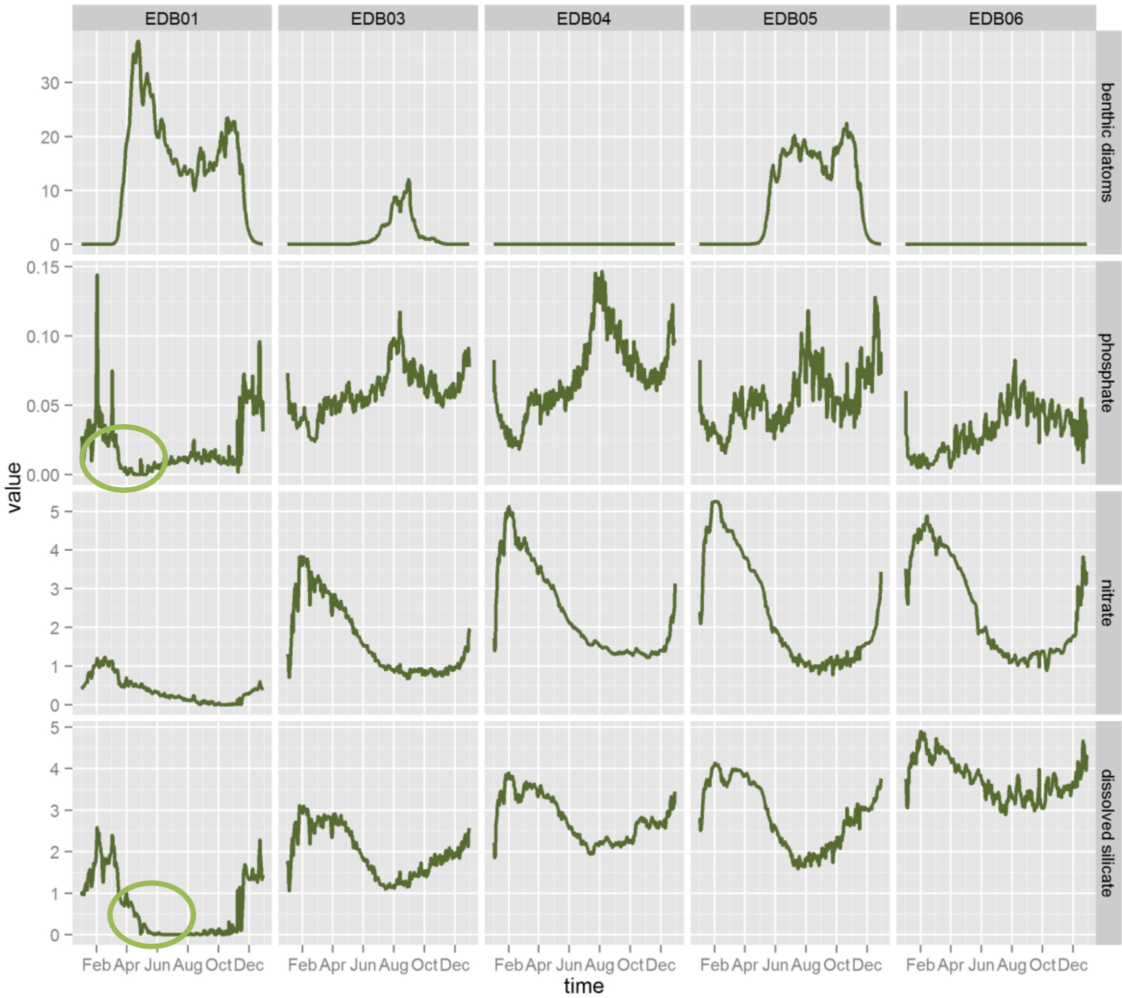

Figure 6.6 Biomass of benthic diatoms (g C/m2) and concentrations of nutrients in g [element]/m^{3}at 5 shallow locations in the Ems estuary. EDB01 – EDB06 indicate a gradient of shallow locations from sea to river through the estuary. Silicate and phosphate depletion in summer occurs at the location EDB01 (green circle).

Light limitation in the Ems-Dollard is caused by high turbidity in combination with water depth. In temperate coastal waters light limitation is common during winter and early spring because of low irradiance. However, in large parts of the Ems estuary, light is limiting for phytoplankton growth even during summer, when irradiance is high. In that period, light limitation is caused by the very high extinction due to suspended solids in the water. Extinction due to living phytoplankton and/or dead organic material is of minor importance (Figure 6.7). Even at a station outside the Ems Estuary plume WZ590, extinction due to phytoplankton is of minor importance.

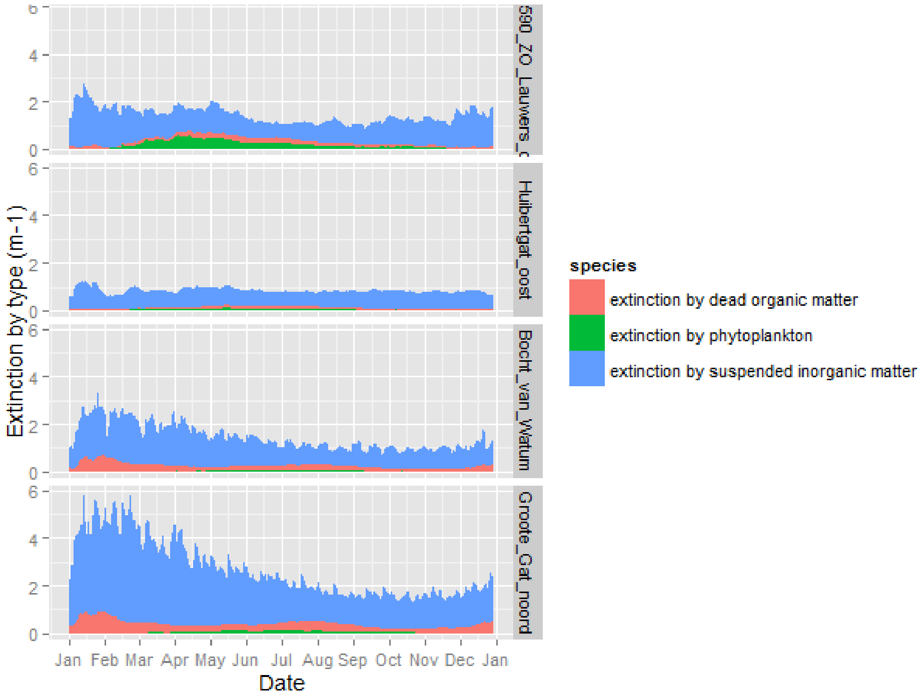

Figure 6.7 Modelled light extinction by phytoplankton (green), organic suspend solids or detritus (red) and the sum of background and suspended inorganic solids (blue). For model technical reasons, the background extinction (0.08) is incorporated in the extinction by suspended inorganic matter, but appears to be unimportant in this system.

6.5 Effects of suspended sediment and nutrient loads on primary production

Primary production was calculated over the areas IM01 – IM10 (Figure 6.8). Values are presented as area-specific values in g C/m^2/y, to compare between areas, and as area-integrated (total) production per area in tonnes C/y.

To reduce the amount of information, we have selected two representative sensitivity runs to test the hypotheses (3, 4 and 5) related to changes in suspended sediment concentration and related to the combination with reduced nutrient inputs from the Ems river. The following runs were compared:

1 Reference run
2 Reduced SPM by 25% over the whole model domain. These results indicate the effect of a general reduction of suspended sediment on primary production in the estuary.
3 Reduced nutrient input (N, P) by 40 % from the Ems river on top of a 25 % reduction of SPM (case 2). These results indicate the effect of reduced nutrient loads once a situation with reduced suspended sediment concentrations has been achieved.

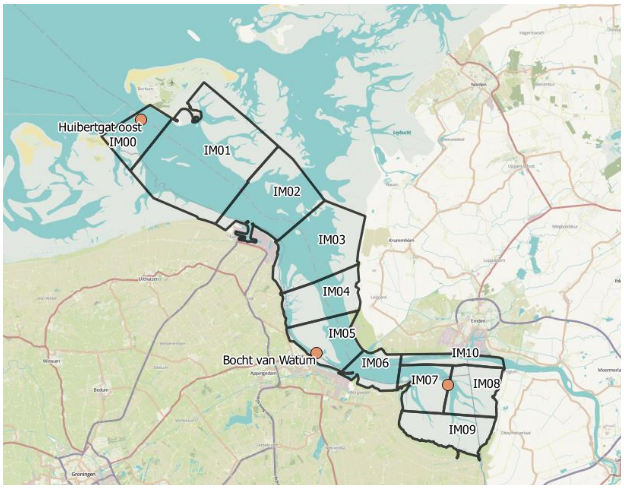

Figure 6.8 Areas for aggregation of primary production results.

Both benthic and pelagic primary production were affected by changes in SPM and nutrients. As expected, pelagic primary production increased. The increase of the sum for all areas was from 28 to 42 kton C/y (50 %) after a reduction of SPM (Table 6.1, Figure 6.9 and Figure 6.10). This result is consistent with the permanent light limitation in all deep parts of the estuary, and in shallow areas during parts of the year. A lower concentration of SPM results in higher availability of light for photosynthesis and growth.

Modelled pelagic primary production increases further when also nutrient loads are reduced, especially in area IM03. To explain this, it should be taken into account that the modelled reduction of nutrients was implemented as a reduction of inorganic and organic substances, including DOC to preserve C/P and C/N ratio's in the river's discharge. Thus, the small increase of simulated pelagic primary production by reduction of nutrients is also caused by a decrease of light extinction in a light-limited phytoplankton community. Overall, the effect of reduced nutrient input from the Ems river is very modest. This can be explained by:

- The strong light limitation for pelagic primary production in the estuary causes a nutrient surplus, and a reduction of it will only have effect in shallow areas in the outer part of the estuary during summer.
- The relatively high transport of nutrients over the North Sea boundary. For 2012, the annual net nitrogen and phosphorus input over the western boundary was an order of magnitude higher than the loads from the Ems river (setup report nr 6). The nutrients imported over this boundary are exported again over the northern boundary, but apparently, the role of nutrients from the Ems river is probably modest in the outer parts of the estuary.

Table 6.1 Pelagic primary production in the reference run and two sensitivity runs (tonnes C/year). The absolute difference in primary production compared to the reference run (for effect of SPM reduction) and the difference between the two sensitivity runs (for effect of N,P reduction) are shown as figures and blue (positive difference), or red (negative difference) bars.

Pelagic					
	reference	**-25% SPM**		**-25% SPM; -40% N,P**	
thousands of tonnes C/y	**net PP**	**net PP**	**effect of SPM reduction**	**net PP**	**effect of N,P reduction**
IM00	1.7	2.3	0.6	2.3	0.0
IM01	10.6	14.5	3.9	15.4	0.9
IM02	3.0	4.5	1.5	5.6	1.1
IM03	3.7	6.1	2.3	7.8	1.7
IM04	1.0	1.5	0.6	2.0	0.5
IM05	0.8	1.1	0.3	1.4	0.3
IM06	0.3	0.4	0.1	0.6	0.2
IM07	0.9	1.7	0.8	2.2	0.4
IM08	4.2	6.5	2.4	6.7	0.2
IM09	1.6	3.1	1.5	3.3	0.3
IM10	0.2	0.3	0.1	0.4	0.1
sum	**28**	**42**	**14**	**48**	**6**

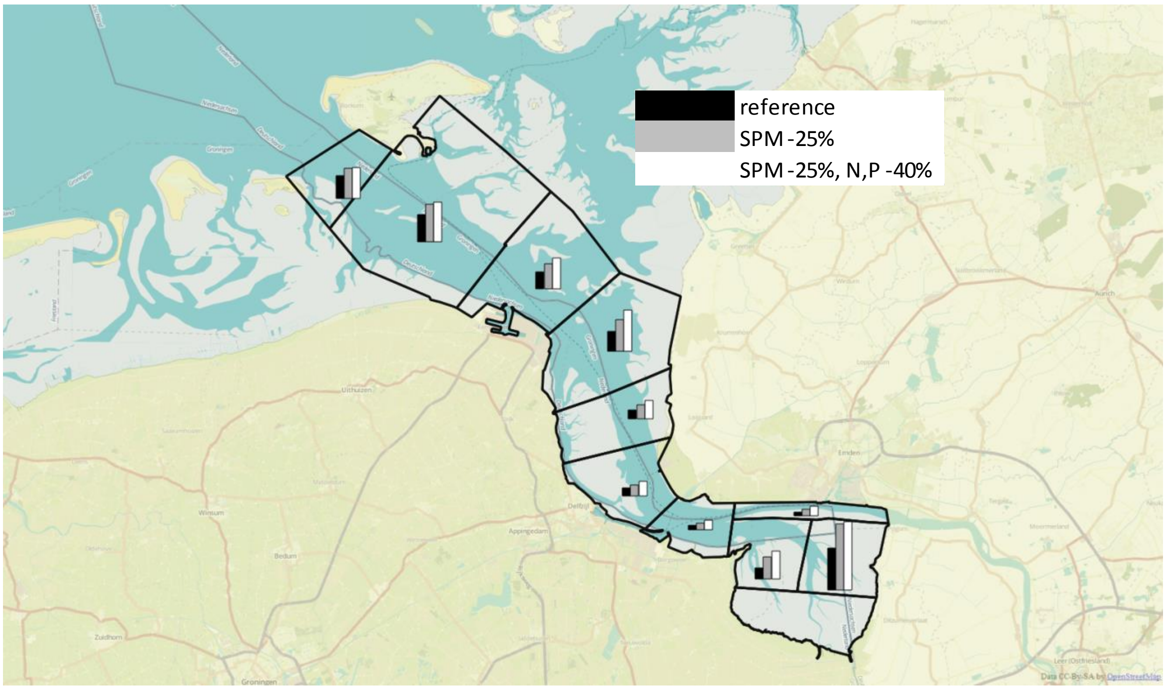

Figure 6.9 Change in area-specific pelagic net primary production (gC/m^2/y) in IMARES primary production areas 1 – 10 as a result of variation in SPM and an additional reduction of nutrient load from the river Ems. Full vertical scale of bars corresponds to 200 gC/m^2/y.

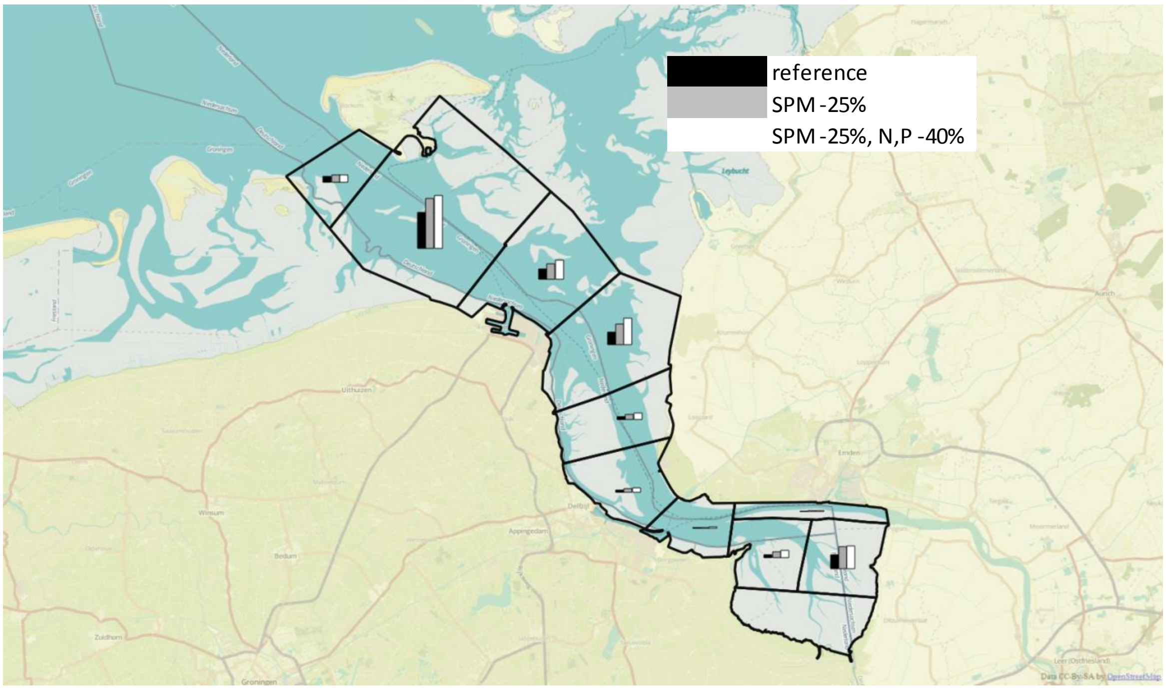

Figure 6.10 Change in total pelagic net primary production (tonnes C/y) for IMARES primary production areas 1 – 10 as a result of variation in SPM and an additional reduction of nutrient load from the river Ems. Full vertical scale of bars corresponds to 14 000 tons C/y.

Benthic primary production was less affected by a reduction of SPM (Table 6.2, Figure 6.11 and Figure 6.12). In some areas (IM09 and IM10) benthic primary production increased slightly, which may be caused by an improvement of light climate. Benthic diatoms may profit by a larger area suitable for growth. In other areas (e.g. IM01 – IM04), benthic primary production decreased upon a reduction of SPM. The decrease is consistent with the increase in pelagic primary production. The reduction of nutrients reduced the primary production by benthic diatoms in the outer part of the estuary. This is consistent with the fact that benthic diatoms are nutrient limited rather than light limited.

Table 6.2 Benthic primary production in the reference run and two sensitivity runs (tonnes C/year). The absolute difference in primary production compared to the reference run (for effect of SPM reduction) and the difference between the two sensitivity runs (for effect of N,P reduction) are shown as figures and blue (positive difference), or red (negative difference) bars.

Benthic					
	reference	-25% SPM		-25% SPM; -40% N,P	
thousands oftonnes C/y	**net PP**	**net PP**	**effect of SPM reduction**	**net PP**	**effect of N,P reduction**
IM00	1.3	1.2	-0.2	1.0	-0.1
IM01	18.7	18.6	0.0	15.3	-3.4
IM02	5.7	6.0	0.3	5.1	-0.8
IM03	2.9	3.0	0.2	2.5	-0.5
IM04	8.6	10.0	1.3	9.8	-0.1
IM05	1.4	1.7	0.3	1.7	0.0
IM06	3.5	3.9	0.4	3.9	0.0
IM07	4.4	5.1	0.7	5.1	0.0
IM08	1.1	1.4	0.3	1.4	0.0
IM09	2.6	3.2	0.6	2.9	-0.2
IM10	0.6	0.7	0.1	1.1	0.4
sum	**51**	**55**	**4**	**50**	**-5**

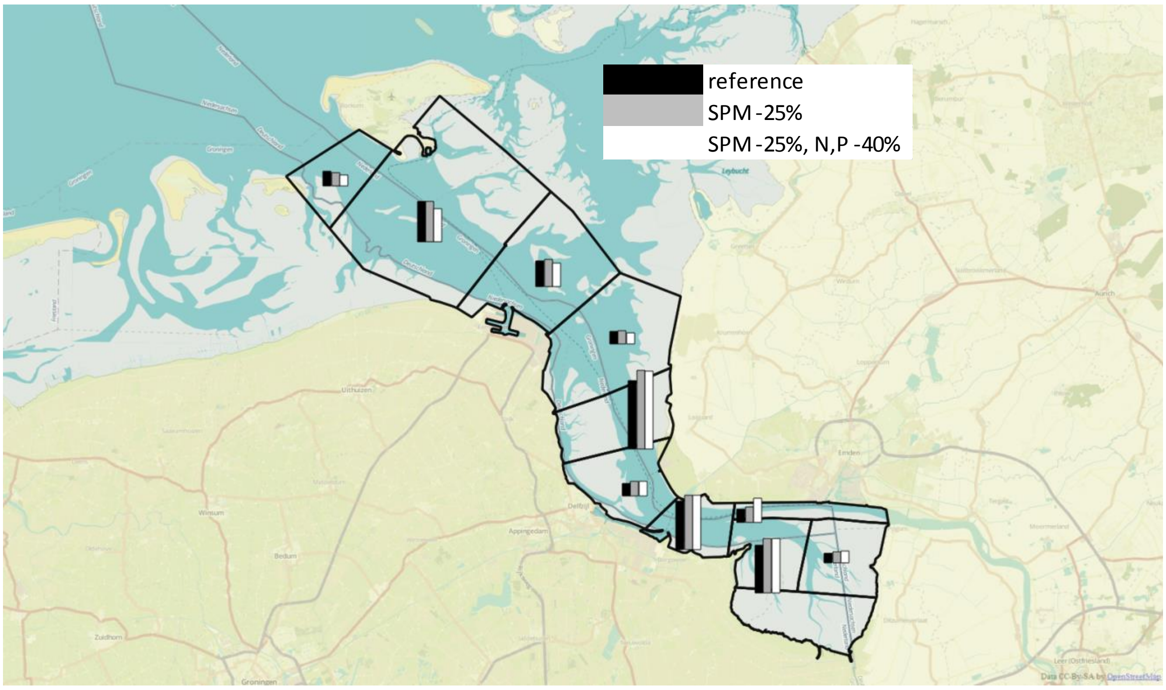

Figure 6.11 Change in area-specific benthic net primary production (gC/m²/y) in IMARES primary production areas 1 – 10 as a result of variation in SPM and an additional reduction of nutrient load from the river Ems. Full vertical scale of bars corresponds to 280 gC/m²/y.

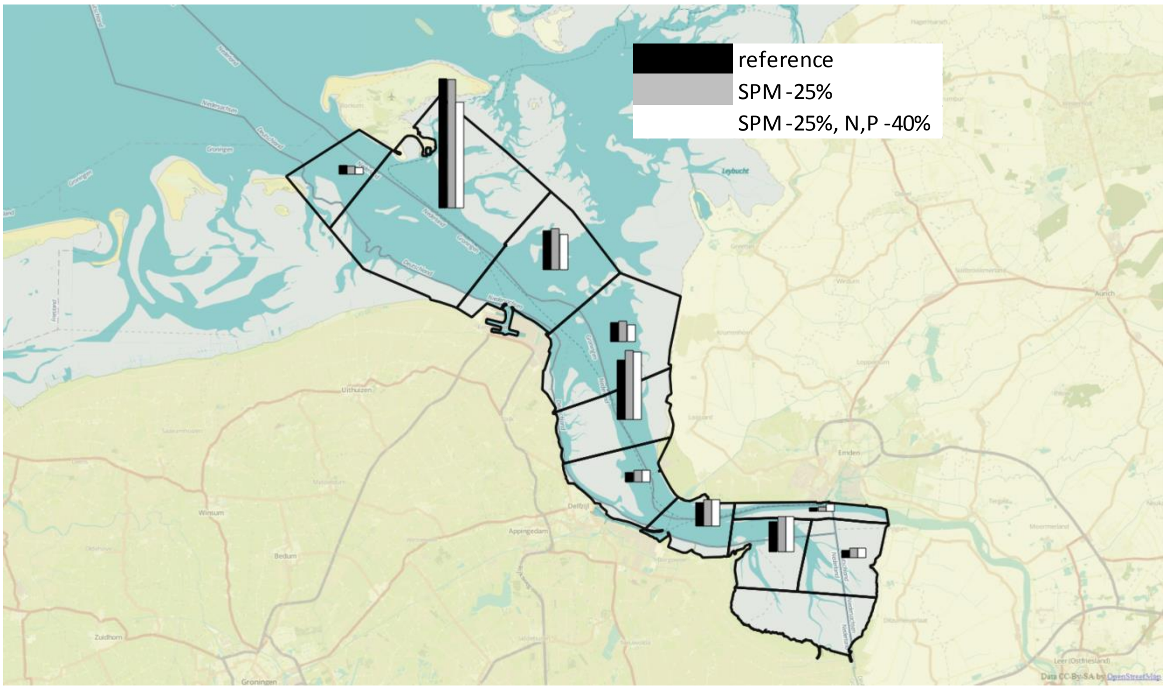

Figure 6.12 Change in total benthic net primary production (tonnes C/y) for IMARES primary production areas 1 – 10 as a result of variation in SPM and an additional reduction of nutrient load from the river Ems. Full vertical scale of bars corresponds to 19 000 tons C/y.

6.6 Changes in algal composition with regards to changes in suspended sediment concentration and nutrient loads

The strong light-limitation of pelagic primary production (Figure 6.5) and the fact that suspended sediments determine most of the light extinction in the estuary (Figure 6.7) illustrate that primary production depends strongly on the concentration of suspended sediment. The effect of changes in suspended sediment on biomass of the different algal groups and chlorophyll-a is presented in Figure 6.13 for two areas IM01 and IM03 (Figure 6.13).

In IM01 and IM03, a reduction of nutrient loads resulted in an increase of chlorophyll-a (Figure 6.13). This increase was caused by an increase in all phytoplankton groups. Benthic diatom biomass decreased as a result of nutrient reduction (Figure 6.13), consistent with the decrease in benthic primary production (Figure 6.12). In IM01, the reduction of benthic primary production upon nutrient reduction was stronger than in IM03 (Table 6.2) and a stronger decrease of benthic diatoms is simulated (Figure 6.13).

The current model simulates three groups of phytoplankton and one group of benthic diatoms. No clear change in the group distribution could be seen upon changes in spm or nutrient loads. So on an aggregated group level, no large changes are expected. It should be noted that the algal group characteristics are based on observed functional group characteristics, such as temperature and light responses and need for silicate. However, the model has not been specifically calibrated to reproduce algal species accurately. Also, within the groups, many different species occur, and variation on the species level cannot be accounted for by the model.

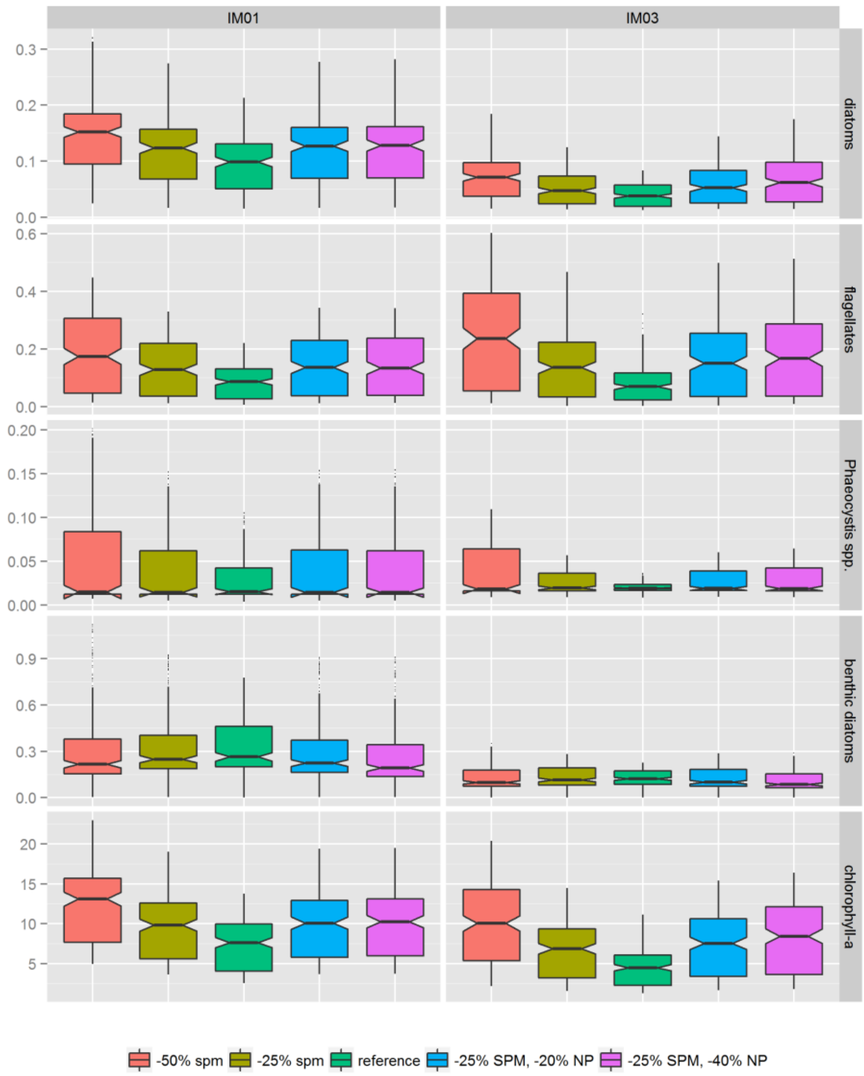

Figure 6.13 Boxplot of modelled phytoplankton (diatoms, flagellates and Phaeocystis spp.) biomass (gC/m^3), benthic diatoms (gC/m^2), and chlorophyll-a (mg/m^3) in the water column for the year 2012. The boxes in the middle represent a reference situation. Boxes to the left represent sensitivity runs with 25 % and 50 % reduced SPM. Boxes to the right represent sensitivity runs with reduced nutrient loads from the river Ems combined with 25% reduced SPM. Upon nutrient load reduction, IM00 did not show a change in primary production, while IM03 showed an increased pelagic primary production and a decreased benthic primary production (Table 6.1, Table 6.2).

6.7 Is water quality at MWTL monitoring stations representative for water bodies?

Hypothesis 7 (section 6.1) states that the monitoring stations in the Ems Estuary are a good representation of the water bodies for WFD ecological status reporting. In this section, model results are used to compare the average concentration in a water body to the modelled concentration at the location of the monitoring stations that should be representative for that water body. Concentrations have been aggregated over time as median and percentile concentrations over summer (chlorophyll-a, oxygen) and winter (nutrients)

For summer conditions in 2012, the median concentrations of extinction, chlorophyll-a and oxygen in ED01 (Ems Estuary Coast) do not differ significantly from the concentration modelled at the corresponding Huibertgat Oost location. Also, modelled 90-percentiles are very similar (Figure 6.15)

For oxygen, the minimum concentration was very similar between the water body and station. Similarly, median and 90-percentile nutrient concentrations during winter at Huibertgat Oost are representative for the conditions in the water body Figure 6.16. Huibertgat oost is therefore a representative station for this water body

Median summer concentration of chlorophyll-a in ED02 (Ems Estuary) is higher than the concentrations at station Bocht van Watum, the representative station for WFD ecological objectives (Rijkswaterstaat, 2009). The 90-percentile summer extinction and chlorophyll-a concentration are both higher than the values at Bocht van Watum, but the variation in chlorophyll-a within the water body is larger than the variation at Bocht van Watum alone. For oxygen, the median and minimum concentration in the water body was very similar to the concentration at Bocht van Watum. Winter nutrient concentrations in ED02 are best represented by the concentrations at Bocht van Watum. On the basis of model results, it is concluded that Bocht van Watum is representative for the water body considering nutrient concentrations, but underestimates the concentration of chlorophyll-a in the water body.

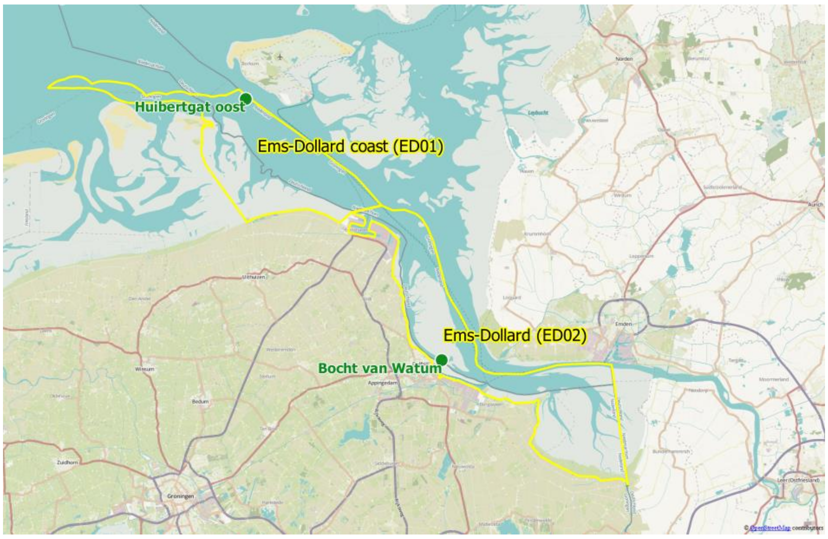

Figure 6.14 Map showing locations of MWTL stations in comparison to the WFD water bodies (Dutch part).

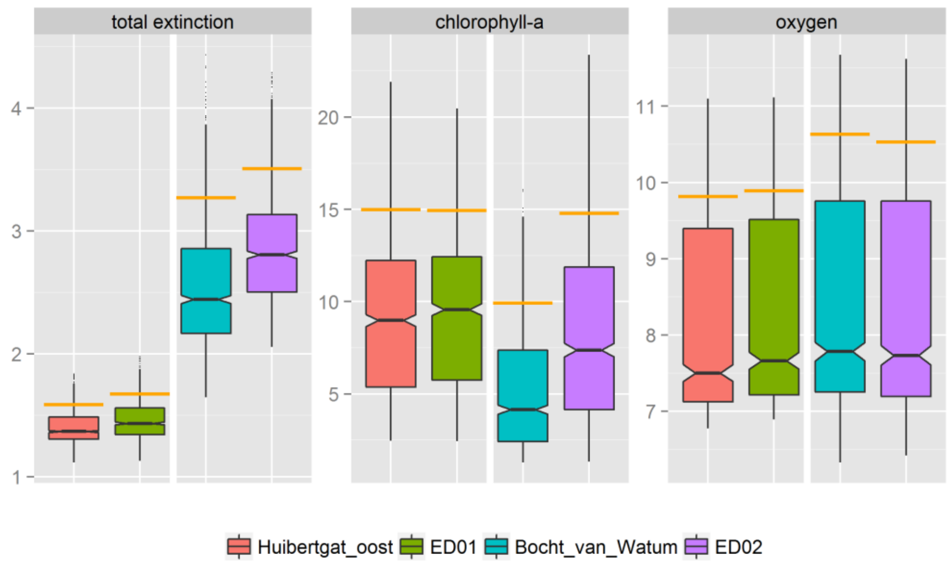

Figure 6.15 Boxplot of the WFD parameter chlorophyll-a and the explaining variables suspended solids and total light extinction during summer (March – September) 2012, aggregated from model results at monitoring locations and the water body that are represented by them. (ED01 is represented by Huibertgat oost, ED02 is represented by Bocht van Watum. total extinction is in m^{-1} ; chlorophyll a in mg/m^3 and oxygen in g/m^3 Boxplots consist of median, 25 and 75 percentiles, total range, and standard error (notches). The orange horizontal lines represent the 90-percentile values of the daily averaged model results, which is an important criteria for WFD objectives.

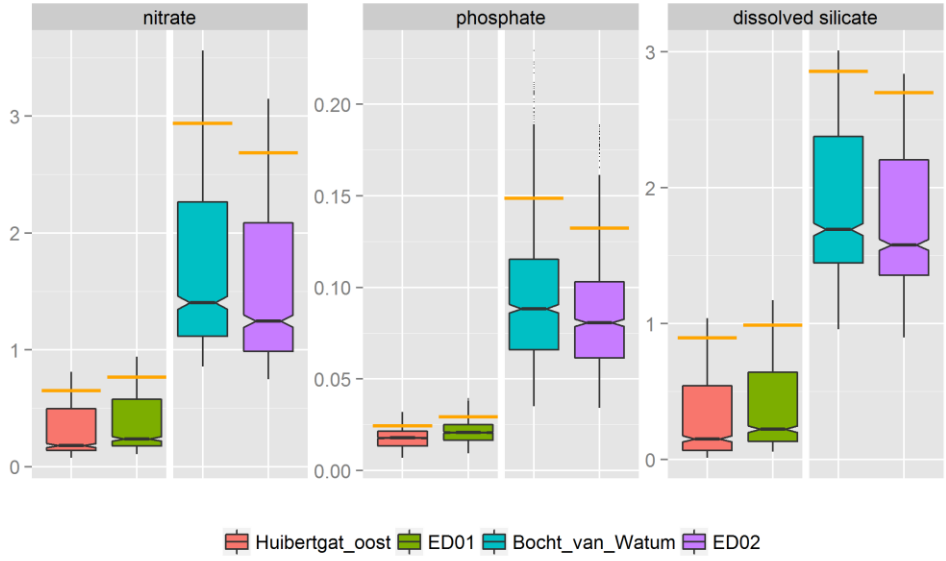

Figure 6.16 Boxplot of the WFD parameter nutrients during winter (October - February) 2012, aggregated from model results at monitoring locations and the water body that are represented by them. (ED01 is represented by Huibertgat Oost, ED02 is represented by Bocht van Watum. All nutrients are in g/m^3. Boxplots consist of median, 25 and 75 percentiles, total range, and standard error (notches). The orange horizontal lines represent the 90-percentile values of the daily averaged model results.

6.8 Conclusions

6.8.1 Limiting factors for primary production

Pelagic primary production is well simulated by the current model and analyses based on this are reliable. Benthic primary production was modelled more conceptually, with nutrients being taken up from the water phase. Under nutrient-limiting conditions therefore, the accuracy of the benthic primary production is therefore unknown. However, benthic production was calibrated so that in total, benthic production was in the same order of magnitude as pelagic production for “IMARES areas” in the Ems estuary, as indicated in the literature. Moreover, the total benthic production is strongly dependent on light availability at the bottom, which was calibrated correctly. Therefore, sensitivity analyses using changes in turbidity are expected to give reliable results, also for benthic primary production.
The main insights resulting from the water quality and primary production model are

- Pelagic primary production in the estuary is mainly limited by light, this is especially true for the deeper parts. In shallow intertidal areas, nutrients become limiting during summer.
- Benthic primary production in the estuary is limited by the availability of intertidal area. Silicate limititation of benthic primary production occurs in the outer part of the estuary.
- A 25 % reduction of SPM leads to a 50 % increase of pelagic primary production, which can be expected as more light comes available. The increased pelagic

production causes a stronger competition for nutrients at shallow parts of the estuary during summer, and this results in a slightly lower benthic production.
- A 40% reduction of nutrient load from the Ems river in addition to a reduction of SPM leads to lower benthic production in in the outer estuary due to enhanced nutrient limitation. The model further predicts a 14% increase of pelagic production. This modest increase was attributed to the reduction of extinction due to organic nutrients from the Ems river. The effect is not expected when only inorganic nutrient loads are reduced

Although pelagic primary production in the estuary proved to be mainly light-limited, silicate and phosphorus limitation also occur in the shallow parts, at least during part of the year. The light limitation as simulated by the model is caused by extremely high turbidity, which could be attributed to suspended sediment particles. This explains the increase of pelagic primary production when SPM concentration was reduced in the model. The benthic primary production was not directly influenced by SPM reduction, but indirectly through the decrease of nutrients available for benthic production. Therefore the benthic production decreased by a reduction of SPM.

Suspended sediment concentration shows an increasing gradient from the North Sea causing a gradient of increasing light limitation from sea to land. Nutrients are entering from the Ems in high concentrations. Through the western boundary, nutrients enter in high amount (order of magnitude higher than the Ems load), but in much lower concentration (setup report nr 6). Together, this causes a gradient of increasing nutrient limitation from land to sea. Therefore, a reduction of nitrogen and phosphorus loads to the estuary on top of a reduction of SPM does not affect primary production of benthic or pelagic algae in the inner part of the estuary (Dollard) much. In the outer part of the estuary, where nutrients are most diluted, primary production of benthic algae is reduced most upon nutrient reduction from the Ems. The reduction is modest, because part of the nutrients used for primary production here come from the North and Wadden Sea through the boundaries. Pelagic primary production increased as a result of reduction of nutrients, which is caused by a slight improvement of available light due to the reduction of the organic component of the Ems river nutrients

6.8.2 Hypotheses

Hypothesis 1, "*Pelagic primary production is controlled by turbidity in the Estuary*" is **confirmed** on the basis of the model results. It has been shown that light is the controlling factor for phytoplankton (Figure 6.5). Furthermore, light extinction in the water is mainly controlled by suspended sediment concentration (Figure 6.7). A reduction in turbidity by reducing suspended sediment concentration caused pelagic primary production to increase (Figure 6.9 and Figure 6.10).

The first part of **Hypothesis 2**, "*Benthic primary production is mainly controlled by nutrients and resuspension*" could be **confirmed**. Benthic diatoms in the model are nutrient limited (Figure 6.6). Moreover, a reduction of nutrient load from the river Ems reduces the primary production of these algae (Figure 6.11 and Figure 6.12). It should be noted that these conclusions are based on a formulation of phytobenthos growth using water column nutrients. On a wider system scale, benthic primary production is also controlled by the available intertidal area, where enough light is available at the sediment interface.

Because resuspension of benthic algae was not included in the current version of the model its effect on benthic biomass and production could not be tested. A further development could be to calibrate the model for resuspended phytobenthos, to estimate the relative contribution of suspended phytobenthos to pelagic production and the effect of resuspension on benthic biomass and production. Currently, the model should be calibrated better for benthic production before this step can be taken.

The first part of Hypothesis 3, "*Measures to reduce turbidity in the estuary will increase the primary production by phytoplankton and therefore contribute to higher carrying capacity for higher trophic levels*" could be **confirmed**. A sensitivity analysis shows that phytoplankton production increases when overall turbidity is decreased (Figure 6.9 and Figure 6.10). This will most likely increase the carrying capacity for higher trophic levels, as the increase in production is most pronounced for diatoms (Figure 6.13), generally a good food source for zooplankton. The second part of the hypothesis is therefore plausible, but was not tested since higher trophic levels are not included in the current study.

Hypothesis 4, "*the effect of decreased nutrient loads from land will reduce the benthic production, counteracting the effect of decreased turbidity in the estuary*" is **confirmed**. Sensitivity analysis shows a slight decrease (5 tonnes C /y, appr. 10 % decrease) of benthic primary production upon a 40 % reduction of nutrient load from the Ems river (Table 6.2, Figure 6.11 and Figure 6.12). This was less than the increase of pelagic primary production (14 tonnes C /y, 50 % increase) upon reduced turbidity, but partly counteracts the increase of production as a result of reduced SPM. However, total production in the estuary increased upon nutrient reduction, because pelagic primary production increased due to reduced extinction of organic nutrients. In short, a 40 % nutrient reduction will shift production from benthic to pelagic, rather than reduce the total primary production in the estuary. The exact result is dependent on the way that nutrient reduction is accomplished, and especially the reduction of organic matter in such a scenario.

Hypothesis 5, "*changes in turbidity and nutrient availability will change algal composition*" could be rejected on the level of functional groups that are represented in the model (diatoms, flagellates, *Phaeocystis* spp.). A shift of the proportion of the different algal groups was not clear from the sensitivity analysis (Figure 6.13), but the model does not distinguish on the species level of diatoms and flagellates. From what is known from the literature, the hypothesis is **plausible**. There is ample evidence from field and laboratory studies that species composition and succession depends on light and nutrient availability (e.g. Sommer, 1983; Riegman et al., 1992). Shifts could further be caused by a changing ratio of nitrogen and phosphorus to silicate (e.g. Egge & Aksnes, 1992).

Hypothesis 6, "*the carrying capacity for higher trophic levels in the ecosystem, reflected in the primary production, has been reduced since the late seventies as a consequence of increased turbidity*", was discussed in accompanying report on monitoring results, report 9. On the basis of measurements it is concluded that primary production has decreased in the outer estuary, but it has not been shown that this is due to increased suspended sediment concentrations. In contrary, in the outer estuary, suspended sediment concentrations and light extinction are lower now than in the seventies (Measurements primary production report nr 9). The lower primary production may be explained by decreased phosphorus concentrations but this has not been studied in more detail. In the inner estuary and Dollard, pelagic primary production has not changed with respect to the seventies.

Hypothesis 7, "*the three MWTL stations in the Ems Estuary are sufficiently representative in order to estimate the ecological status with regard to phytoplankton abundance*" could be **confirmed**. The comparison made in this study was based on summer concentrations of chlorophyll-a, extinction and oxygen, and winter concentrations of dissolved reactive nutrients. For those substances, the stations are representative for the whole water body (Figure 6.15). However, for benthic primary production, the stations are not representative. Monitoring of shallow stations is needed in order to obtain knowledge on benthic primary production.

7 Summary

7.1 Introduction

The numerical model results provide quantitative information that can be used to test the hypotheses formulated in phase 1 of this study (see also chapter 1). The hypotheses related to hydrodynamics, but especially sediment dynamics, will be addressed in section 7.2; those related to primary production in section 7.3.

7.2 Sediment dynamics

7.2.1 Conceptual model of driving forces on the SSC in Ems Estuary

Based on the model results and interpretation of available data, a conceptual model with the main forcings driving the sediment dynamics in the Ems Estuary is developed, including:

1. The hydrodynamics (redistributing sediment within the estuary)
2. The availability of sources and sinks of suspended sediments within the estuary (how much and how fast is sediment permanently stored within the system)
3. The exchange over its boundaries: the Wadden Sea and North Sea on the downstream side and the Lower Ems River at the upstream side (how much sediment enters the system)

1. Hydrodynamics

During the past centuries, loss of tidal flats through large-scale land reclamations probably made the tides in the Ems estuary more flood-dominant (or less ebb-dominant, such as in the Dollard). In the past decades, the tides in the Ems Estuary have changed less (compared to the past centuries, but also compared to the lower Ems River). Instead, deepening of tidal channels has strengthened estuarine circulation patterns and contribute to increased suspended sediment concentrations, especially in the Dollard.

2. Sources and sinks

The estuary experiences major changes in its sediment sinks. The changes in tidal flats during past centuries caused less sedimentation in the intertidal area. The resulting loss in sediment sinks probably lead to an increase in suspended sediment concentration. This increase cannot be quantified with the WED model, since the required detailed morphological data does not exist.

Ports act as a sediment sink in which all sediment deposits. Until ~1990, sediment concentrations were also reduced because part of this deposited sediment was not brought back into the estuary. There was large-scale sediment extraction from the port of Emden. Ending this practice has led to larger suspended sediment concentrations after 1990.

Note that, when the present-day situation (with ports and dredging and disposal) is compared with a hypothetical scenario without ports (hence no dredging, disposal or extraction) the model results suggest limited effect on sediment concentrations in the estuary, except for a change in distribution (higher concentrations near disposal sites and lower sediment concentrations elsewhere in the estuary).

Relative sea level rise (eustatic and resulting from gas extraction) creates space for sediments to deposits, thereby acting as a sink for the sediment. Such a sediment extraction will likely reduce the suspended sediment concentration. The estimated sediment sink due to sea level rise is probably sufficiently to have a significant impact on suspended sediment dynamics.

3. Boundaries

The sediment concentrations in the Wadden Sea and in the North Sea strongly influence the suspended sediment concentration in the estuary. Although the whole system of Wadden Sea and Ems Estuary responds to changes in the North Sea, a resulting variation in sediment concentration in the adjacent Wadden Sea governing the concentrations in the Ems estuary is much more likely. Changes in the Wadden Sea are a.o. related to land reclamations, closure of the Lauwerszee. The numerical model simulations suggest that an increase in the boundary conditions is a more likely explanation for the observed increase in SSC at Huibertgat (1990-2011) when compared to changes occurring within the estuary itself.

The influence of the lower Ems River, on a yearly-averaged basis, is that it acts as a sink, rather than a source. However, it may be possible that during high discharge conditions, sediment is flushed from the lower Ems River into the Ems estuary and has effects of the sediment concentrations in (at least the more upstream parts of) the Ems estuary. A sensitivity analysis showed that even a very crude overestimated sediment pulse from the lower Ems River in the WED model, the extent north of Eemshaven is limited. If there are effects, they are mostly in the Dollard basin and only in the first half of the year (following the large discharges of the winter period). This sensitivity analyses is not elaborated more extensively.

7.2.2 Conceptual model for changes in the lower Ems River

The ER model results indicate that the transition from a low-turbid to hyper-turbid estuary is the result of tidal amplification (despite constant phase lag differences or the relative strength of overtides) and decreasing riverine flushing in response to channel deepening. The strong increase in sediment import started during a period when the bed roughness was still typical for sand bed conditions. The bed roughness decreased as a result of the strong increase in suspended sediment concentrations. This further increased the sediment import capacity of the system and hence sediment concentration. The effect of hydraulic roughness is so large that a return to a pre-dredging depth is insufficient to significantly reduce sediment import and hence suspended sediment levels in the estuary. This means that not only the bed level needs to be raised; also large quantities of mud need to be removed in order to restore the system to its pre-dredging conditions.

7.2.3 Hypotheses

The hypotheses defined in report 2 related to sediment dynamics and hydrodynamics have been addressed in chapter 1, 3, 4, and 5 of this report. The results are summarized below.

1) *Based on a statistical analysis of MWTL data on suspended matter, it can be proven that the increase in the sediment concentration in the Ems Estuary is statistically significant.*
   Correct. The sediment concentration in the Ems Estuary is significantly increasing at the 95% confidence level (see Figure 1.3 and report 3): 0.8 mg/l/year at Huibertgat, 3.1 mg/l/year at Bocht van Watum Noord, 1.0 mg/l/year at Bocht van Watum, and 3.8 mg/l/year at Groote Gat Noord.

2) *The sediment dynamics in the Eastern Wadden Sea have remained constant despite changes in salt marsh works and biological factors. As long as the hydrodynamics in the Ems Estuary remain unchanged, so does the flux from the Eastern Wadden Sea into the Ems Estuary.*
   Rejected. In some parts of the Wadden Sea the sediment concentration has increased (Figure 1.3), and mechanisms that may be responsible for such a change have been identified (closure of the Lauwers Zee, long-term variations in the wind climate, dredging

and dumping). An increase in the SSC in the Wadden Sea will lead to higher suspended sediment concentrations in the Ems Estuary.

3) *Sediment trapping in the Lower Ems River (the tidally influenced part of the river Ems) should lead to a reduction of the total sediment mass in the Ems Estuary. This is partly compensated or reversed through flushing at high river discharge events. This exchange of sediments between the Ems Estuary and Lower Ems River is strongly influenced by the Geisedam.*
Unknown. Extracting sediment from the entrance of the lower Ems River leads to a large reduction in suspended sediment concentration in the Ems estuary. On the other hand, the higher sediment concentrations in the lower Ems will also influence the Ems estuary due to diffusion by tidal currents (especially during large discharge events). Which of these two opposing effects is stronger, has not been ascertained.

4) *The sediment concentration in the Ems Estuary has increased because of a loss of tidal flats, leading to (1) modified tides and (2) less sediment sinks.*
Probably true over longer timescales (centuries) but not on the timescales on which this study focusses (decades). In the presence of extensive tidal flats (such as historically in the Ems estuary), tides are generally more ebb-dominant. However, there is insufficient historical data available to quantify and verify the impact of changes of the tidal flats with the applied models. The loss of intertidal areas has reduced the natural sediment sink in the system with 0.15 to 0.5 million ton/year. This reduced sediment sink has very likely contributed to an increase in suspended sediment concentrations.

5) *The sediment dynamics in the Dollard area have marginally changed, so the Groote Gat station (where the sediment concentration does increase) is not representative for the Dollard area.*
Rejected. The various scenarios generate contrasting spatial distribution of changes in SSC. The computed effect of ending sediment extraction suggests a spatially uniform increase in SSC throughout the Dollard. The presence of ports results in a reduction of SSC in large parts of the estuary, but an increase near disposal sites. The Groote Gat station is located fairly close to a disposal site, so the observed increase here (Figure 1.3) may be local (with SSC decreasing elsewhere). The effect of deepening generates largest increase in SSC on the flats, rather than in the tidal channels. It is likely that the observed increase in SSC at Groote Gat results from a combination of mechanisms, and therefore on average the increase at Groote Gat station is representative for the Dollard.

6) *Sea level rise does not change the sediment dynamics of the Ems estuary.*
Rejected. Sea level rise provides a sufficiently large sediment sink for large quantities of sediment to deposit, and therefore to a reduction in SSC in the estuary. The contribution of gas mining is probably equally important to eustatic SLR, although the relative SLR because of gas mining is finite and will decrease in time.

7) *The sediment concentration in the Ems Estuary has increased due to dredging and disposal because of*
   a. *recirculation processes*
   b. *fining of the sediment bed.*

   Partly true. The effect of dredging and disposal is, compared to a situation without ports, mainly a spatial redistribution of sediments but has a limited impact on the suspended sediment concentration. The SSC merely increases near disposal sites, but decreases elsewhere. However, the change in the extraction strategy from the port of Emden ended the reduction in suspended sediment concentration that it provided up to 1994. The ending of sediment extraction is probably an important mechanism for the observed increase in suspended sediment concentrations. Part b) of the hypothesis has not been addressed because this effect is too difficult to distinguish from other processes, in the model and in available data (when an area becomes more muddy, more dredging is needed, so it is difficult to distinguish the effect of additional fining as a result of dredging).

Hypothesis 7 *(The sediment concentration in the Ems Estuary has increased due to dredging and disposal because of (a) recirculation processes and (b) fining of the sediment bed)* is partly true.

8) *Long-term natural and anthropogenic changes in the intertidal areas and the tidal channels of the Ems Estuary have sufficiently modified the tidal propagation to significantly influence sediment dynamics.*
True. The changes in the extent of the tidal flats (especially the infilling of the Dollard in the past centuries) must have influenced tidal propagation. Also the long-term change in tidal channels was large, and this must have affected the tidal dynamics. However, these effects cannot be numerically verified due to lack of sufficient detailed topographic, historic data (see also Hypothesis 4 above). The changes for which data is available (the past decades) are comparatively small, but have still had a large effect on sediment dynamics. The main mechanism for this change was an increase in vertical residual circulation. Tidal propagation was only marginally affected in the past decades, but changed significantly over longer timescales (centuries).

9) *The deepening and realignment of the lower Ems River has so much influenced the tides in the Ems Estuary that (1) the Ems Estuary is importing more fine sediments and (2) the Lower Ems River is importing more fine sediments.*
Probably not true. The tidal discharge increased with 2 to 6% (depending on the location in the estuary) from the 1940's to now (chapter 3). The tidal discharge is probably less important for estuarine suspended sediment transport then estuarine circulation (salinity-driven flows), see chapter 4. Therefore the change in tidal dynamics in the Ems Estuary has probably had a limited effect on sediment import in the Ems Estuary. Note that this hypothesis addresses the effect of changes in the tidal dynamics in the Ems Estuary on the sediment dynamics in the Ems Estuary and the lower Ems River. Deepening has led to a strong tidal amplification in the lower Ems River, and as a result to a large increase in sediment concentration there.

7.3 Primary production

Primary production by phytoplankton in the Ems Estuary is primarily light-limited. Therefore, it can be expected that all man-made or natural variation in turbidity have had, and will have effects on primary production, phytoplankton biomass, and most likely also species composition. Indeed, sensitivity analysis shows an increase of net primary production by phytoplankton over the whole estuary from 41 to 54 tonnes C/y at a turbidity reduction of 25%. Thus, the relative primary production increase is in the same order of magnitude as the reduction in turbidity, approximately 25%. However, the effect varies strongly between the different areas in the estuary (Table 6.1).

For benthic diatoms the situation is slightly more complex. The area where microphytobenthos can grow depends on available light and therefore on the total area of intertidal areas, and less on turbidity. Growth and production at these places is limited by phosphate and silicate availability. Both a reduction of SPM alone, and in combination with a reduction in nutrient loads from the Ems river resulted in an overall reduction of benthic production in the area. This illustrates the fact that benthic diatoms in the estuary are not light limited. In the model, they are limited by P or Si for growth, but in nature, they may also be limited by diffusion rate of inorganic carbon, pH, or self-shading ((Admiraal et al., 1982; Cook & Røy, 2006).

From the analysis in section 6, we can summarize the results by answering the initially postulated hypotheses (see section 1.2). Hypothesis 2 and 6 have also been tested in the monitoring study (report 9)

Hypothesis 1, “*Pelagic primary production is controlled by turbidity in the Estuary*” is **confirmed** on the basis of the model results. It has been shown that light is the controlling factor for phytoplankton (Figure 6.5). Furthermore, light extinction in the water is mainly controlled by suspended sediment concentration (Figure 6.7). A reduction in turbidity by reducing suspended sediment concentration caused pelagic primary production to increase (Figure 6.9 and Figure 6.10).

The first part of **Hypothesis 2**, “*Benthic primary production is mainly controlled by nutrients and resuspension*” could be **confirmed**. Benthic diatoms in the model are nutrient limited (Figure 6.6). Moreover, a reduction of nutrient load from the river Ems reduces the primary production of these algae (Figure 6.11 and Figure 6.12). It should be noted that these conclusions are based on a formulation of phytobenthos growth using water column nutrients. On a wider system scale, benthic primary production is also controlled by the available intertidal area, where enough light is available at the sediment interface.

Because resuspension of benthic algae was not included in the current version of the model its effect on benthic biomass and production could not be tested. A further development could be to calibrate the model for resuspended phytobenthos, to estimate the relative contribution of suspended phytobenthos to pelagic production and the effect of resuspension on benthic biomass and production. Currently, the model should be calibrated better for benthic production before this step can be taken.

The first part of Hypothesis 3, “*Measures to reduce turbidity in the estuary will increase the primary production by phytoplankton and therefore contribute to higher carrying capacity for higher trophic levels*” could be **confirmed**. A sensitivity analysis shows that phytoplankton production increases when overall turbidity is decreased (Figure 6.9 and Figure 6.10). This will most likely increase the carrying capacity for higher trophic levels, as the increase in production is most pronounced for diatoms (Figure 6.13), generally a good food source for zooplankton. The second part of the hypothesis is therefore plausible, but was not tested since higher trophic levels are not included in the current study.

Hypothesis 4, “*the effect of decreased nutrient loads from land will reduce the benthic production, counteracting the effect of decreased turbidity in the estuary*” is **confirmed**. Sensitivity analysis shows a slight decrease (5 tonnes C /y) of benthic primary production upon a 40 % reduction of nutrient load from the Ems river (Table 6.2, Figure 6.11 and Figure 6.12). This was less than the increase of pelagic primary production (14 tonnes C /y) upon reduced turbidity, but partly counteracts the increase of production as a result of reduced SPM. However, total production in the estuary increased upon nutrient reduction, because pelagic primary production increase was slightly higher (6 tonnes C/y) than the reduction of benthic primary production. In short, a 40 % nutrient reduction will shift production from benthic to pelagic, rather than reduce the total primary production in the estuary.

Hypothesis 5, “*changes in turbidity and nutrient availability will change algal composition*” could be rejected on the level of functional groups that are represented in the model (diatoms, flagellates, *Phaeocystis* spp.). A shift of the proportion of the different algal groups was not clear from the sensitivity analysis (Figure 6.13), but the model does not distinguish on the species level of diatoms and flagellates. From what is known from the literature, the hypothesis is **plausible**. There is ample evidence from field and laboratory studies that species composition and succession depends on light and nutrient availability (e.g. Sommer, 1983; Riegman et al., 1992). Shifts could further be caused by a changing ratio of nitrogen and phosphorus to silicate (e.g. Egge & Aksnes, 1992).

Hypothesis 6, "*the carrying capacity for higher trophic levels in the ecosystem, reflected in the primary production, has been reduced since the late seventies as a consequence of increased turbidity*", was discussed in accompanying report on monitoring results, report 9. On the basis of measurements,

Hypothesis 7, "*the three MWTL stations in the Ems Estuary are sufficiently representative in order to estimate the ecological status with regard to phytoplankton abundance*" could be **confirmed**. The comparison made in this study was based on summer concentrations of chlorophyll-a, extinction and oxygen, and winter concentrations of dissolved reactive nutrients. For those substances, the stations are representative for the whole water body (Figure 6.15). However, for benthic primary production, the stations are not representative. Monitoring of shallow stations is needed in order to obtain knowledge on benthic primary production.

8 Literature

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