Mud dynamics in the Ems-Dollard, phase 3

Scenarios for improvement

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Deltares

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Summary
Rijkswaterstaat has initiated the project "Onderzoek slibhuishouding Eems-Dollard" (Research on mud dynamics in the Ems-Dollard). This project explores the reasons for the historic increase in turbidity in the Ems Estuary, as well as possible measures to improve the water quality in the area. As part of this project, hydrodynamic, sediment transport and water quality models were set up and simulations have been run and analysed to better understand the present-day status of the Ems Estuary (reported in parallel reports).

This report presents results of model scenario studies conducted to explore the effect of different measures to improve the conditions in the Ems Estuary. The objective of these measures is to decrease the turbidity and increase primary production. Four different measures were chosen to be analysed in model scenario studies:

1. Disposal of dredged sediment in the North Sea
2. Sediment extraction from ports (and disposal on land)
3. Creation of intertidal area to increase sedimentation (also called 'adaptive poldering')
4. Restoration of channel depth in the Oost Friesche Gaatje and Emden Fairway

Results were calculated for pre-defined indicators, including maps of SPM concentrations, siltation in ports and tabulated SPM concentrations for defined areas in the estuary. Assessments of model results, including consideration of the limitations of the models, indicate that sediment disposal in the North Sea and sediment extraction from ports with disposal on land are the most effective of the four proposed scenarios for reducing turbidity.

Two of the sediment scenarios (sediment disposal in the North Sea and restoration of channel depth) were further analysed with the primary production model. Sediment disposal in the North Sea had the largest effect with respect to primary production, with almost 17% increase in pelagic primary production for the whole estuary.

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

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0.1	Sep. 2014	Katherine Cronin					
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Contents

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1 Introduction

The Water Framework Directive (WFD) requires EU member states to achieve good ecological and chemical status of all designated water bodies (rivers, lakes, transitional and coastal waters) by 2015. In the management plan (Rijkswaterstaat, 2009) for the implementation of the WFD (and Natura 2000) in the Netherlands, the context, perspectives, targets and measures for each designated water body have been defined. The requirements for the Ems Estuary (see Figure 1.1 for location) are that the mud dynamics need to be better understood (before 2015), and driving forces for increase in turbidity need to be identified.

Given these requirements, Rijkswaterstaat has initiated the research project ‘Mud dynamics in the Ems Estuary’ (*Onderzoek slibhuishouding Eems-Dollard*). The aim of this project is (I) to 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 therefore improve the ecological status of the estuary.

These objectives are also included in the flow chart of the project structure (Figure 1.2).

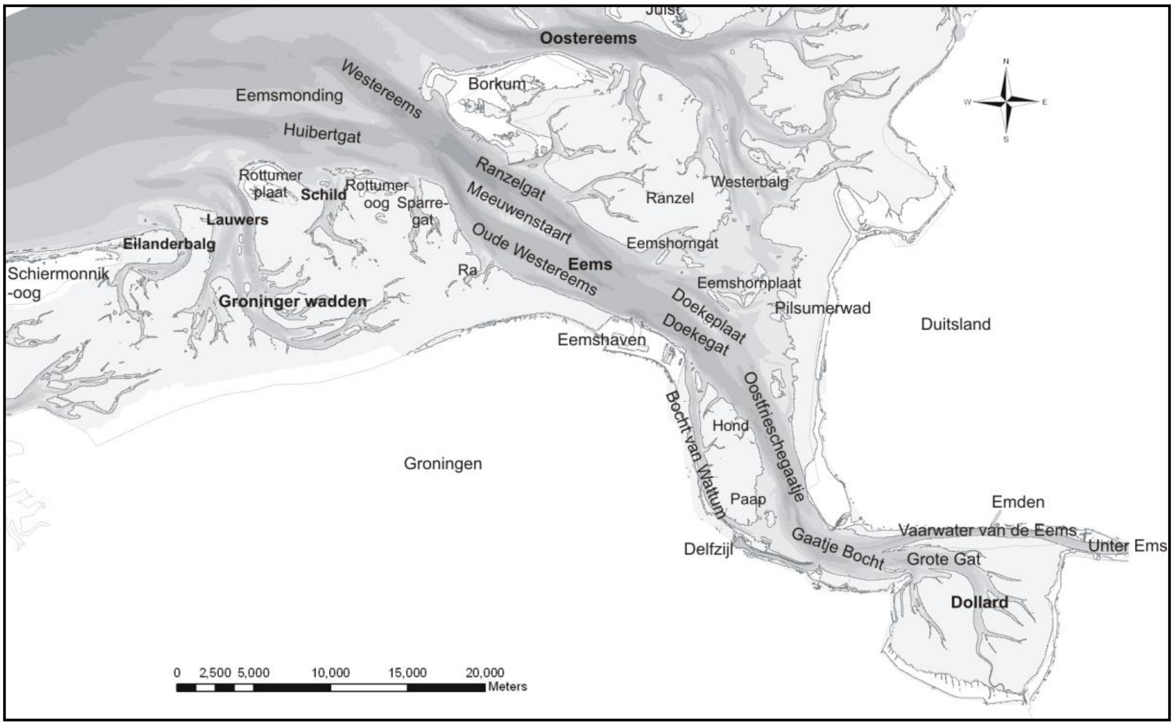


Figure 1.1 Map of Ems Estuary with names of the most important channels and flats (Cleveringa, 2008) in Dutch and German. The English name of the ‘Vaarwater van de Eems’ is the Emden navigation channel or Emden Fairway. The English name of ‘Unter Ems’ is the lower Ems River.

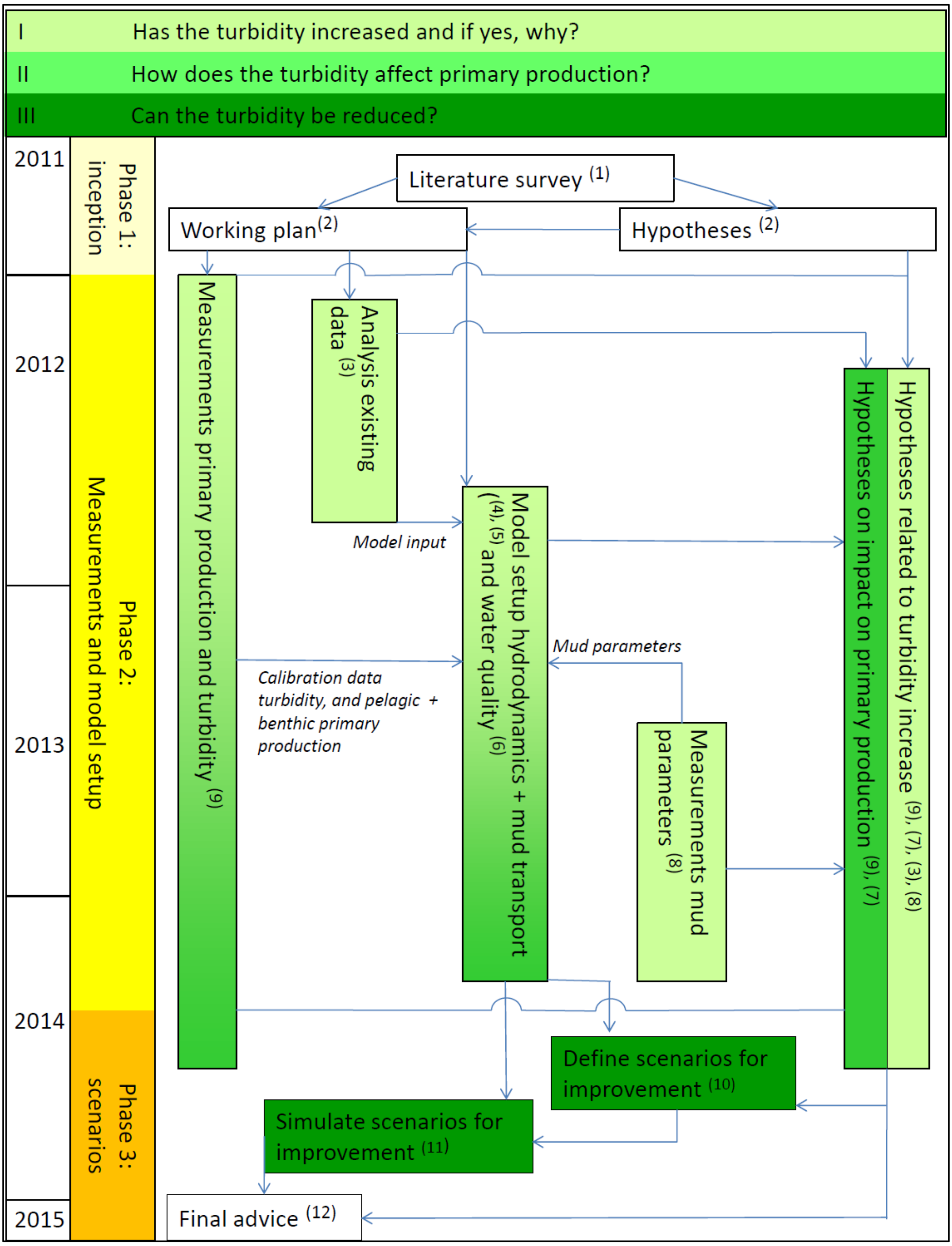


Figure 1.2 Flow chart for the structure and timetable of the study. Green colouring of the phase 2 activities relates to the colour of the main research questions I, II, and III. See Box 1 for a description and Table 1.1 for the references (1) – (12)

This research project explores mechanisms that may be responsible for the present-day turbidity levels in 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 (including this report) 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 and validate 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 consists 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 this 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 (note)
11	**2014**	**3**	**3**	**Model scenarios**
12	2015	3	1, 2, 3	Final report

1.1 Objectives and approach of the study

The objectives of the current study were to:

1. Identify a number of potential measures for reducing the turbidity and improving the water quality, specifically the primary production, in the Ems Estuary; and
2. Evaluate the effectiveness of the most promising measures by using the developed models to calculate their impact on suspended sediment concentration and primary production in the Ems Estuary.

Identification of potential measures was the focus of various meetings with stakeholders. This led to a ‘long-list’ of 16 measures. These measures were then prioritized during a meeting on April 1st 2014, based on nine evaluation criteria that had been developed by Deltares and Rijkswaterstaat. Based on the scoring of the 16 potential measures with the evaluation criteria, the four most promising measures were identified for further analysis.

The effect of the four selected measures was quantified using the models developed during phase 2 of the research project. The measures were translated into model scenarios, including a number of alternatives per scenario. A set of indicators was defined for presenting the model results and these indicators were calculated for all model scenarios and alternatives, as well as for a baseline simulation representing the current ‘baseline’ conditions (2012). The scenario results were compared to the model baseline results in order to evaluate the effectiveness of the scenario. The calculation of the indicators also allows a comparison between the scenarios. Each scenario was also evaluated using expert judgement and knowledge of the model applicability for the specific conditions.

Two of the model scenarios were further analysed with respect to their influence on primary production.

1.2 Structure of the current report

This report starts with a summary of the baseline model (Chapter 2).

The remainder of the report describes the selection of measures and the assessment of their effectiveness in improving the quality of the Ems Estuary. The procedure to define potential measures and the selection of the most promising measures is described in Chapter 3. The results of the model analyses on the effect of these measures on SPM and siltation is described in four chapters, namely:

(1) Disposal of dredged sediment in the North Sea (Chapter 4);
(2) Extraction of sediment from the ports (Chapter 5);
(3) Adaptive poldering (expansion of inter-tidal areas) (Chapter 6);
(4) Restoration of channel depth (Chapter 7).

In Chapter 8, the impact of two of these measures on primary production is explored. All results are synthesized in Chapter 9 and main conclusions and recommendations are given in Chapter 10.

2 Summary of the baseline model

2.1 Introduction and objectives of the baseline model

The Ems Estuary has undergone large changes in the past decades to centuries. Tidal flats were reclaimed, tidal channels and the lower Ems River were deepened, and several ports were constructed. The impact of these interventions can be summarised as follows:

- The hydrodynamics and sediment transport drivers have changed.
- A large amount of sediment is regularly dredged from the ports and tidal channels, and dispersed elsewhere in the estuary.
- The natural depositional areas in the system have largely disappeared.

During the past decades in particular, the turbidity in the Ems Estuary has been increasing (see report 3 and De Jonge et al., 2014), negatively impacting the estuarine primary production.

The key questions and the overall objectives of this study are to determine:

1) Has the turbidity in the Ems Estuary increased and why?
2) What is the impact on primary production? and
3) Can this be mitigated (can the turbidity be reduced)?

These questions can be addressed using a combination of field data and numerical models. For this purpose, a series of models, known as an effect-chain model, has been set-up and calibrated. The effect chain models jointly describe the effects of changes in the physical and morphological environment on chemical and biological variables. The aim of the effect-chain model (hydrodynamics, sediment transport, and water quality) is to allow quantification of changes in suspended sediment concentration and resulting changes in primary production, resulting from human impacts in the past and future, within the Ems Estuary. Each individual model describes a different set of processes within this chain of events. In this study, the following three models were “chained” (Figure 2.1).

- 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.

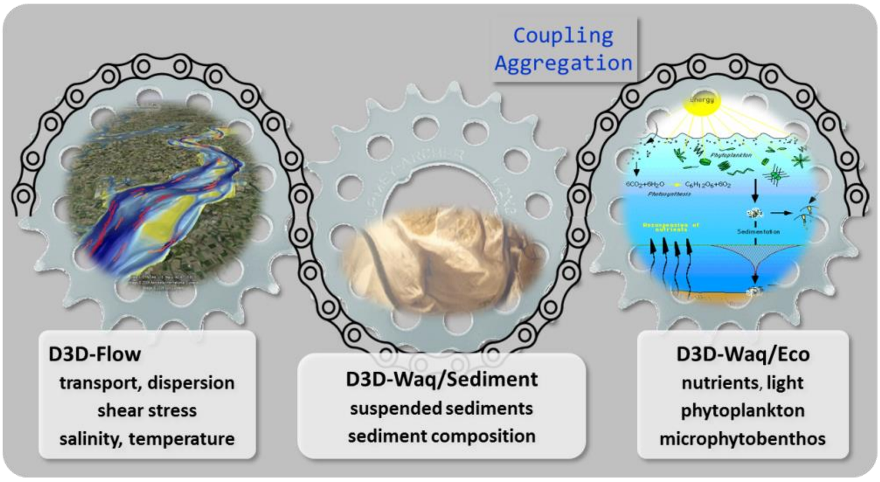


Figure 2.1 General set up of a linear effect-chain model.

The ability of the models to address the questions that have been posed about the Ems Estuary is determined by the physical and/or ecological processes the models reproduce. The most important processes which each of the models must be able to reproduce are summarized below.

Hydrodynamic model:

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

Suspended sediment model:

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.

Water quality / Primary production model:

e) Pelagic and benthic primary production under influence of light and nutrient availability

This chapter presents a summary of the model set-up, calibration/validation and analyses for the year 2012. This model is referred to as the baseline model, and is described in previous reports of this study (report 4 for hydrodynamics, report 5 for sediment transport and report 7 for model analysis) The main points about the model which are relevant for the application and discussion of the scenario studies presented further in this report are summarized in this chapter, namely:

1. Definition of the model baseline scenario of 2012 (including dredging and disposal amounts and locations, the method for including these processes in the model, calibration and validation);
2. Concentrations of suspended sediment calculated in the baseline model;
3. The applicability of the model for assessment of measures (i.e. strengths and limitations);
4. Conclusions about the effect of sediment dumping and channel deepening.

2.2 The baseline model for hydrodynamics (2012)

The model domain of the model used in the current study, including the most important observation point, is shown in Figure 2.2.

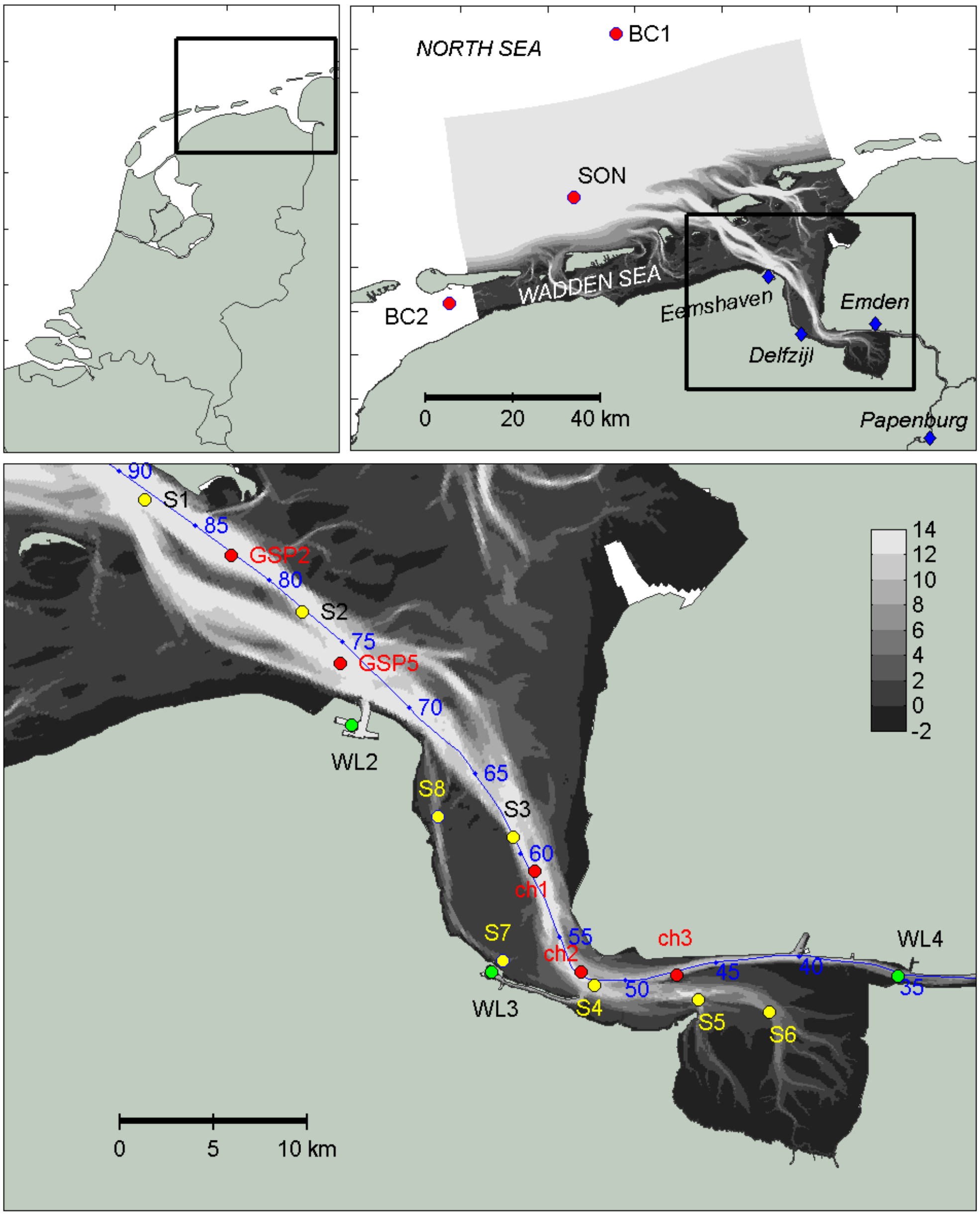


Figure 2.2 Top right: map of the Ems estuary and model domain with the ports of Emden, Delfzijl, and Eemshaven and observation stations for waves (SON) and salinity (BC1 and BC2). Lower panel: more detailed map with observation stations Yellow dots stations indicate suspended sediment concentration observation points, green dots are water level observation points, and red dots represent flow velocity observations and model output. The blue markers and numbers are Ems kilometres, a standard reference in the estuary. Only the bed level between -2 and 14 m is shown to highlight the difference in tidal flats and channels, but the channels and offshore sea may be up to 30 m deep.

The hydrodynamic model was nested in a North Sea model including tides and storm setup with boundaries along the North Sea and the Western Wadden Sea. Fresh water discharges originated from Lauwersmeer, Delfzijl, Nieuwe Statenzijl, and the Eems at Herbrum and Leer. The model has 8 vertical σ-layers, increasing logarithmically in thickness from the bed to the surface (2, 3, 5, 8, 13, 19, 25 and 25%). The choice for 8 layers is a trade-off between computational efficiency (requiring as little cells as possible) and computational accuracy (with an increasing amount of grid cells the vertical variation in flow velocity, salinity, and sediment concentration (report 5) is more accurately resolved). Wave-induced bed shear stresses were generated by running the SWAN wave model for the domain in offline mode.

Table 2.1 Main processes and parameter settings of the hydrodynamic model.

Parameter	
Timestep (s)	30 seconds
Vertical layers	8 vertical σ-layers (2, 3, 5, 8, 13, 19, 25 and 25%).
Horizontal viscosity	Uniform (1 m^2/s)
Vertical mixing	k-ε turbulence model (with background viscosity of 1 10^{-5} m^2/s)
Bed roughness	Spatially varying Manning's n.
Offshore Boundary conditions	Water levels (nested in operational model) and salinity (MWTL observations)
Discharges	Discharges (from Water Boards and NLWKN) with (near)-zero salinity
Wind	Uniform but time-varying wind (measured at Beerta)

The model was run and validated for 2012 and 2013 using a large number of salinity and water level observations, as well as velocity measurements obtained by Groningen Seaports and Rijkswaterstaat. Locations of the monitoring stations are shown in Figure 2.2.

Water Levels

Water levels are a good indicator for the tidal dynamics and therefore tide-induced flow velocity. The computed water levels are compared with one-year observations in the frequency domain (using harmonic analysis; Pawlowicz et al, 2002) at 4 selected water level stations covering the estuary (Table 2.2 and Figure 2.2). Typically, the relative error in computed water level amplitudes A_h and phases ϕ_h of the individual constituents is less than 5%, with even higher accuracy in the outer reaches of the estuary. From the most seaward station (S1) to the most up-estuary station shown here (WL3) the tides (observed as well as computed) are amplified by ~50%.

Flow velocities

Flow velocity measurements were taken for a period of 5 months at two stations (GSP2 and GSP 5) located in the estuary mouth. The amplitudes and phases of the modelled flow velocity at these stations (see report 4) are within 20% of the observations.

With respect to residual flow, large-scale horizontal flow patterns computed with the model were semi-quantitatively compared with observations by de Jonge (1992). The observed residual flow patterns are based on a large number of transect observations collected from 1971 to 1978. Residual flow patterns are influenced by density-driven flows (and hence discharge), wind-driven flow, and the tidal cycle. Since observations were obtained during varying meteorological conditions, a full quantitative comparison is not possible. Although there are limitations of the data-model comparison, the model is considered to reasonably reproduce observations.

Table 2.2 Observed / modelled water level amplitudes (A_h) and phases (ϕ_h) of the 4 largest tidal constituents at stations S1 and WL1 – WL3 (report 4). See Figure 2.2 for the location of stations.

Constituent	Parameter	Station			
		S1	WL2	WL3	WL4
M_2	A_h [cm]	104 / 102	124 /122	141 / 138	156 / 147
	ϕ_h [^{o}]	248 / 247	281 / 275	300 / 295	313 / 313
S_2	A_h [cm]	31 / 30	35 / 35	40 / 39	42 / 44
	ϕ_h [^{o}]	327 / 325	5 / 359	234 / 272	43 / 45
N_2	A_h [cm]	13 / 13	17 / 16	20 / 18	23 / 20
	ϕ_h [^{o}]	236 / 235	275 / 269	298 / 294	312 / 314
M_4	A_h [cm]	9 / 9	10 / 10	18 / 17	18 / 13
	ϕ_h [^{o}]	336 / 334	39 / 34	70 / 74	114 / 96

Waves
Wave modelling was also conducted in order to compute the additional bed shear stresses caused by the presence of (breaking) waves in the North Sea, Wadden Sea, and within the Ems-Dollard estuary itself. In the sediment model, the hydrodynamics computed with the 3D FLOW model is used to compute advection of sediment. Resuspension is computed with bed shear stress fields from the 2D FLOW/WAVE model. The bed shear stress is therefore composed of a flow component, a wave-component, and also the wave-current interaction.

The wave model was set up within the Delft3D modelling suite using the numerical model SWAN. SWAN (acronym for Simulating WAves Nearshore) is an energy balance based frequency domain model developed by Delft University of Technology (Booij et al., 1999; Holthuijsen, 2007). It is a state-of-the-art shallow water phase-averaging wave model, and takes into account the following processes:

- wave propagation in time and space, including shoaling and refraction,
- frequency shifting due to currents and non-stationary depth;
- wave generation by wind;
- white-capping and depth-induced breaking;
- wave-induced set-up.

Results of the wave model were compared to measurements from a wave buoy located just north of Schiermonnikoog in the North Sea (Figure 2.7). This comparison shows that the computed wave height is slightly larger than observed. The model was not further calibrated, but a sensitivity analysis was conducted, where the wave height imposed at the model boundary was decreased with 10 % and 20% respectively. The results indicate that the computed wave height and period is relatively insensitive to the wave height provided at the boundary: the computed wave height and period is apparently mainly determined by local wind-generated waves and the user-defined uniform bottom friction coefficient.

Model accuracy and applicability for the analysis of measures
The applicability of the hydrodynamic baseline model for the analysis of measures is based on the accuracy for calculating:

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

For both validation years, 2012 and 2013, the errors in tidal constituent water level amplitudes and phases are less than 5%. The error in the flow velocity is typically 10% (amplitude) or less (phase). Both the model and observations suggest that the dominant type of tidal asymmetry is High Water slack tide asymmetry (with a longer duration of HW slack compared to LW slack), generally leading to import of fine sediment. The effect of deepening on tidal dynamics can be predictively modelled with the applied model, as long as the calibration conditions do not change (mainly related to the bed roughness).

Although not shown in this chapter, the absolute value and the intra-tidal variation in salinity typically differs 1-2 ppt from observations. Qualitatively, the spatial residual flow patterns are in line with observations (report 4).

With the available data, the hydrodynamic model seems sufficient to capture the essential flow dynamics, i.e. the (changes in) tidal dynamics and residual flow in the Ems Estuary. As such, it is considered applicable for further analysis of suspended sediment and water quality analyses of the Ems Estuary.

2.3 The baseline model for suspended sediments (2012)

Introduction and objectives
The second model in the effect-chain is the suspended sediment model. The objectives of this model are to (1) allow quantitative analysis relating changes in the estuary (channel deepening, dredging strategies) to the suspended sediment dynamics in the Ems Estuary, and (2) to provide suspended sediment (turbidity) conditions for the water quality modelling. The most important processes the suspended model must be able to reproduce are:

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

Model formulations
Sediment transport is simulated with the mud buffer model (van Kessel et al., 2011, implemented in Delft3D-WAQ), in which fine sediment is stored in a sandy matrix within the seabed. This model distinguishes two bed layers: an upper layer (S_1) which rapidly accumulates and erodes, and a deeper layer (S_2) in which sediment accumulates gradually and from which it is only eroded during energetic conditions (spring tides or storms), see Figure 2.3.

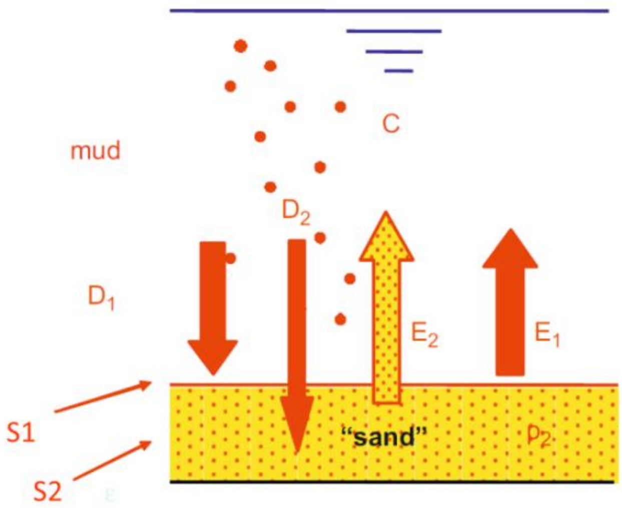


Figure 2.3 Schematic representation of the buffer model. Layer 1 (S1) is the thin fluff layer overlying layer 2 (S2), with default erosion and deposition fluxes: sediment settles from suspension directly to S1 and S2 (with the relative deposition flux determined by the factor α (see report 5).

This S_2 layer represents a sandy layer in which fine sediment accumulates during calm conditions. When the bed shear stress exceeds a critical value the sandy layer becomes mobile, and fine sediment that infiltrated earlier into this layer is slowly released. However, the transport of the sand layer itself is not modelled, but prescribed as a layer of a constant, and user-defined, thickness. Most sediment is stored (buffered) in this S_2 layer; S_1 represents the typically thin fluff layer consisting of mud, which fluctuates according to the daily dynamics of the system (see report 5 for more details).

Two sediment fractions are used, IM1 with a large settling velocity (1.2 mm/s) and IM2 with a small settling velocity (0.25 mm/s). The settling velocity of IM1 and IM2, representing fairly large and rapidly settling flocs and micro flocs respectively, is based on the analysis of the soil samples collected in 2013. The spatial distribution of IM1 and IM2 is determined by the model: all sediment in the model domain entered through the open boundaries, where IM1 and IM2 were prescribed at equal sediment concentrations.

Spatially uniform values for the critical shear stress for erosion τ_{cr} are prescribed for the S_1 layer and the S_2 layer. The critical shear stress for the fluff layer is very low ($\tau_{cr,1}$ = 0.05 Pa), implying that sediment in the top layer is easily resuspended. Sediment in S_2 is assumed to erode during more energetic conditions only, when a substantial amount of sand is brought in suspension and the mud trapped in the sand layer is released. This occurs at larger shear stresses than the initiation of motion of sand particles. In this study, $\tau_{cr,2}$ is set to 0.9 Pa.

The thickness of the sand bed (layer S_2) is set to 10 cm, representing the zone where active mixing by biological activity and (bedform-related) sediment transport takes place. The three erosion parameters included in the model, M_0, M_1, and M_2 are obtained through calibration (van Kessel and van Maren, 2013). Flocculation and consolidation are not modelled. The use of 2 bed layers represents model behaviour similar to consolidation: during low energy conditions sediment is progressively buried in layer 2 (and is therefore no longer regularly resuspended).

Although biological processes (influencing a.o. the erodibility of the intertidal mud deposits and the settling velocity of sediments) are known to have an effect on seasonal variations in sediment dynamics (Kornman and de Deckere, 1998; van der Lee, 2000), they are not part of the model. Full details of the suspended sediment model processes are given in report 5.

Dredging and disposal

Nine areas are defined from which sediment is dredged once every week (from layer S_1 and layer S_2), and disposed in the dumping locations designated for the dredging sites (See Figure 2.4). Dredging areas include the Ports of Eemshaven (1), Delfzijl (2) and Emden (7), the Emden fairway (3-6), the Eems River (9) and a small portion of the Dollard (8). Sediment dredged from the Eems River (9) is extracted.

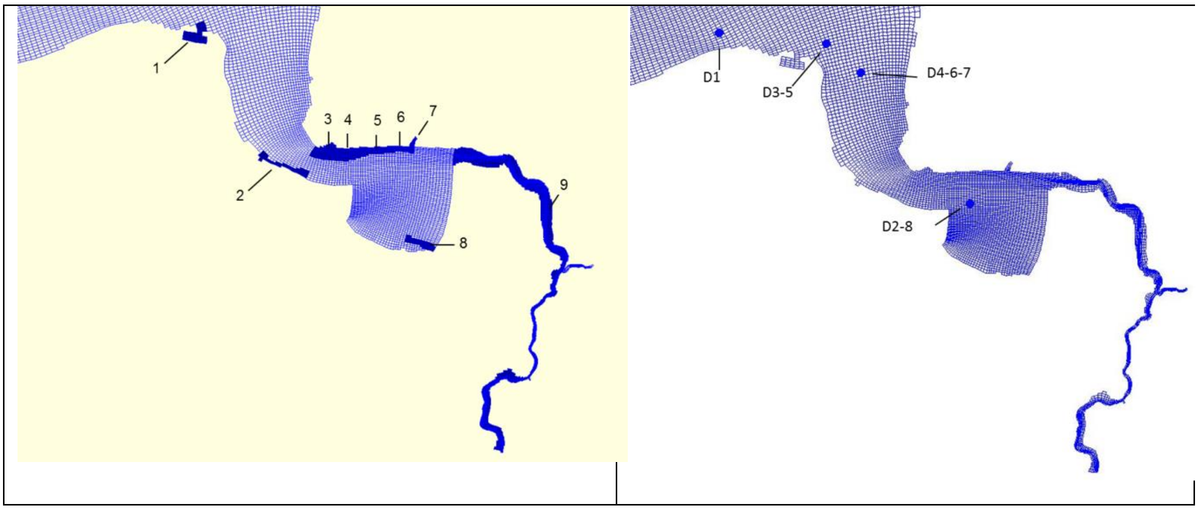


Figure 2.4 Dredging areas 1-9 (left) and sediment disposal areas (right) included in the suspended sediment model. Each dredging area has an assigned disposal area, see also Table 2.3.

Table 2.3 Disposal areas for the dredging areas, corresponding to the numbering in Figure 2.4

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

In the model simulation, all sediment which settles in the ports and channels is removed and is disposed in the model grid cell corresponding to the actual disposal site. Hence, the amount of dredged and disposed sediment is not imposed by the user, but is determined by modelled sediment dynamics. This also implies that no extra sediment is added during dredging and disposal scenarios.

In each dredging area, when active, the sediment is dredged from layer S_2 (where most of the sediment mass is stored). In the model, dredging occurs weekly, following a fixed sequence. The dredging of the areas is sequential, with three days intervals. This means, for example, that dredging in Area 2 will occur 3 days after dredging in Area 1, etc. (see Table 2.4). During each dredging event, the sediment of an entire dredging area is removed instantaneously.

Because the model was setup to simulate the long-term effect of dredging and dumping, the modelled dredging and dumping have been simplified with respect to reality:

- The dredging and disposal interval is not based on actual dredging and disposal schemes (which are not known), but regular (as described above).
- The model underestimates deposition in the Emden fairway. To increase the dredged sediment mass from this area, sediment is also dredged from the port of Emden and disposed on the disposal locations of the Emden fairway. In reality, the port of Emden is not dredged, because the mud is kept navigable through re-aeration.
- All sediment depositing in Delfzijl is disposed on its disposal ground in the Dollard, whereas in reality 80 to 90% is removed through water injection dredging. With water injection dredging, the sediment enters the Ems Estuary 5 to 10 km seaward of the Dollard disposal site. This has been partly done to compensate for the underestimation of deposition in the Emden area.

After completion of the study, it was additionally realised that:

- The disposal sites D1 and D2-8 are in too shallow water (-1 m) whereas in reality sediment is disposed in deep water (next to the disposal site in the model). Verification with the correct locations revealed that this introduces a local effect (the increase in turbidity in the direct vicinity of the disposal sites is overestimated), but the effect on the large-scale distribution of suspended sediments is small.
- In the model, a small amount of sediment (several thousand ton/year) is dredged from a small channel in the Dollard and disposed at D2-8. In reality, sediment dredged from the small channel is not disposed at D2-8 but next to the channel. Compared to the other dredging quantities, this effect is negligible.

Disposal of sediment occurs at four prescribed disposal areas in the Ems Estuary and Dollard (Figure 2.4 and Table 2.3 above). All sediment is dumped in the near bed layer. As a result, some of the sediment will diffuse upward in the water column (representing the entrainment of the dredging plume). However, the majority of the sediment will rapidly settle on the bed. Depending on the deposition flux, which is determined by the available amount of mud in the seabed, this sediment will be quickly deposited on the bed (low mud availability in the seabed near the dump site) or remain in suspension longer and so be transported elsewhere by the currents (large mud availability) (Figure 2.4). Disposal of sediment dredged at a specific location is spread out over 3 days, thus avoiding unrealistic concentration peaks in the proximity of the disposal location.

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

Table 2.4 Dredging schedule in relative day numbers for the dredging areas (Figure 2.5), as implemented in the model

Dredging Area	Dredging schedule (relative day numbers)
1	1, 8, 15, etc.
2	4, 11, 18, etc.
3	7, 14, 21, etc.
4	10, 17, 24, etc.
5	13, 20, 27, etc.
6	16, 23, 30, etc.
7	19, 26, 33, etc.
8	22, 29, 36, etc.
9	25, 32, 39, etc.

Calibration and validation

The suspended sediment model was setup using input from the soil sampling analysis, calibrated using measurement data of 2012 (Imares, GSP, and MWTL data, and port siltation rates) and validated with measurements from 2013 (Imares and MWTL data).

A reference calibration run was made for 2012. To do this, the model was initialized by a certain initial amount of sediment (based on a previous model run), and the model was run by repeating the same simulation of 2012 for a number of years, until it reached dynamic equilibrium. Each scenario executed in this study is also run until it is in dynamic equilibrium.

Dynamic equilibrium of a model simulation is characterised by regularly re-occurring sediment concentration levels. This can be seen for example if the concentrations and patterns in one year are *essentially the same* as in the previous year, with no increasing or decreasing trend. The suspended sediment model attains near-dynamic equilibrium after about 3 years (see report 5 for details). To reach full dynamic equilibrium (where the sediment concentration and available mass of sediment is *exactly* the same as the previous year) would require many more years of simulation. This is unfeasible from a practical point of view, and therefore every fourth year is used for scenario comparison.

In making comparison of model runs, for example for evaluating scenarios of the effects of different measures, the comparison is made between two simulations that have reached dynamic equilibrium. Dynamic equilibrium is needed to compare the effect of model scenarios, because without dynamic equilibrium computed changes in sediment dynamics may be dominated by transient effects. These transient effects generate a temporal increase or decrease in sediment concentrations which may differ completely from the long-term effect of the scenarios.

The yearly averaged suspended sediment concentration near the surface, computed for the calibration run after it has reached dynamic equilibrium, is provided in Figure 2.5. The monthly averaged surface sediment concentrations were compared to the Imares monitoring stations where measurements were available every two (summer) to four (winter) weeks. Results in Figure 2.6 show that the model reproduces the observed up-estuary increase in the surface sediment concentration, and the seasonal variation of the sediment concentration with larger sediment concentrations during the winter months. The largest deviations between observations and model results occur in February and November. Even though two-weekly snapshot measurements only provide an indicative value for comparison with a sediment transport model, the reasonable correspondence suggests the model reproduces the actual estuarine suspended sediment concentration gradient.

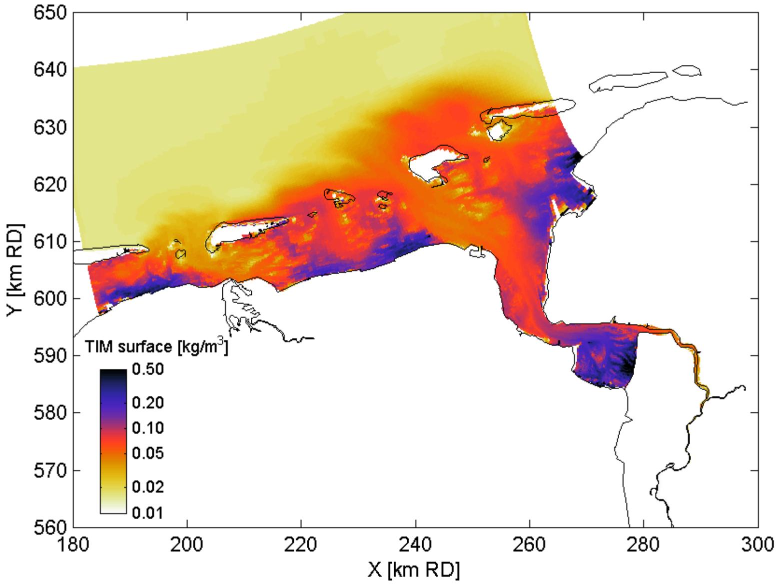


Figure 2.5 Yearly averaged surface suspended sediment concentration (also referred to as TIM, Total Inorganic Matter, in kg/m^3), computed in the calibration run for 2012 (with reference settings), after the model has reached dynamic equilibrium.

Additional comparisons of these model results were made with measurements from individual stations, showing that the seasonal variation in suspended sediment concentration is well approximated by the model (report 5). The sediment concentration in the lower Ems River, draining into the Ems estuary near the port of Emden is underestimated by the model. The near-surface sediment centration is probably around 1 kg/m^3, but the computed annually averaged near-surface sediment concentration is about ten times lower. As detailed in report 5, the sediment dynamics in the approach channel to Emden and in the lower Ems River cannot be reproduced with the modelling approach adopted for this study.

The sediment fluxes into the ports calculated with the model were compared with sediment fluxes estimated from long-term averaged dredging volumes (Table 2.5). The computed deposition in the ports of Eemshaven and Delfzijl are within 10% of the estimated deposition flux. Deposition in the Emden area is strongly underestimated, resulting from underestimated suspended sediment concentrations in this area. Finally, a comparison of calculated and observed mud-content in the bed sediment was made. It was found that the model reproduces the pronounced up-estuary increase in bed mud content (Figure 5.25 in report 5).

After the initial reference simulation made for the re-calibration, an extensive sensitivity study was conducted to see if adjusting some of the key model parameters would improve the model results. Parameters relevant for settling velocity, sediment erosion and sediment buffer layer thickness were varied. None of the alternatives to the reference settings improved the overall model results with respect to suspended sediment concentration, spatial distribution of mud and port siltation. Therefore the reference settings were considered to be the best representation of the estuarine suspended sediment dynamics.

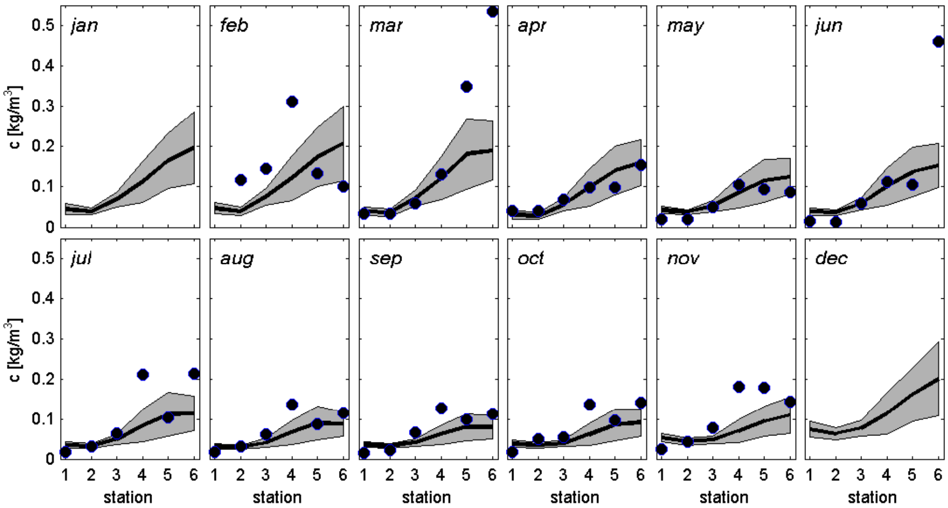


Figure 2.6 Monthly averaged computed surface sediment concentration (black line, with gray shading indicating the standard deviation, computed from hourly model output) and observed surface sediment concentration (black dots, February through November) in 2012 at stations Imares 1 to Imares 6 (in kg/m^3). See Figure 2.2 for the location of stations in yellow (S1-S6).

Table 2.5 Estimated fluxes (based on net sinks or dredging volumes) and computed fluxes for the reference calibration simulation

Port / area	**Estimated siltation flux (million tons/year)**	**Computed siltation flux (million tons/year)**
Eemshaven	0.5	0.46
Delfzijl	0.8	0.82
Emden area	1.6	0.59

The sediment transport model was validated by simulating the year 2013, using the reference model settings for suspended sediments and the hydrodynamics of 2013. The computed suspended sediment concentrations were compared with observations and computed fluxes and siltation rates were also assessed. The observed suspended sediment concentration is lower in 2013 than in 2012, especially in the first half of the year, because the wave height was lower. The modelled suspended sediment concentration was also lower in the first half of 2013 than in 2012. This shows that the mechanism responsible for sedimentation (wave stirring) is captured by the model. Since the model reproduces this inter-annual variation in sediment concentration, this validation provides further confidence in the model.

Based on the results of the model re-calibration, sensitivity analysis and validation, the reference model simulation as described above, was considered the best simulation for 2012. This model simulation has been used further in the study for the assessment of scenarios and is referred to as the ***Baseline Model*** for suspended sediment.

The sediment transport model was mainly calibrated against the Imares measurements and the GSP measurements. As detailed in Report 5 (Chapter 3), the MWTL measurements measure lower SSC levels than the GSP and Imares measurements. The primary production measurements reduced the resulting sediment concentration fields. With a model better reproducing the MWTL measurements, light extinction (measured at the same time and location as MWTL SSC) is better reproduced, but even more observed primary production rates are more accurately simulated.

Assessment of model accuracy and applicability

The accuracy and uncertainties of the model have been assessed in this study in a qualitative manner, by considering the results of the model with respect to the objectives. The key processes to be reproduced with the sediment transport module are:

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

These processes are modelled by including resuspension by waves and tidal currents, storage of fine sediment in a deeper bed layer, and transport by tidal, salinity-driven and wind-driven flow. With a good representation of the hydrodynamics and a reasonable reproduction of the sediment dynamics, the model provides a useful instrument to analyse trends in suspended sediment dynamics of the Ems Estuary. Specific target variables related to the suspended sediment model are:

- *Sediment concentration*
- *Port siltation*
- *Residual sediment transport*

The applicability of the model with respect to these 3 parameters is discussed below:

<u>*Sediment concentration:*</u> The suspended sediment concentration determines the water column transparency (turbidity), which is essential for modelling primary production. This parameter is directly measured and can be compared with model output. Sediment concentration is measured for a number of stations in the Ems Estuary, and the model has been primarily calibrated & validated against these sediment concentrations. Quantitatively comparing the computed sediment concentration with the observed sediment concentration is not straightforward because (1) there are inaccuracies and inconsistencies in the data, (2) suspended sediment concentrations vary strongly over the tidal cycle and (3) spatial variation is equally important as the temporal variation at individual locations (but data on this spatial variation is not readily available).

Typically, the observations fall within the tidal range of the computed sediment concentration. Therefore the model is considered to reproduce the suspended sediment concentration with reasonable accuracy, especially for the area of interest, i.e. the Ems Estuary. The model results do not reproduce the hyper-turbid conditions of the lower Ems River well, but this is not as critical for the application of the model to evaluate measures in the Ems Estuary.

<u>*Port siltation*</u>: Port siltation determines the amount of sediment that needs to be dispersed after dredging. Dredging and port construction effect estuarine sediment dynamics by dispersing sediment back into the system. Port siltation is estimated based on actual dredging volumes. Modelled siltation in the ports of Delfzijl and Eemshaven is in good agreement with observations. In these ports, which probably act as near-perfect sediment traps, the siltation rate is primarily depending on the ambient suspended sediment concentration. The suspended sediment concentration in these areas is well reproduced, and therefore also siltation rates (with computed siltation rates within 20% of the observations).

Siltation in the Emden navigation channel is strongly underestimated by the model because too little sediment is transported there. The total amount of sediment dredged and released in the model (1.9 million tons/year) is therefore lower than the actual values (2.9 million tons/year), estimated from dredging requirements. To partly compensate for this in the model, all sediment dredged from the ports of Delfzijl and Eemshaven is released on disposal grounds whereas in reality about half of the deposited sediment is remobilised by water injection dredging and not removed from the ports by dredgers. Why the sediment transport into the Emden navigation channel is so large remains insufficiently understood, and could be the result of:

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

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

<u>Residual sediment transport:</u> Residual transport by tides and salinity are important with respect to changes in the system, and the resulting impact on variables such as sediment concentration and port siltation. The tide-induced residual sediment transport has a different response to deepening compared to residual transport by estuarine circulation (which is more sensitive to the water depth). Although important, the computed residual transport is difficult to compare with observations as long-term in-situ observations are needed to compute the residual transport.

Over timescales of several years, the residual up-estuary transport is equal to the sediment stored in sediment sinks. In the Ems estuary, the most important sinks are the lower Ems River and the Bocht van Watum. Neither of these are reproduced by the model (because the model is in dynamic equilibrium and sinks are not prescribed), and therefore the model does not predict a net up-estuary transport. The seasonal variation in sediment concentration, as observed and computed in the Dollard (station Groote Gat), can result from a combination of estuarine circulation and wave-induced resuspension at the estuary mouth. In 2013, the wave-induced resuspension at the estuary mouth was much lower than in 2012, and as a result, the computed suspended sediment concentration in the Dollard was lower as well. This is supported by observations, revealing lower concentrations in the Dollard in 2013 than in 2012. Even though the net sinks are not part of the model, a seasonal variation in residual sediment fluxes which are strongly influenced by estuarine circulation, are simulated. This indicates that the model is suitable to compute the effect of changes in channel geometry which will in turn strongly influence the estuarine circulation.

Overall assessment:
The sediment transport model developed for the Ems Estuary reasonably captures the main suspended sediment characteristics as indicated by the available data. Although some limitations have been identified, there is confidence that the model sufficiently represents the main processes controlling suspended sediment concentrations in the Ems Estuary. As such, it is applicable for making an initial assessment of the effectiveness of different measures for reducing suspended sediment in the estuary.

Such quantitative assessment of scenarios can be made by simulating the scenario in a model, and repeating this simulation for a number of years until it has reached a dynamic equilibrium. The indicative effect of a scenario can be quantified as the difference between these scenario results and the baseline model results, also taking into consideration the known model limitations.

2.4 The baseline model for water quality (2012)

The Delft3D water quality model was set up for the year 2012 to simulate water quality and primary production in the Ems Estuary. The water quality model describes the transport and fate of nutrients, algae and detritus as a function of external forcing functions and loadings. The model processes are shown schematically in Figure 2.7. The water quality model is the final model in the effect chain, and therefore the results of both the hydrodynamic model and the suspended sediment model are used as input for the water quality model.

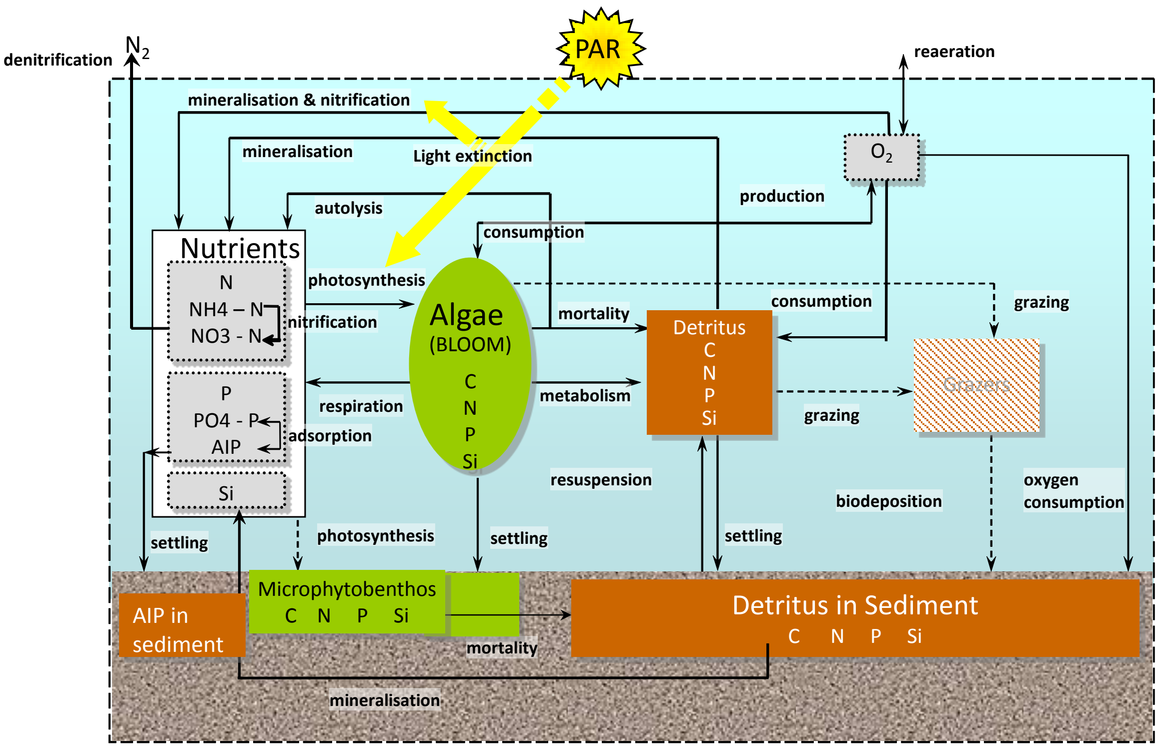


Figure 2.7 Generic Ecological Modelling configuration for modelling primary production in marine environments. This scheme shows a simplified sediment nutrient model. In the current study, nutrient cycling in the sediment has been modelled in more detail than presented here using a layered sediment approach which allows simulation of sediment-water interaction of dissolved substances.

The model was calibrated on MWTL measurements for 2012. The model was validated using MWTL observations for 2013 and additional measurements by IMARES for 2012 and 2013.

A first requirement of the model is a representative transport and dispersion of water and substances. The results of the hydrodynamic model have been used as a base, but because the water quality model simulates many more substances and processes than the hydrodynamic and sediment model, the model grid was aggregated vertically (to 1 layer) and horizontally for performance reasons (Figure 2.8). Horizontal aggregation of the grid was courser in deeper areas, and finer in shallow (< 5 m NAP) areas. The effect of aggregation on model quality was tested by comparing salinity gradients with measurements. It was concluded that salinity was simulated well (report 6).

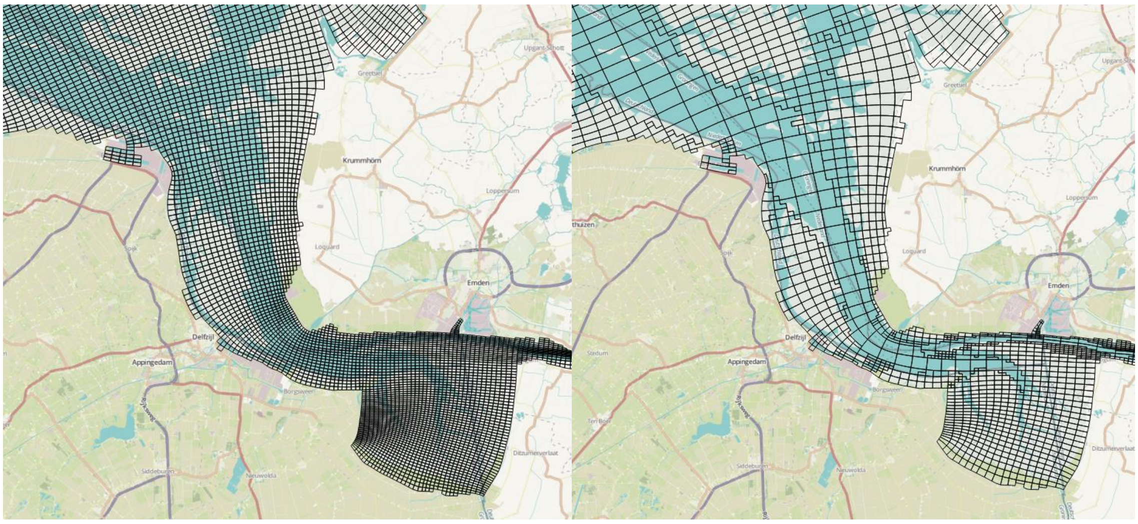


Figure 2.8 Part of the model domain showing the hydrodynamic model grid consisting of approximately 200 000 segments (left) in 8 layers and aggregated water quality and primary production model grid (right) consisting of approximately 5000 segments.

An important step in the simulation of primary production is a correct simulation of light availability, which is a function in incident radiation and extinction in the water column. Apart from a background extinction, the model calculates total extinction as the sum of extinction due to:
- Dissolved organic matter
- Dead particulate matter
- Living phytoplankton
- Suspended sediment

In the Ems estuary, suspended sediment contribute most to the total extinction. Suspended sediment is not simulated by the water quality and primary production model itself, but is forced based on results of the sediment model described in the previous section.

Running the model with standard settings caused excessive growth of phytoplankton in the river Ems and in very shallow parts of the Dollard. This was caused by underestimated suspended sediment concentrations. The sediment model was developed to simulate the suspended sediment dynamics in the Ems Estuary, but underestimates suspended sediment concentrations in the river. The excessive growth was prevented by setting a minimum extinction to a minimum of 20 in the river and in the very shallow parts (< 1 m below NAP) of the Dollard.

The suspended sediment model was mostly calibrated against SSC data collected by GSP and IMARES, which measure higher SSC values than data collected as part of MWTL. In order to reproduce extinction rates measured on the MWTL locations, it was necessary to reduce the SSC fields computed by the sediment transport model in 2012 with a factor 2 (also better reproducing MWTL SSC observations). A further improvement could be obtained by redistribution of the suspended sediment concentration over the year for each segment, so that the average sediment concentration and the total variation over the year was conserved for each segment. The improvement obtained here was small, but especially in spring, suspended sediment concentrations improved (report 6).

At this stage, when extinction was calculated reasonable to well, average phytoplankton chlorophyll-a was also simulated reasonable to well, and it was concluded that no further improvement could be achieved by adapting global phytoplankton parameters.
Benthic primary production was calibrated less accurately due to uncertainty in the observations, and the difficulties to take spatial variation into account. Growth parameters were adapted so that average chlorophyll-a was in the same order as the observations, and that benthic primary production was in the same order of magnitude as pelagic primary production in the estuary.
For the validation year, 2013, no correction of modelled suspended sediment was necessary in order to produce correct average extinction. The only modification with respect to extinction was that the application of a minimum extinction in the Ems river and the shallow parts of the Dollard.

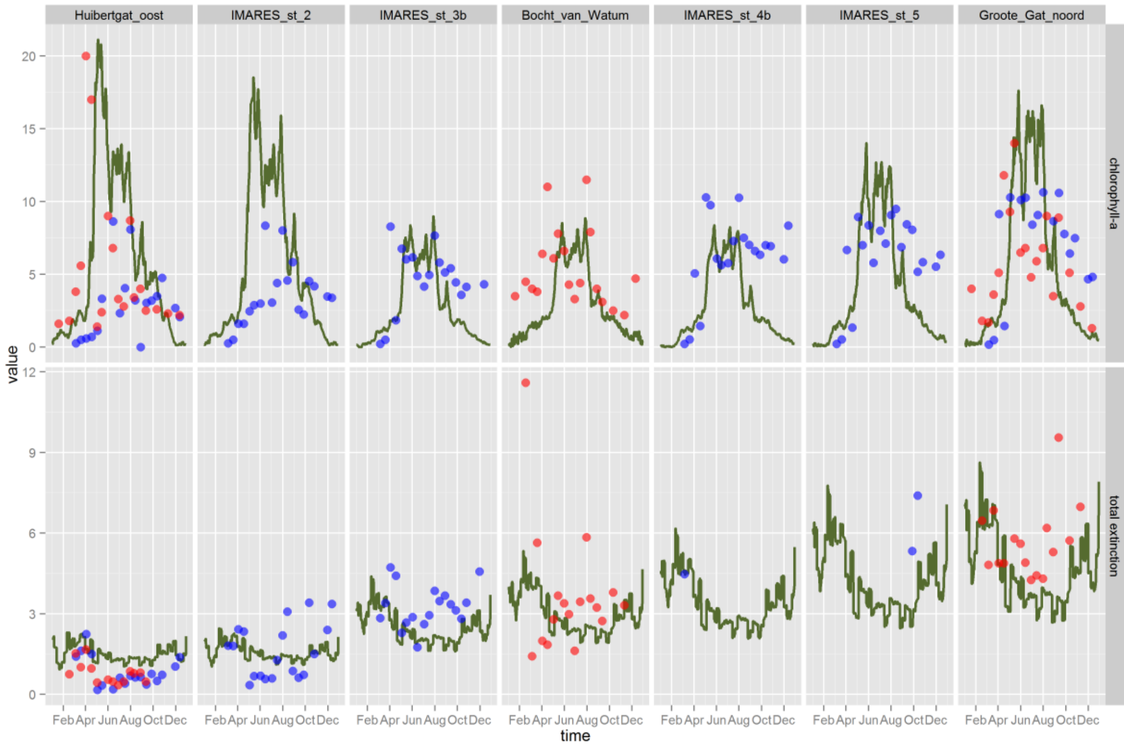


Figure 2.9 Simulated chlorophyll a (µg/L) and total extinction (m^{-1}) in the Ems estuary for 2012, at MTWL stations Huibertgat, Bocht van Watum and Groote Gat and additional IMARES stations 2, 3b, 4b and 5. The green line represents modelled daily averages, filled blue circles (●) and red circles (●) indicate measurements from the MWTL program and IMARES, respectively.

The overall conclusions from the calibration and validation of the model were that the water quality model simulates physical and chemical processes, such as mixing, nutrient loads and boundaries well enough to be used for scenarios studies (Figure 2.9). Pelagic primary production and algal biomass are simulated well enough except for some shallow parts of the Dollard. Scenario results for benthic primary production should be interpreted qualitatively. Due to higher uncertainties with calibration and validation, quantitative changes as a result of scenarios should be interpreted with care.

2.5 Main findings from the model analysis report

The baseline sediment model was used to study changes in hydrodynamics and suspended sediment concentrations in the Ems Estuary as a result of channel deepening and dredging strategies. The main findings of this study are (see report 7 for details) that

- Deepening of tidal channels strengthens up-estuarine residual circulation and transport, contributing to greater suspended sediment concentrations, especially in the Dollard.
- Until ~1990, sediment concentrations were lowered by large-scale sediment extraction from the Emden area. Ending this practice has led to larger suspended sediment concentrations after 1990.
- Sediment extraction from ports (without disposal at sea) has a large effect and leads to a large decrease in suspended sediment concentrations.
- The effect of dredging and disposal from ports is primarily a spatial redistribution of sediments, more than leading to a long-term change. Comparing the present-day situation in the baseline model (with ports and dredging and disposal) to a scenario without ports (and hence no dredging and disposal) reveals that constructing ports (1) reduces the overall turbidity levels in the estuary and (2) increases the turbidity near the disposal sites. The modelled disposal sites from Delfzijl and Eemshaven were in too shallow water (see section 2.3), and therefore overestimate locally the effect of disposal (even though the modelled effect is already small).
- Primary production by phytoplankton in the Ems-estuary is limited by light availability in the water column. Microphytobenthos primary production is restricted to areas where enough light is available at the bottom, in reality the available intertidal area. Benthic production could become limited by silica in the outer part of the estuary.
- Model sensitivity analyses show that a reduction of SPM in the whole estuary leads to increased pelagic primary production in the whole estuary, and a decrease of benthic primary production in the outer estuary. This decrease is explained by increased competition for nutrients with phytoplankton. Reduction of nitrogen and phosphorus from the Ems river reduced benthic production in the outer estuary further, but increased pelagic primary production.

Additionally, a semi-quantitative analysis of changes to bathymetry and loss of inter-tidal areas was made (not using the model). 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 transported from the system. Both lead to an increase in suspended sediment concentration.

3 Selection of scenarios

3.1 Introduction

As described in the previous chapter, the Ems Estuary has undergone large changes in the past decades and centuries. The awareness is growing that measures need to be taken to improve the ecological functioning of the Ems Estuary in the future. Van Schie and Firet (2014) identified a set of measures that could potentially reduce the turbidity in the estuary, focussing strongly on measures which influence the tidal dynamics. Some of these measures were numerically investigated by RHDHV (2013), applying the same hydrodynamic models described in report 4 (ERD and WED model).

In the current study, measures were identified in an iterative discourse between experts and stakeholders. A number of potential measures to reduce turbidity in the estuary were identified in various stakeholder/expert meetings (elaborated in section 3.2). These measures were prioritized by stakeholders and experts based on selection criteria such as feasibility and effectiveness, (section 3.3). The four most promising measures identified in this process were simulated as scenarios using the developed model. The effectiveness of the various scenarios was assessed by using a pre-defined set of indicators, which is described in section 3.4.

3.2 Potential measures

On April 1st 2014 a meeting was held with stakeholders (Nature Conservation Organisations and Port authorities, government) and experts (Knowledge institutes, Universities). Building on earlier, similar meetings (resulting in RHDHV 2013 and van Schie and Firet, 2014) a number of measures were defined which could potentially improve the ecological functioning of the estuary. These selected measures are summarized in Table 3.1 – see Schmidt et al. (2014) for further details.

Table 3.1 Potential measures to reduce turbidity and increase primary production in the Ems Estuary or investigations to increase knowledge on the estuarine dynamics, and expected effect. See legend for colour definition

No.	Measure or Investigation	Expected effect based on several expert and stakeholder consultation meetings
1	Sediment extraction from ports (with disposal on land)	Substantial reduction in turbidity and increase in primary production
2	Sediment extraction from the Dollard	Local effect on suspended sediment concentration and limited effect on primary production because the turbidity remains high
3	Increase sedimentation in the Bocht van Watum	Reduction of turbidity in an area which is important for primary production. Effect is of short duration because the Bocht van Watum is almost filled up
4	Adaptive poldering of the Dollard to increase sedimentation	Local effect on suspended sediment concentration and limited effect on primary production because the turbidity remains high
5	Adaptive poldering between Delfzijl and Eemshaven to strengthen sedimentation	Reduction in turbidity and increase in primary production
6	Restoration of multiple channel system	Change in horizontal circulation and impact on turbidity. The proper dimensions of the new tidal channels are difficult to determine accurately
7	Bypass in Ems River with a meandering channel in the Dollard	Large impact on tidal dynamics and therefore turbidity. Many uncertainties related to channel dimensions and impact
8	Redistribute sediment dredged from the ports differently (within the Ems Estuary)	Effect expected to be limited.
9	Relocate discharge locations	Effect on hydrodynamics and therefore sediment transport expected to be limited, and difficult to quantify
10	Restoration of channel depth of the Friesche Gaatje and Emden fairway	Reduction in turbidity and increase in primary production in the Ems Estuary
11	Reduction of mud supply from the Wadden Sea	Reduction in turbidity and increase in primary production in the Ems Estuary
12	Impact of nutrient sources	Insight how different nutrient sources in the estuary influence the primary production
13	Impact of nutrient levels	Insight how nutrient levels influence the primary production
14	Impact of spatial distribution of turbidity on primary production	Insight where a reduction in turbulence is most beneficial for an increase in primary production
15	Dispose sediment dredged from the ports in the North Sea	Reduction in turbidity
16	Strengthen sedimentation in the saltmarshes	Reduction in turbidity

Legend:

Mud extraction	Morphological measure
Knowledge increase	Other

3.3 Selection of measures to be further analysed

The 16 measures in Table 3.1 were prioritized based on 9 criteria defined by Rijkswaterstaat and Deltares, given in Table 3.2.

Table 3.2 Criteria for evaluation of the measures in Table 3.1, in order of importance (With criterion 1 considered most important by stakeholders and experts, and criterion 9 least important). Scoring of the yellow criteria was done by Deltares, Scoring of the blue criteria was done by Rijkswaterstaat, following the recommendations of stakeholders.

Number	Criterion
1	Increases understanding of processes and system functioning
2	Expected effectiveness
3	Sustainability
4	Can be realised on the short term
5	Costs of realisation
6	Impact on other estuary functions
7	Societal and political support
8	Suitability and reliability of the model
9	Cost of model simulations

During the workshop on April 1st 2014, participants were asked to prioritize the criteria and score the 16 measures. Based on the input of stakeholders and experts, Rijkswaterstaat ranked the 16 measures for criterion 3 through 7. Criterion 1, 2, 8, and 9 were ranked by Deltares, based on experience with the developed models.

The scoring of measures 1-16 (Table 3.1) with criteria 1-9 (Table 3.2) leads to the priority list in Table 3.3.

This list, along with the accompanying argumentation, was submitted to a group of experts proposed by the stakeholders. In consultation with the experts, a set of measures to be investigated with the model was selected. In this process, most importance was given to the criteria concerning the expected effectiveness of the measures, the suitability of the model, and costs of model simulations (since the project budget is limited).

Table 3.3 Score of the 16 measures for each of the 9 indicators, ranked in order of resulting priority. Selected measured are in bold. Measures 11 to 14 have not been scored by RWS since these are meant to increase knowledge, and cannot be physically implemented.

No.	Measure	1	2	3	4	5	6	7	8	9
15	**Dispose sediment dredged from the ports in the North Sea**	++	++	0	++	-	0	++	++	+
1	**Sediment extraction from ports (with disposal on land)**	++	++	0	+	+	0	++	++	+
10	**Restoration channel depth of the Friesche Gaatje and Emden fairway**	++	0	++	--	--	-	--	+	0
4	**Adaptive poldering of the Dollard to increase sedimentation**	++	+	+	0	0	+	0	+	--
5	Adaptive polder between Delfzijl and Eemshaven to strengthen sedimentation	++	+	+	-	-	0	-	+	--
6	Restoration of multiple channel system	++	-	--	+	-	0	+	-	--
2	Sediment extraction from the Dollard	+	+	--	+	+	0	+	++	+
3	Strengthen sedimentation in the Bocht van Watum	+	+	--	+	+	0	+	+	+
16	Strengthen sedimentation in the saltmarshes	+	0	+	++	+	+	++	-	-
8	Redistribute dredged sediment	+	0	0	++	+	0	++	0	+
7	Meandering channel in the Dollard	0	+	+	--	--	+	-	--	--
9	Relocate discharge locations	0	-	0	0	-	0	0	+	0
12	Impact of nutrient sources	++	+						++	++
14	Impact of spatial distribution on primary production	++	+						++	++
13	Impact of nutrient levels	++	+						+	++
11	Reduction of mud supply from the Wadden Sea	++	+						+	+

The following measures were selected to evaluate for impact on suspended sediment dynamics (the scenario number is given in parentheses):

1) Dispose sediment dredged from the ports in the North Sea (No. 15)
2) Sediment extraction from ports with disposal on land (No. 1)
3) Restoration channel depth of the Friesche Gaatje and Emden fairway (No. 10)
4) Adaptive poldering of the Dollard to strengthen sedimentation (effectively sediment extraction) (No. 4).

The effect of these scenarios on the suspended sediment concentration is quantified with scenarios using the models developed earlier in the project (summarised in chapter 2; for more detail see reports 4 and 5). The effect of two contrasting scenarios on primary production is quantified in chapter 8 (using the model developed in report 6; Table 1.1).

3.4 Indicators for suspended sediment concentration

The effect of scenarios on suspended sediment concentration is quantified by extracting model output for 3 indicators. These indicators are based on the yearly averaged concentrations/values in the model obtained after implementing the improvement scenario and running the model for several years (3+) until a new dynamic equilibrium is reached. To understand the simulated effect of a particular scenario on sediment dynamics, the results from the scenario are compared with the baseline model (described in report 5 and 7). This baseline model is calibrated against the present-day suspended sediment dynamics (sediment concentration, spatial mud distribution, and port siltation). The indicators for suspended sediment predictions are:

1) ***SPM fields***: Maps with the spatial distribution of the absolute and relative change in near-surface yearly averaged suspended sediment C_{new} relative to the sediment concentration C_{old} computed with the baseline model. The absolute change is defined as $C_{new} – C_{old}$ and the relative change as $(C_{new} – C_{old})/C_{old}$. Surface suspended sediment concentrations are used because the near-surface sediment concentration has the greatest impact on primary production.
2) ***Port Siltation:*** Dredging quantities (absolute amounts in million tons/year) for the various ports and channels, based on estimates from actual dredging amounts as well as calculated values from the baseline model and the scenario alternatives.
3) ***Average SPM concentrations per area:*** Tabulated values for the average surface and near-bed concentrations of suspended sediment in twelve predefined areas in the Estuary. These areas are important for the analysis of primary production in the Ems Estuary as they have been used historically to monitor changes in the estuary (defined during the Boede measurements and used by Imares; see report 9).

3.5 Indicators for primary production

The effect of scenarios on primary production is quantified by extracting results of 4 indicators from the water quality model output. These indicators are compared with the reference model (described in reports 6 and 7) to understand the effect of a particular scenario on primary production. This baseline model is calibrated against the present-day situation with regards to concentrations of chlorophyll-a, nutrients, oxygen and organic carbon in the water. The indicators for primary production predictions are:

1 ***Pelagic primary production***: Yearly aggregated pelagic primary production expressed as tonnes C/y and as % difference for assessment areas.

2 ***Benthic primary production*** Yearly aggregated benthic primary production expressed as tonnes C/y and as % difference for assessment areas important for primary production (described later).

3 ***Sum of pelagic and benthic primary production:*** Yearly aggregated pelagic plus benthic primary production expressed as tonnes C/y and as % difference for assessment areas.

4 ***Limiting Factors:*** Strength of limitation (light, nitrogen, phosphorus, silica) of primary production during the year for assessment areas.

4 Disposal of dredged sediment in the North Sea

4.1 Scenario definition

In this scenario, the sediment that is dredged from ports and approach channels is disposed of in the North Sea. Four new disposal locations are evaluated, one of which (Loc8) is outside the area of influence for the estuary (Figure 4.1).

Sediment is dredged annually from the ports and approach channels in the estuary. This dredged sediment is currently disposed within the estuary. In report 7 it is concluded that extracting sediment from the ports (dredging of sediment and disposal on land) leads to a reduction in suspended sediment concentration. This will be further elaborated in Chapter 5. Sediment extraction is costly because of storage and legislative reasons (extraction of sediment from the Dutch coastal foundation needs to be compensated by nourishments elsewhere). An alternative is to dispose sediment in the North Sea.

The further offshore the sediment is disposed, the higher the operational costs related to shipping time (see Table 4.2). However, disposal further offshore may reduce the turbidity in the estuary, and therefore also dredging requirements (and long-term costs). To evaluate the impact of disposal location on sediment concentration and dredging requirements in the Ems Estuary, a range of dredge dispersal locations was selected and implemented in the model.. The most landward station (Loc5) is located within the Wadden Sea (near the main fairway), while the second station (Loc6) is in the North Sea. The third and fourth disposal sites (Loc7 and Loc8) are progressively further into the North Sea (see Figure 4.1). All dredged sediments from Eemshaven, Port of Delfzijl, the Emden area are disposed offshore in each of the Locations 5-8 resulting in model alternatives 1-4, respectively (see Table 4.1). The baseline model (to which alternatives 1-4 are compared) uses port-specific disposal grounds (see Figure 4.2 for locations). These disposal sites are in closer to the intertidal areas flanking the channels than the actual disposal sites are (see also section 2), and therefore the effect of disposal is locally overestimated. Figure 5.7 in report 5 outlines the specific relationships between port and original disposal grounds). Location 8 was chosen as being outside the area of influence.

The effectiveness of the model scenarios is evaluated by comparing the indicators defined in section 3.4 (suspended sediment concentration distribution, port siltation, and area-averaged sediment concentration). For the two most contrasting scenarios, the change in sediment mass in the bed (relative to the baseline scenario) is also evaluated.

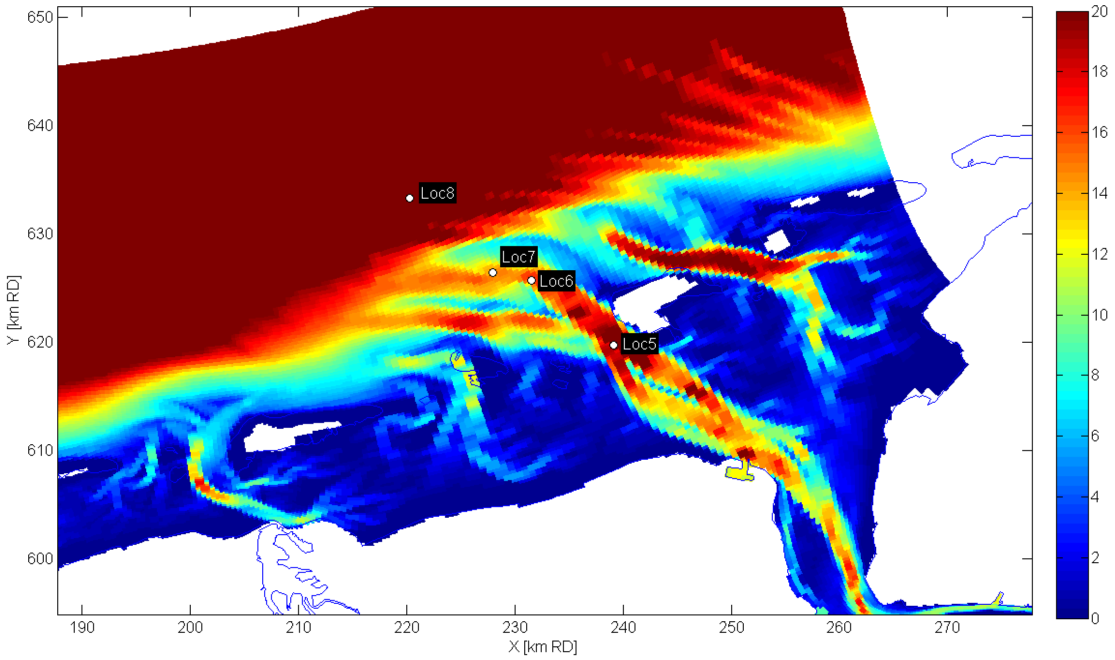


Figure 4.1 Model bathymetry with locations (Loc5-Loc8) for offshore disposal of dredged sediment in the alternatives.

Table 4.1 Offshore disposal alternatives

Alternative	Locations	Ports	Extraction	Bathymetry	Disposal grounds
baseline		Yes	No	2005	Ems Estuary (Figure 4.2)
Alt 1	Loc5	Yes	No	2005	All in Location 5
Alt 2	Loc6	Yes	No	2005	All in Location 6
Alt 3	Loc7	Yes	No	2005	All in Location 7
Alt 4	Loc8	Yes	No	2005	All in Location 8

Table 4.2 Approximate increase in sailing distance, one way (in km relative to present) per port and per alternative

Alternative	Locations	Emden	Delfzijl	Eemshaven
Alt 1	Loc5	18	25	8
Alt 2	Loc6	25	32	15
Alt 3	Loc7	33	40	23
Alt 4	Loc8	43	50	33

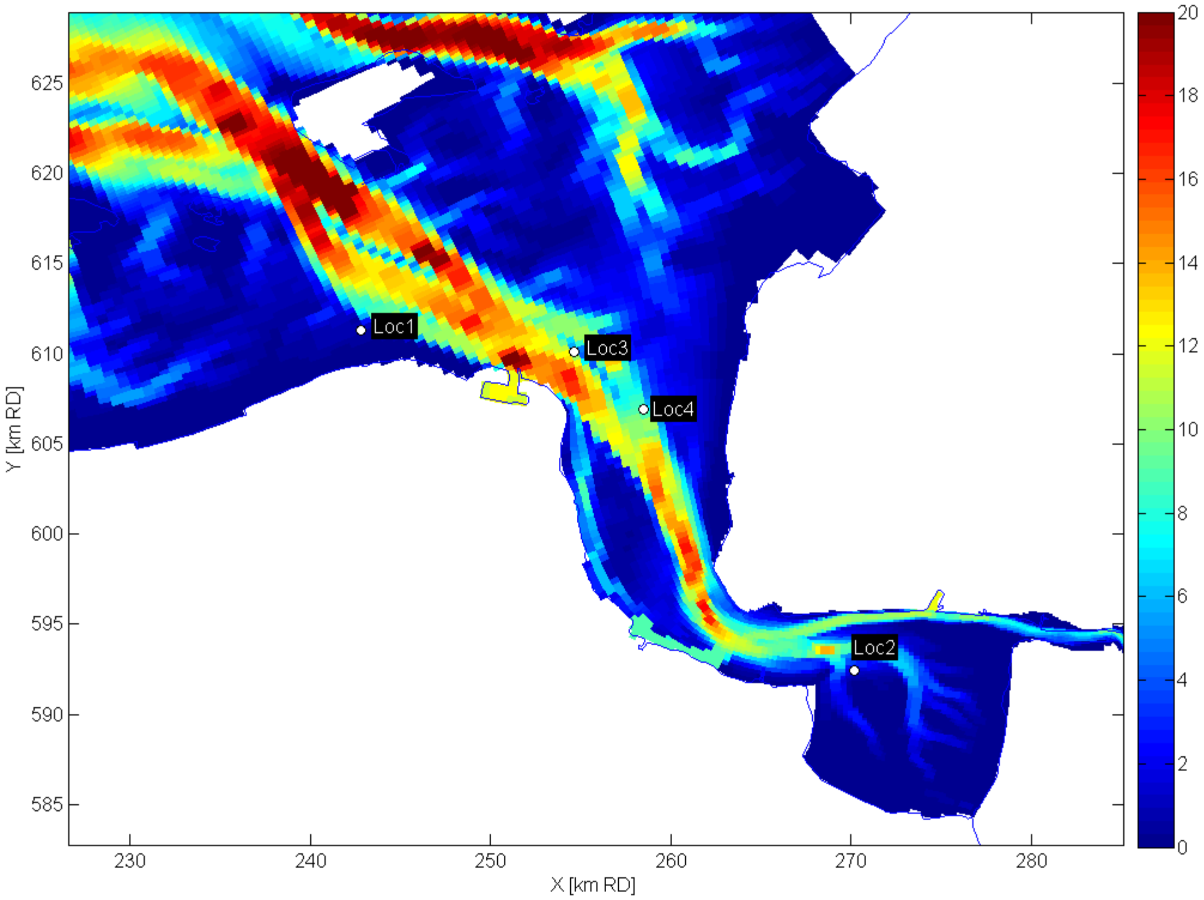


Figure 4.2 Model bathymetry with present disposal locations in the baseline model. Sediment from Eemshaven is disposed in Loc1, sediment from the Port of Delfzijl and the Dollard is disposed in Loc2, sediment from the Emden area is disposed in Loc3 and Loc4.

4.2 Results

4.2.1 SPM fields

Figures 4.3 to 4. 6 show the results of the four scenario alternatives with disposal in the North Sea compared to the baseline model (2012), in which dredged sediment was disposed at various locations within the estuary. In Alternative 1, all the sediment is disposed further seaward than existing disposal sites, but still inside the Wadden Sea (Location 5, see Figure 4.1). The change in yearly averaged suspended sediment concentrations, compared to the baseline model is shown in Figure 4.3. Sediment concentrations are lower overall within the estuary, compared to the baseline. Sediment concentrations do however increase substantially around the island of Borkum, extending eastward into the North Sea and Wadden Sea. The eastward transport follows from the dominant eastward transport in the Wadden Sea.

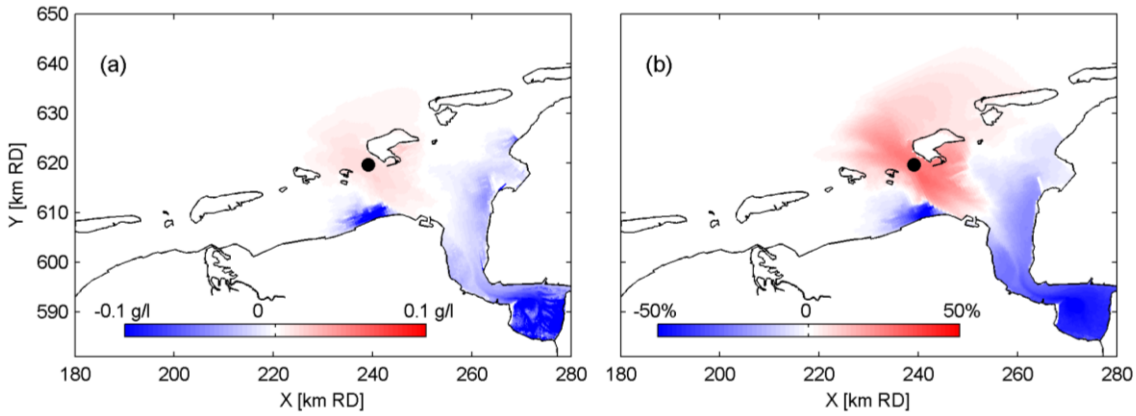


Figure 4.3 Absolute (a, in g/) and relative (b, in %) difference in yearly averaged surface suspended sediment concentration relative to the baseline scenario for disposal alternative 1 at Location 5 marked by black spot (Alt1 -baseline)

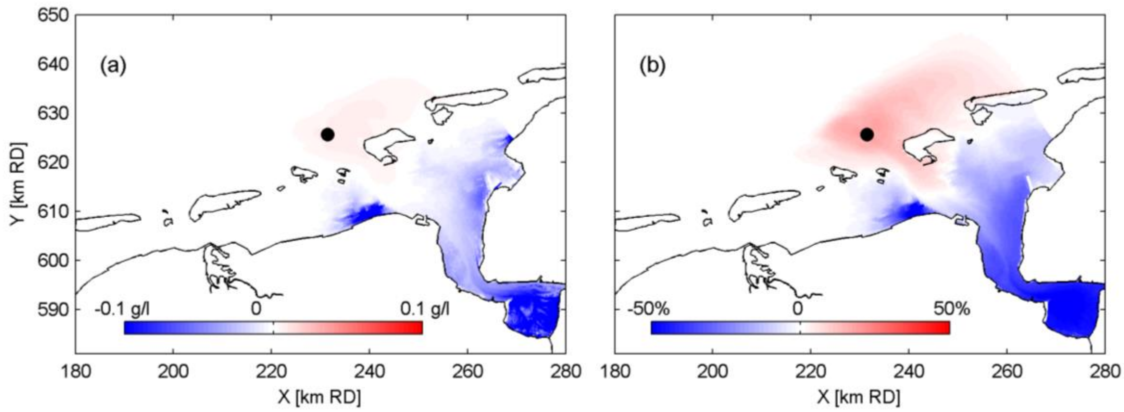


Figure 4.4 Absolute (a, in g/) and relative (b, in %) difference in yearly averaged surface suspended sediment concentration relative to the baseline scenario for disposal alternative 2 at Location 6 marked by black spot (Alt2 -baseline)

Similar patterns are observed for disposal on Location 6 (Alternative 2 - when disposal occurs just outside the Wadden Sea) (Figure 4.4). For Alternative 3 (Location 7) the sediment remains just outside of the Wadden Sea, and is also transported to the east (Figure 4.5). In the deeper waters of Location 8 (Alternative 4) however the sediment remains further offshore and does not enter the Wadden Sea, as can be seen in Figure 4.6. This is the scenario with the largest reduction in sediment concentration at the mouth of the estuary. For all simulations, the local increase near disposal site loc1 (see Figure 4.2 for location) is overestimated because the disposal site is too close to the intertidal area (see section 2.3). The impact of the exact disposal location on the overall suspended sediment concentration patterns in the estuary is small, however, over longer timescales (years, such as simulated with the equilibrium model).

For all alternatives there is a strong reduction of suspended sediments in the estuary, particularly in the Dollard and near the entrance of the Ems River. This will also have large consequences for future maintenance dredging requirements, which is evaluated in the next section.

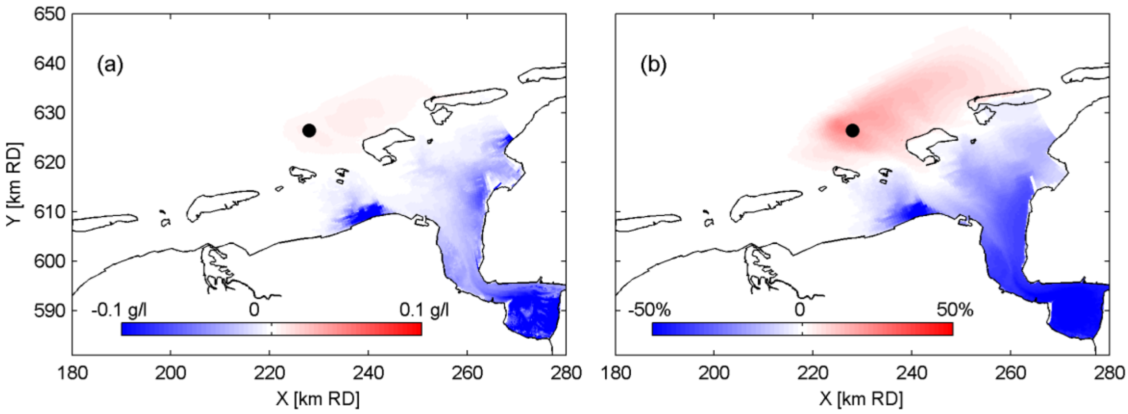


Figure 4.5 Absolute (a, in g/) and relative (b, in %) difference in yearly averaged surface suspended sediment concentration relative to the baseline scenario for disposal alternative 3 at Location 7 marked by black spot (Alt3 -baseline)

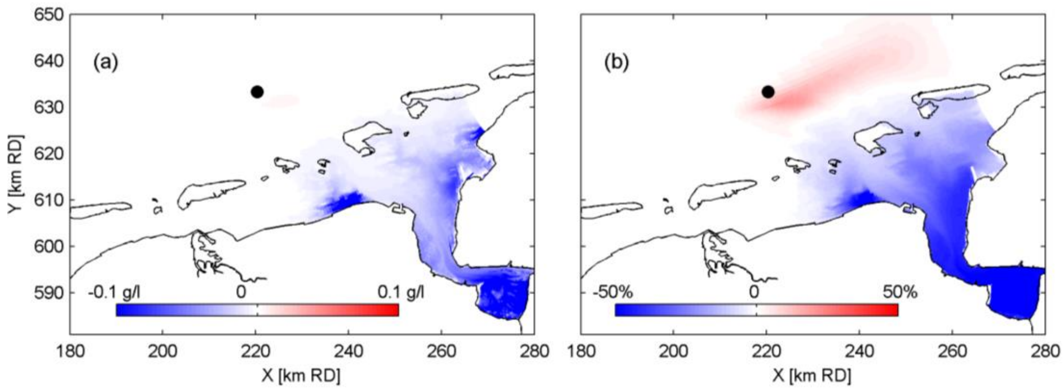


Figure 4.6 Absolute (a, in g/) and relative (b, in %) difference in yearly averaged surface suspended sediment concentration relative to the baseline scenario for disposal alternative 4 at Location 8 marked by black spot (Alt4 -baseline)

4.2.2 Port siltation

In the baseline study, siltation in the ports of Eemshaven and Delfzijl were well reproduced: the estimated siltation (based on dredging requirements) is 0.5 and 0.8 million tons (Table 4.3). The modelled siltation in the port area of Emden was strongly underestimated in the baseline model (0.6 million tons/year compared to the 1.6 million tons/year estimated from dredging requirements).

Similar to the reduction in suspended sediment concentrations (previous section), the amount of sediment entering the three ports at Eemshaven, Delfzijl and Emden decreases with offshore disposal (Table 4.3). The exception is Eemshaven for alternative 1, showing a slight increase in sediment deposition in the port. The reduction in sediment entering the ports increases the further offshore the sediment is disposed. For the scenario furthest offshore (Alternative 4), this reduction is roughly 25% for Eemshaven, 50% for Delfzijl and 55% for Emden, leading to a potentially large reduction in dredging costs in these locations.

As explained above, the siltation in the port of Emden is underestimated. In this part of the model domain, the governing physical sediment transport processes are insufficiently represented (see report 5 for more details). Therefore the effect of scenarios on the port of

Emden should be carefully interpreted and are more uncertain. The model better represents the siltation in the ports of Delfzijl and Eemshaven (and nearby suspended sediment concentrations, see report 5), and therefore the reduction in dredging requirements computed for these ports is more certain.

Table 4.3 Sediment fluxes (in million tons/year), estimated from dredging requirements, and computed for the baseline simulation and the alternative disposal locations

Port	Estimated	baseline	Alt. 1	Alt. 2	Alt. 3	Alt. 4
Eemshaven	0.5	0.46	0.48	0.41	0.38	0.34
Delfzijl	0.8	0.82	0.52	0.45	0.43	0.40
Emden area	1.6	0.59	0.34	0.30	0.28	0.26

4.2.3 Average SPM concentrations per area

The extent to which disposal offshore influences the suspended sediment concentration in the Ems Estuary can be examined in more detail by looking at the twelve main areas (Figure 4.7) regarded important for the monitoring of primary production parameters in the estuary. The results (Figure 4.8) can be summarised as follows:

- With increasing distance of the offshore sediment disposal, the sediment concentration inside the estuary decreases (as also concluded in section 4.2.1).
- The reduction in sediment concentration (relative to the baseline) increases in an up-estuary direction.
- Disposal alternatives 1 and 2 do not reduce, and will even increase, the sediment concentration seaward of Eemshaven (Area 1_2 and 2).
- The relative change in sediment concentration is the same near the bed and near the surface.
- To the south of Eemshaven, the difference between the four alternatives is relatively small compared to the difference with the baseline scenario.

4.2.4 Sediment mass in the bed

In order to put the impact of the dredging scenarios in perspective, the changes in total sediment mass are presented in this section. The total amount of bed sediment in the system decreases with the seaward distance of the sediment disposal area. The change in bed sediments is illustrated in Figure 4.9, revealing a reduction in mud content in the deeper parts of the estuary and an increase in the outer estuary. These relative changes should be carefully interpreted, because the largest changes occur in areas where the original amount of sediment in the bed is low (so a small absolute change leads to a large relative change). The changes in the absolute sediment mass are much lower where there is more sediment in the bed. The total amount of sediment in the model domain (in the bed and in suspension) is (for the baseline simulations and alternative 1 – 4) 521, 520, 520, 519, and 519 million ton. Most of this sediment is stored in the bed of the North Sea (low mud content but large area).

4.3 Model applicability

The applicability of the model to simulate the dredging and disposal scenarios is determined by the modelled accuracy of the following processes:

- Port siltation rates
- The up-estuary transport of disposed sediment.

4.3.1 Port siltation

Dredging and disposal is an integral part of the model. Port siltation is computed by the model, and depends on sediment supply towards the port and trapping within the port (which in turn depend on the hydrodynamics, sediment concentration, and sediment settling properties). Sediment that deposits in the port is dredged and disposed in designated areas. When sediment is dumped further offshore, and the sediment concentrations decrease, the modelled port siltation and offshore disposal automatically decrease as well. The model reproduces present-day siltation rates (based on dredging quantities) in the ports of Delfzijl and Eemshaven, which suggests that sediment supply and trapping in the ports are well reproduced by the model. Though siltation is underestimated in the Emden area (as described in Section 2.3 of Chapter 2, the amount dredged in the model is compensated for by increasing the amount of dredged sediments disposed elsewhere from the other two ports. However, the model overestimates the effect of Delfzijl (disposal location loc4 in Figure 4.2) relative to that of Emden (disposal locations 2 and 3) because (1) all sediment from Delfzijl is disposed at loc4 whereas in reality 80% of sediment is removed from the port by agitation dredging, and (2) sediment deposition in the area around Emden is underestimated.

The integrated modelling of dredging and disposal, combined with the good reproduction of present-day siltation rates, gives confidence in the model capability to model the disposal scenarios sufficiently accurately.

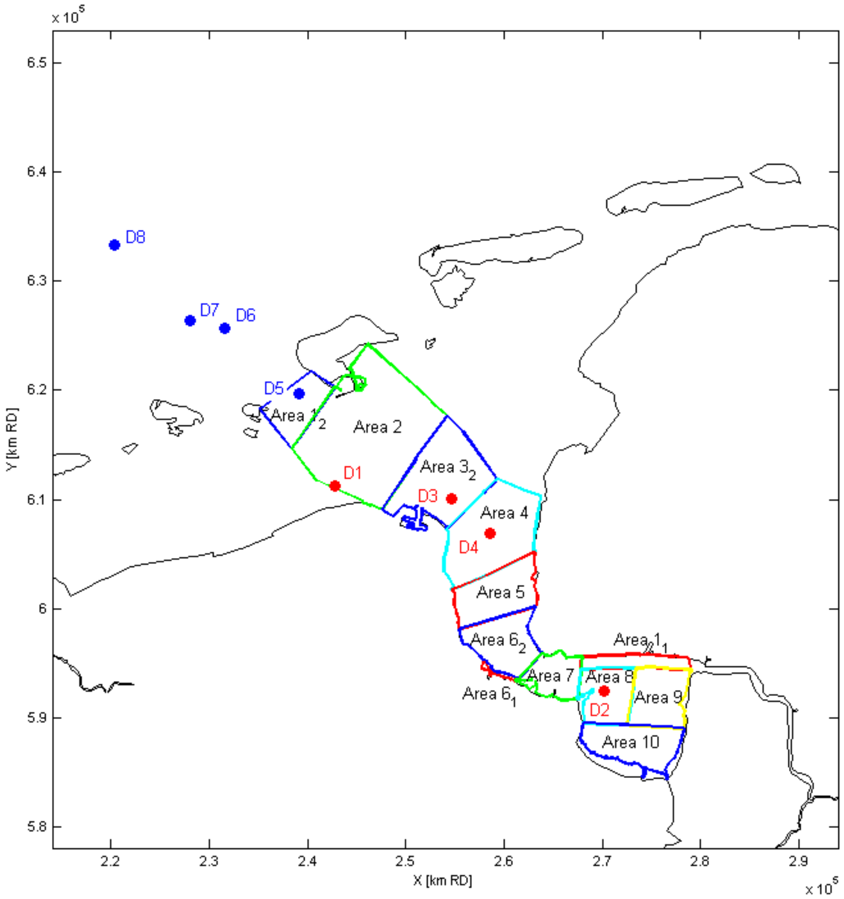
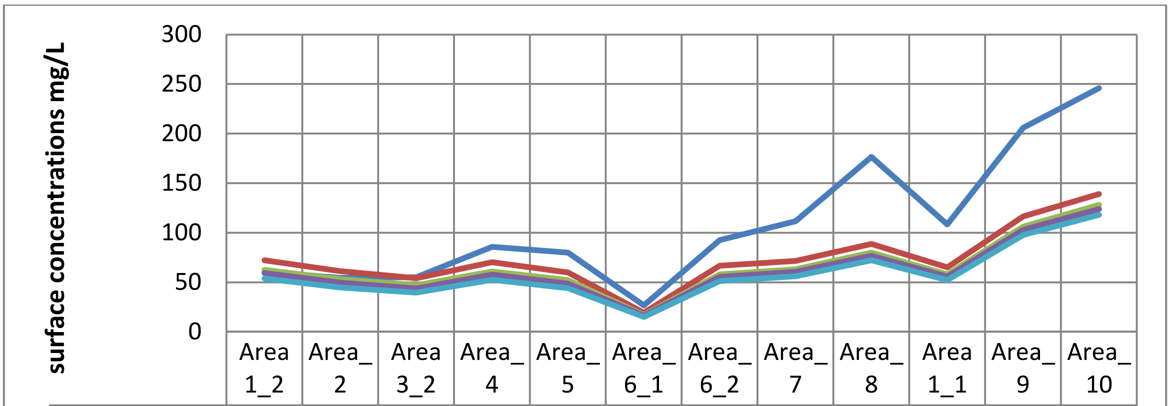
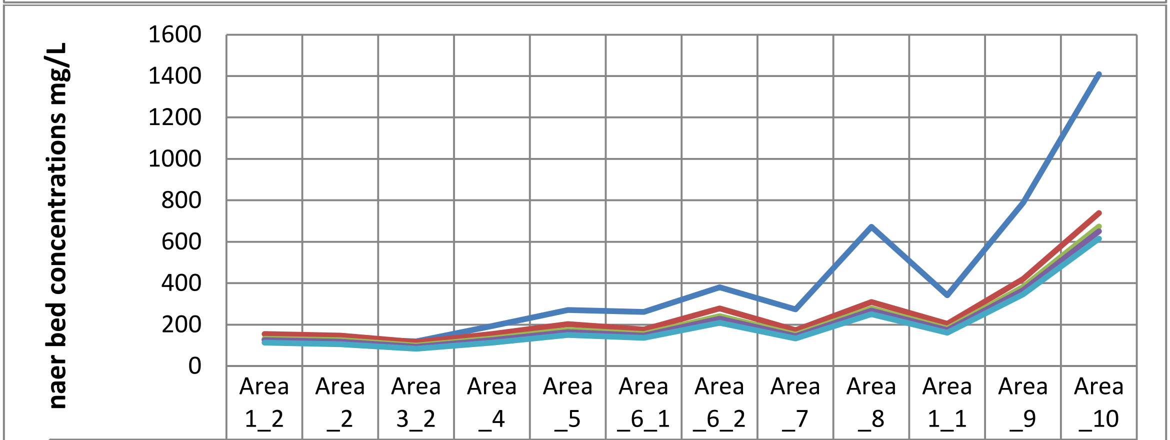


Figure 4.7 Definition of areas used to spatially average the suspended sediment concentration and disposal locations (old locations D1-D4 in red and new locations D5-D8 in blue)



	Area 1_2	Area_2	Area 3_2	Area_4	Area_5	Area_6_1	Area_6_2	Area_7	Area_8	Area 1_1	Area_9	Area_10
reference	61	54	55	86	80	27	92	112	177	108	206	246
Alt. 1	72	61	54	70	60	19	67	72	89	65	116	139
Alt. 2	62	53	47	61	52	17	58	63	80	58	106	128
Alt. 3	59	50	44	58	49	16	56	60	77	56	103	124
Alt. 4	54	45	40	53	44	15	51	56	72	52	98	118



	Area 1_2	Area_2	Area 3_2	Area_4	Area_5	Area_6_1	Area_6_2	Area_7	Area_8	Area 1_1	Area_9	Area_10
reference	128	132	118	194	270	261	380	274	672	341	789	1410
Alt. 1	155	147	116	155	202	176	278	173	309	204	420	739
Alt. 2	132	125	99	133	175	155	241	152	278	181	381	674
Alt. 3	125	118	93	125	165	148	228	144	267	173	367	650
Alt. 4	113	105	84	113	150	136	208	133	250	161	346	615

Figure 4.8 Surface (upper panel) and near bed (bottom panel) suspended sediment concentrations for the studied alternatives and the baseline model. Concentrations are yearly averaged values, and spatially averaged per area. Alternatives 1-4 refer to disposal of dredged sediment at the new North Sea disposal sites, Loc5-Loc8. See Figure 4.7 for location of disposal sites and area definition.

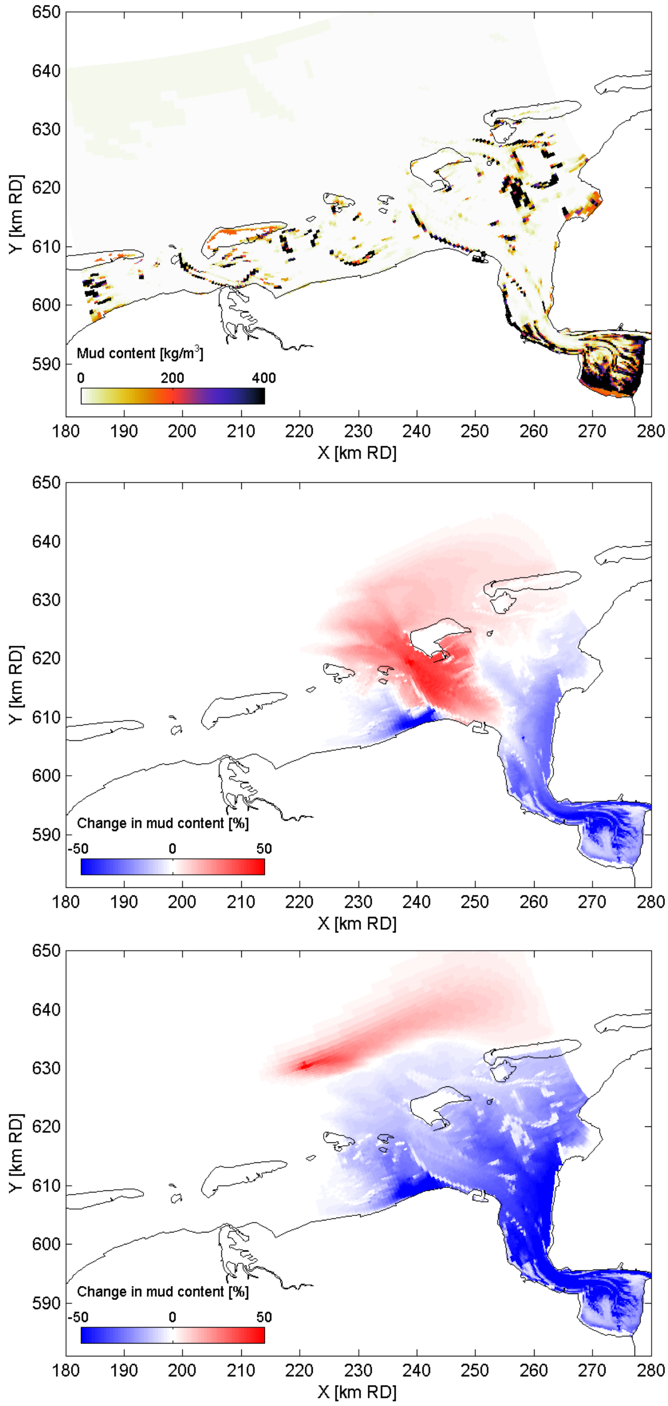


Figure 4.9 Mud content in the bed of the baseline model (top panel, in kg/m^3) and changes in mud content for alternatives 1 (middle panel) and 4 (lower panel).

4.3.2 Up-estuary transport

The disposed sediment is transported back into the estuary by two mechanisms:

- Lateral spreading of disposed sediment by the oscillating tidal currents
- Residual transport of sediment

Lateral spreading

In a three-dimensional model as applied here, the lateral spreading or horizontal transport of sediment in the water column is primarily driven by the instantaneous 3D current profile. The model reproduces sediment spreading because (i) the instantaneous currents are sufficiently reproduced and (ii) the tidal phase lags are correctly simulated (see report 4 – Figures 3.7 - 3.8).

The rate of spreading or transport is strongly influenced by water-bed exchange mechanisms. This exchange rate is determined by the buffer capacity of the model. The sediment model applied in this study has been specifically designed to reproduce the buffer capacity of the seabed (see van Kessel et al., 2011).

Residual transport

Long-term residual sediment transport in the Ems Estuary is mainly generated by asymmetries in the flow and by sources and sinks. The type and degree of the modelled tidal asymmetry is in agreement with observations in the vicinity of disposal location Loc 1 within the estuary (Figure 4.1 and report 4), where observations are available (e.g. GSP2; see report 5 for details). There is insufficient data available to calibrate residual flows with sufficient accuracy. However, the depth-averaged residual circulation cells are in qualitative agreement with observations (see report 4, Section 3.4.3). The residual circulation is important for residual sediment transport deeper into the estuary (see report 7), but it is expected that this effect is not so important north of Eemshaven.

Although it has not specifically been studied, it is not expected that disposing sediment at specific times in the tidal cycle (e.g. flood or ebb) would have a large impact. All model results are yearly average concentrations (so not linked to individual tidal cycles), or fluxes after the model simulation has reached dynamic equilibrium.

4.3.3 Dynamic equilibrium

The baseline model and all model scenarios are in dynamic equilibrium, which means that the sediment concentration for consecutive years is (for each individual model scenario, see text box in section 2.3) very small. For complete equilibrium conditions, there is no net transport over the boundaries, since the model does not have net sediment sinks. The various scenarios primarily influence internal distribution within the model domain, and not (necessarily) over the model boundaries.

Achieving full equilibrium requires a large number of simulation years because of the large sediment mass in the system (as explained in section 4.2.4), which cannot be executed because of the large associated computational effort. However, because dynamic equilibrium is defined as a small change in SSC, any difference between approximate equilibrium and full equilibrium will not influence the scenario outcomes (which are expresses in a change in SSC).

4.3.4 Summary

To reproduce the effect of different dredge disposal locations, the model needs to reproduce (A) port siltation and (B) up-estuary residual sediment transport. Port siltation rates are reproduced by the model. Up-estuary transport is determined by (1) lateral sediment spreading and (2) residual transport. It is recognized that residual transport resulting from natural sediment sinks (such as the Bocht van Watum) is underestimated. However, the largest sinks in the estuary are the ports, and port siltation (in Eemshaven and Delfzijl) is well represented by the model.

Given that the processes related to port siltation and up-estuary transport are both well represented in the model, it is considered that the model is able to adequately reproduce the effect of North Sea disposal options on sediment concentration and dredging requirements within the Ems Estuary. However, even though the model can be considered a good model to reproduce suspended sediment concentrations and port siltation, model uncertainties remain. The computed effects of offshore disposal are very large, and given the model uncertainties discussed above, more research needs to be done to verify the explorative results presented in this chapter.

It should be realised that the offshore disposal is essentially the same as *extracting* sediment from the estuary. The effect of *extracting* sediment from the ports (either by offshore disposal or bringing sediment on land) is not the same as the effect of *dredging and disposal* (which is the current practice). Report 7 suggests that the effect of dredging and disposal from the ports is mainly a local redistribution of suspended sediment concentrations (SSC), and not so much an increase of average SSC levels (compared to an estuary without ports).

4.4 Conclusions

Four locations were chosen to simulate a range of disposal locations offshore (from the Wadden Sea to the North Sea) and compared to the present (baseline) situation where the sediment from these ports and fairways is released inside the estuary. The main conclusions are:

- The further offshore the sediment is disposed, the greater the effect in terms of reducing the suspended sediment concentrations within the estuary.
- For the disposal location furthest offshore (Alternative 4), there is a large reduction in suspended sediment concentration: up to 50%. The sediment disposed at this location is essentially removed from the system.
- An offshore disposal area behind Borkum could also be considered to remove sediment from the system, but this would have a larger sailing distance.
- For the location least offshore (Alternative 1), the reduction in suspended sediment concentration in the Dollard is also high, but the concentration north of Eemshaven increases.
- South of Delfzijl, the difference between the various disposal alternatives becomes low, and every alternative leads to a strong reduction. The reduction in sediment concentration is higher in the Dollard than in the most seaward part of the estuary.
- Port siltation rates decrease with the distance offshore the material is disposed. Siltation in the ports deep in the estuary (Delfzijl, Emden) decrease with ~40% for alternative 1 to just over >50% for Alternative 4 (Table 4.3). Siltation in Eemshaven may increase slightly for Alternative 1 but decrease by 26% for Alternative 4.
- The large computed effect of seaward disposal of dredged sediment does not imply that the current practice of dredging and disposal leads to a large increase in SSC relative to an estuary without ports.

The suitability of the model to simulate these scenarios is determined by its capacity to model port siltation and up-estuary transport. The modelled port siltation and some aspects of the up-estuary transport (lateral spreading) can be substantiated by observations. The computed residual up-estuary transport is also determined by processes which are less well reproduced (sediment sinks are underestimated) or cannot be adequately validated (residual currents).

5 Extraction of sediment from ports (and disposal on land)

5.1 Scenario definition

In this measure, the sediment that is dredged from the ports of Eemshaven, Delfzijl and Emden, is extracted (dredged and then disposed of on land).

Large amounts of sediment (close to 3 million tons/year) are annually dredged from the ports and approach channels, and disposed further seaward. Using the model developed in this project, it was concluded that extraction of sediment from the ports has a large impact on the sediment concentration (report 7). Extracting sediment from the ports may therefore be an effective scenario to reduce the turbidity in the Ems Estuary. This is evaluated with four scenarios (Table 5.1), where sediment is extracted from the three individual ports (Alternatives 1 to 3) and from all three ports combined (Alternative 4): see Figure 5.1 for port locations. In the baseline simulation, the dredged sediment is disposed of on the disposal grounds belonging to each port (see Figure 5.2). In these alternatives, the effect of sediment extraction from each port individually and from all ports combined was quantified relative to the baseline model using the indicators introduced in section 3.4.

Table 5.1 Alternatives for sediment extraction from ports

Alternatives	Ports	Extraction	Bathymetry	Extraction
baseline	Yes	No	2005	none
Alt 1	Yes	Yes	2005	from Eemshaven
Alt 2	Yes	Yes	2005	from Delfzijl
Alt 3	Yes	Yes	2005	from Emden area
Alt 4	Yes	Yes	2005	from all three ports

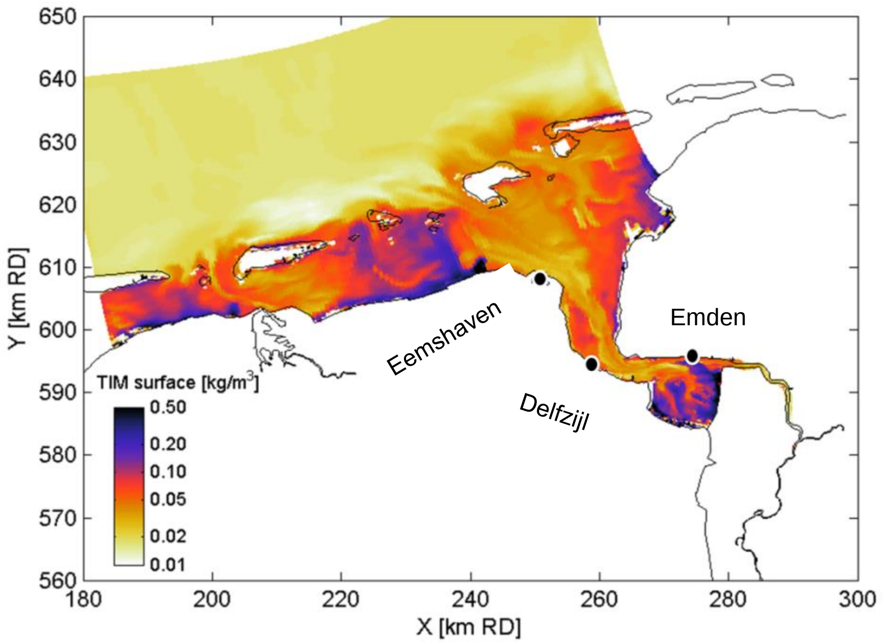


Figure 5.1 Ports from which sediment is extracted (black dots) with the yearly averaged near-surface suspended sediment concentration in the baseline scenario (Total Inorganic Matter, TIM) in colour scale.

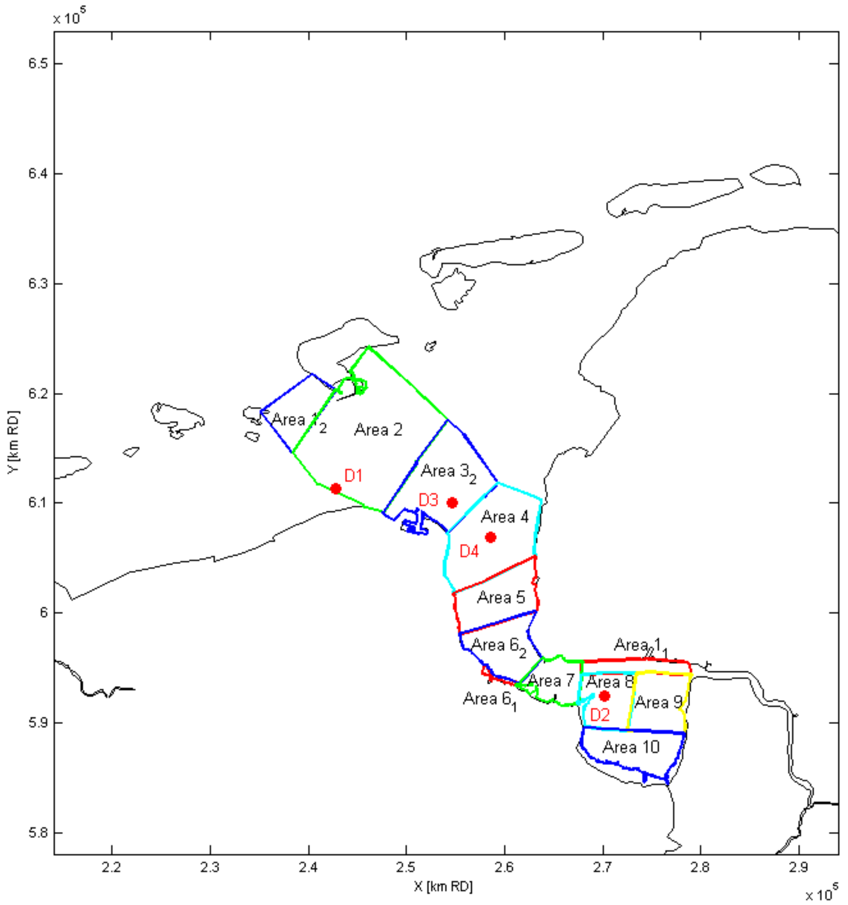


Figure 5.2 Definition of areas used to spatially average the suspended sediment concentration and existing disposal locations (D1-D4, in red). In the baseline simulation, sediment from Eemshaven is disposed in D1, sediment from the Port of Delfzijl and the Dollard is disposed in D2, sediment from the Emden area is disposed in D3 and D4.

5.2 Results

5.2.1 SPM fields

Extracting sediment from Eemshaven (Alt1) results in a reduction of < 10 mg/L (~ 10%) in the Ems Estuary itself, but in a larger reduction in the Wadden Sea (~ 20-30%) (Figure 5.3). The area where concentrations are maximally reduced is surrounding the disposal location for the sediments (D1 in Figure 5.2).

For Alt2, extracting sediment from Delfzijl (Figure 5.4), the largest reduction can be seen within the estuary and closest to the Dollard (~ 50%), as the sediment from Delfzijl was disposed near the Dollard in the baseline model (D2 in Figure 5.2). The effect of Alt3 (Figure 5.5), sediment extraction from Emden area, is more diffuse (20-30% within the estuary), as sediment used to be disposed around the mouth of the estuary (D3 and D4 in Figure 5.2). Here the change is also < 10 mg/L. The effect is largest in Alt4, the alternative in which sediment from all three ports is extracted (Figure 5.6). Relative to the baseline model, the effect is ~ 50% reduction within the entire estuary. These results are comparable to those for the sediment disposal in the North Sea, Alternative 4 (see Figure 4.6).

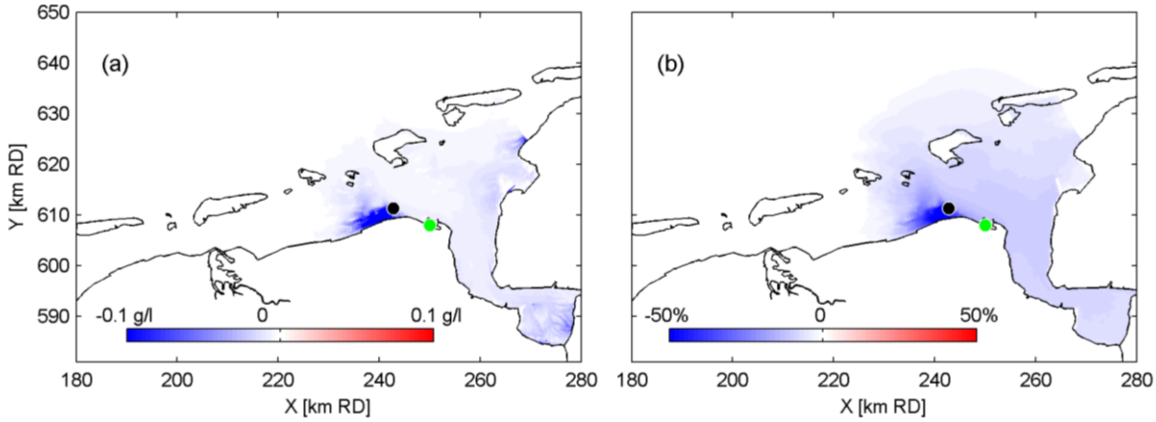


Figure 5.3 Absolute (a, in g/) and relative (b, in %) reduction in yearly averaged surface suspended sediment concentration relative to the reference scenario for extraction Alt 1 (Alt1 -baseline). Eemshaven port is marked in green and the corresponding disposal location in black (D1 in Figure 4.2)

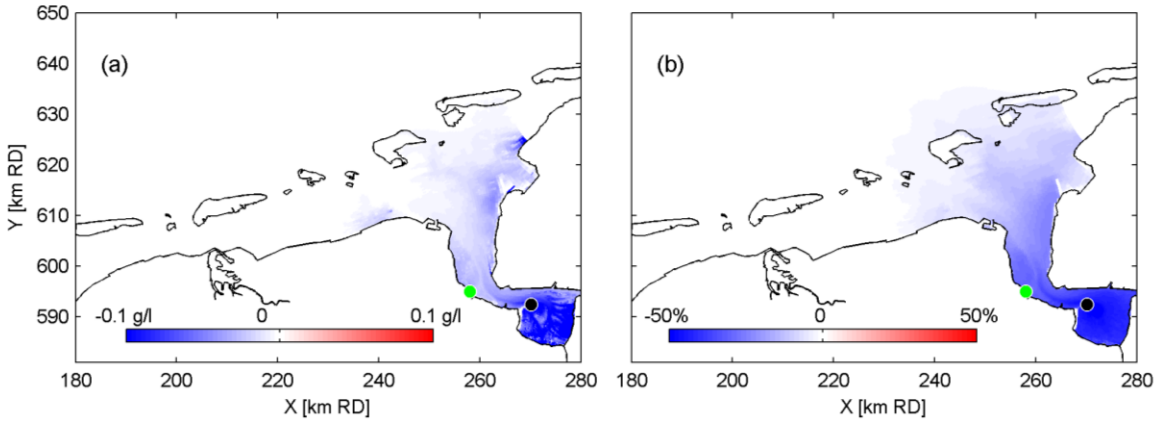


Figure 5.4 Absolute (a, in g/) and relative (b, in %) reduction in yearly averaged surface suspended sediment concentration relative to the reference scenario for extraction Alt 2 (Alt2 -baseline). Delfzijl port is marked in green and the corresponding disposal location in black (D2 in Figure 4.2)

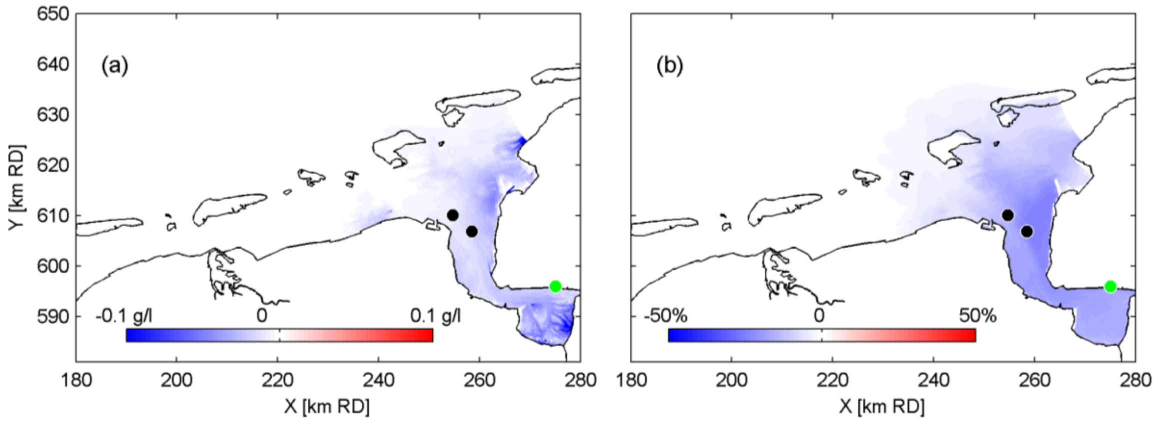


Figure 5.5 Absolute (a, in g/) and relative (b, in %) reduction in yearly averaged surface suspended sediment concentration relative to the reference scenario for extraction Alt 3 (Alt3 -baseline). Emden port area is marked in green and the corresponding disposal location in black (D3 and D4 in Figure 5.2)

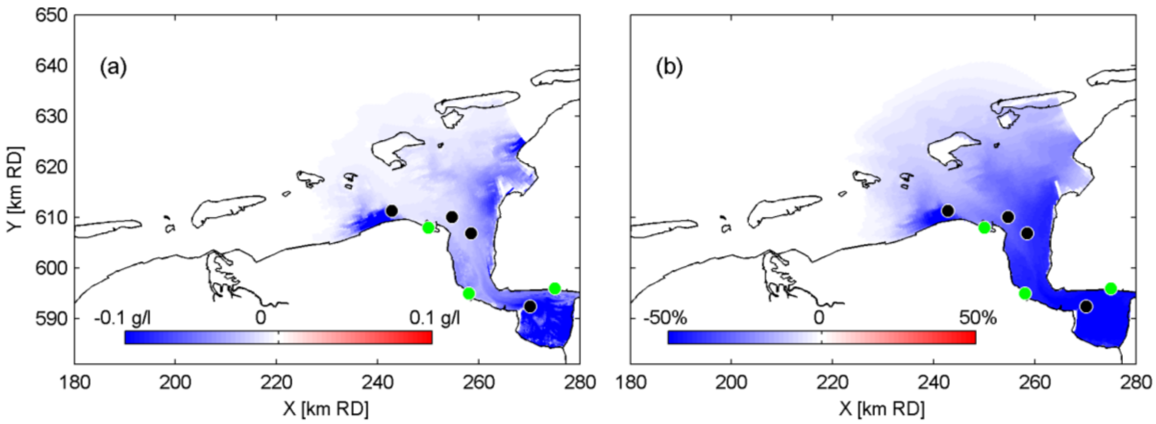


Figure 5.6 Absolute (a, in g/) and relative (b, in %) reduction in yearly averaged surface suspended sediment concentration relative to the reference scenario for extraction Alt 4 (Alt4 –baseline. All three ports marked in green and the corresponding disposal locations in black (D1-D4 in Figure 4.2)

Similarly to the SSC patterns discussed in the previous chapter, the local increase near disposal sites loc1 and loc4 (see Figure 4.2 for locations of disposal sites) is overestimated because the disposal site is too close to the intertidal area. The impact of the exact location on overall suspended sediment distribution patterns is small though over the timescales of interest for this study.

5.2.2 Port siltation

When sediment dredged from the ports is extracted and disposed on land as opposed to being disposed in the estuary, the sediment concentrations in the estuary decrease (see section above). As a result, the port siltation rates also decrease. The sediment mass extracted from the ports will therefore be smaller than the mass dredged and disposed from the same ports in the baseline simulation.

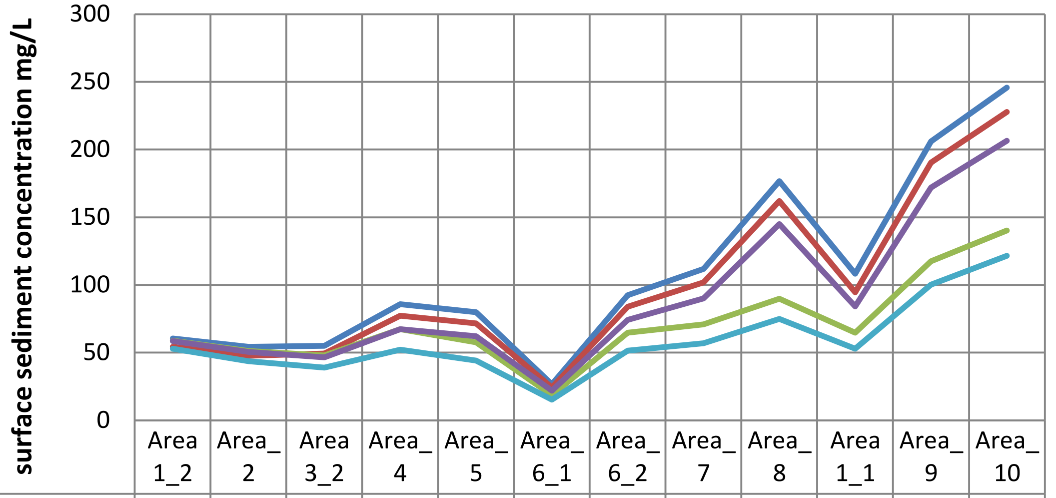
The reduction in port siltation is greatest (for all ports) when the sediment is extracted from all three ports (Alternative 4, Table 5.2). The most effective single port is Delfzijl (Alternative 2). The port where extraction is least effective for reducing port siltation rates is Eemshaven, because the sediment is disposed the furthest away in the baseline situation. The individual contributions of all individual ports should be carefully interpreted though, see section 5.3 for more details.

Table 5.2 Sediment fluxes (in million tons/year), estimated from dredging requirements, and computed for the baseline simulation and the sediment extraction alternatives

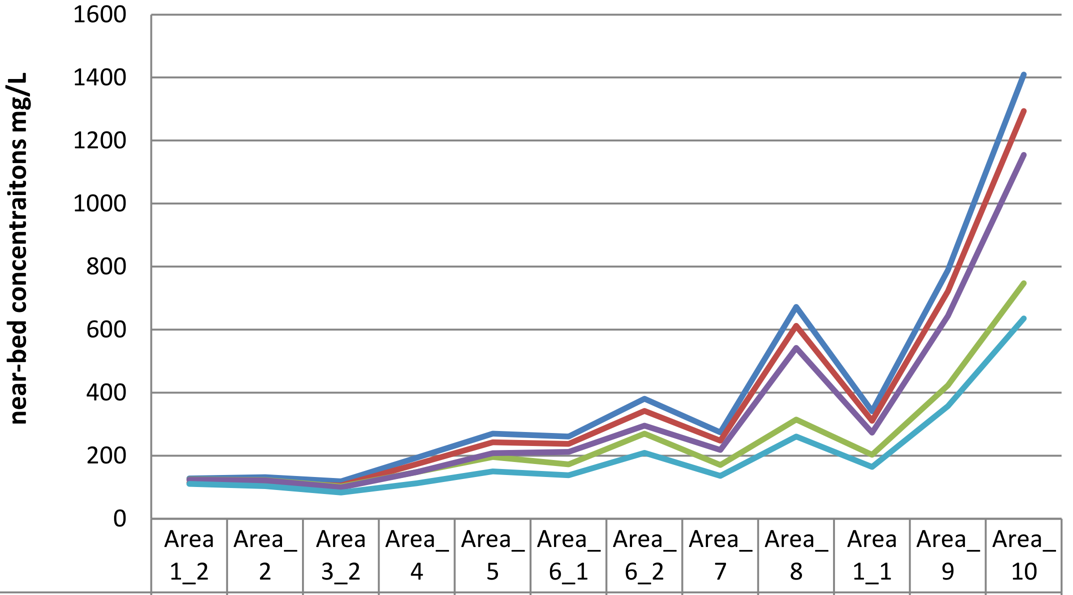
Port	Estimated	baseline	Alt. 1	Alt. 2	Alt. 3	Alt. 4
Eemshaven	0.5	0.46	0.40	0.41	0.41	0.34
Delfzijl	0.8	0.82	0.74	0.51	0.65	0.40
Emden area	1.6	0.59	0.53	0.34	0.47	0.27

5.2.3 Average SPM concentrations per area

Extraction from all three ports has the greatest influence relative to the baseline on the areas in the inner part of the Ems Estuary (from Area 5 inward – see Figure 5.7). The next greatest effect is extraction from Delfzijl. Extraction from Eemshaven and Emden has a lesser influence in the inner estuary which can be related to the location of the disposal grounds near the mouth at D1 and D3 (Figure 5.2).



	Area 1_2	Area_2	Area 3_2	Area_4	Area_5	Area_6_1	Area_6_2	Area_7	Area_8	Area 1_1	Area_9	Area_10
reference	61	54	55	86	80	27	92	112	177	108	206	246
Alt. 1	54	48	49	77	72	24	84	102	162	94	190	228
Alt. 2	59	51	48	67	58	19	65	71	90	65	117	140
Alt. 3	59	50	46	67	62	22	74	90	145	84	172	206
Alt. 4	53	44	39	52	44	15	51	57	75	53	100	121



	Area 1_2	Area_2	Area 3_2	Area_4	Area_5	Area_6_1	Area_6_2	Area_7	Area_8	Area 1_1	Area_9	Area_10
reference	128	132	118	194	270	261	380	274	672	341	789	1410
Alt. 1	114	114	105	173	242	237	342	248	613	310	722	1294
Alt. 2	124	123	103	148	196	172	270	170	315	203	424	748
Alt. 3	124	121	99	148	208	211	295	218	542	273	644	1155
Alt. 4	111	103	83	112	150	138	208	136	261	164	357	636

Figure 5.7 Surface (upper panel) and near bed (bottom panel) suspended sediment concentrations for the studied alternatives and the baseline model. Concentrations are yearly averaged values, and spatially averaged per area. Alt1 is extraction from Eemshaven, Alt2 is extraction from Delfzijl, Alt3 is extraction from Emden, and Alt4 is extraction from all ports. See Figure 5.2 for area definition.

5.3 Model applicability

Extraction means that sediment that used to be disposed of at various locations within and just outside the estuary is now disposed on land and therefore completely removed from the system. The applicability of the model to reproduce the effect of extraction on estuarine turbidity levels and port siltation rates is mainly determined by the accuracy at which the baseline model reproduces port siltation (Chapter 2).

The baseline model reproduces siltation in the ports of Eemshaven and Delfzijl because the suspended sediment concentration is reproduced by the model (see Chapter 2). Therefore, the physics governing siltation in these ports is sufficiently represented by the model. However, the model strongly underestimates deposition rates in the Emden area: 0.6 million tons/year in the model against observations of 1.6 million tons/year (see also report 5 and chapter 2). This is related to the complex and poorly understood sediment transport processes in the port of Emden.

In reality, 80 to 90% of the sediment depositing in the ports of Delfzijl is not removed and disposed offshore, but is resuspended using water injection dredging. In the baseline model however, *all* sediment in these 2 ports is removed and released on their disposal grounds to compensate for the underestimation of deposition rates in Emden. By removing and releasing all sediment from these 2 ports, the *total amount* of dredged and disposed sediment in the baseline model realistically represents the actual total amount of dredging and dumping from the three ports. In the model, the amount of sediment dredged and disposed from Delfzijl is therefore:

(1) Disposed further away from the port: in reality a large amount of the sediment leaves the port at its entrance whereas in the model sediment is disposed several kilometre south, in the Dollard.
(2) Much larger in a relative sense compared to Emden. In the model, more sediment is dredged and dispersed from Delfzijl than from Emden. In reality, the amount of sediment dredged from the Emden area, and disposed in the Ems Estuary, is 4-5 times larger than the amount of sediment from Delfzijl.

Extraction of sediment from the Emden area results in very similar patterns in turbidity reduction compared to extraction from Delfzijl (although the effect of Delfzijl on the Dollard is stronger). Therefore the model shortcomings explained above (that more sediment is dredged from Delfzijl than from Emden) has little effect on the total reduction in suspended sediment (using all three ports). As a consequence, the overall effect of extracting sediment from all ports on the total turbidity reduction in the estuary is realistic. However, as already discussed in the previous chapter as well, the model can be considered a good model to reproduce suspended sediment concentrations and port siltation, but model uncertainties on siltation in Emden remain.

It should be realised that the effect of *extracting* sediment from the ports is not the same as the effect of *dredging and disposal* (which is the current practice). Previous studies (report 7) suggest that the effect of dredging and disposal from the ports is mainly a local redistribution of SSC, and not so much an increase of average SSC levels (compared to an estuary without ports).

The model is in dynamic equilibrium, which means that the sediment concentration for consecutive years is, for each individual model scenario (see text box in section 2.3). In contrast with the previous chapter, there are sinks in the model through extraction from the ports. This residual transport is generated by the model by the lower suspended sediment concentrations leaving the model domain (the incoming sediment concentration is user-defined). For already very small changed in suspended sediment concentrations, the residual transport over the model boundary will already change. That such a change near outflow boundaries exists, is demonstrated by Figure 5.3 toFigure 5.6.

5.4 Conclusions

The main conclusions based on the model scenario simulations are:

- The reduction in suspended sediment concentration in the estuary as a result of extraction from the three ports individually and all ports combined is largest in the areas where the dredged sediment is presently disposed.
- Extraction of sediment from the Eemshaven has the largest effect in the Wadden Sea (> 100 mg/l near-surface on an annual basis in the vicinity of the disposal grounds).
- Extraction of sediment from Delfzijl has the largest effect in the Dollard (> 100 mg/l reduction in near-surface SSC, on an annual basis over the entire Dollard basin).
- Extraction of sediment from Emden area has a more uniform effect over the whole estuary. Additionally, the actual effect of this sediment extraction is expected to be larger in reality as siltation in the port and fairways is underestimated in the baseline model.
- When extraction occurs from all three ports simultaneously the relative reduction in surface suspended sediment concentrations compared to the baseline model (present-day conditions) is > 50%.
- There is an increasing up-estuary reduction in surface and near bed sediment concentrations for all scenarios as the amount of sediment in the system available for redistribution is reduced.
- The large computed effect of seaward disposal of dredged sediment does not imply that the current practice of dredging and disposal leads to a large increase in SSC relative to an estuary without ports.

6 Adaptive poldering of the Dollard to increase sedimentation

6.1 Scenario definition

This scenario is to have adaptive poldering of the Dollard (i.e. opening up an existing polder, creating new intertidal areas), creating a sediment sink and thus increasing sedimentation. This type of scenario may occur if in the future the estuary is extended to create new nature areas (as in Figure 6.1). It also partly represents the past situation, when before 1860, the intertidal area of the Ems Estuary was substantially larger than at present and the Dollard was about twice as large (report 3).

A man-made intertidal area of 10 km^2 (roughly corresponding to the intertidal area in Figure 6.1) which is flooded twice daily by tides with range of 2 m, and with water carrying 0.25 kg/m^3 of sediment in suspension, receives a daily sediment flux of 20 x 10^6 m^2 x 2 m x 0.25 kg/m^3 or 10 million kg. This is equivalent to 3.6 million tons/year. If this man-made intertidal area is an effective sediment trap (which it will be shortly after construction, if not exposed to incoming waves), then about half of the sediment flux would probably deposit (i.e. 1.8 million tons/year). With such extraction rates, the impact on SSC would be comparable to the extraction scenarios in the previous chapter.

Figure 6.1 Illustration of stepwise sediment infilling in man-made intertidal areas along the Dollard, from Braaksma (2012). Newly created intertidal areas (left) fill up with sediment, leading to near-complete infilling after a certain number of years. When sufficiently filled up with sediments, a new intertidal area is created (right). The intertidal area at the left is shown within the orange oval at right. (This is for illustration only and is not simulated in the model scenario).

The preferred method to compute the effect of this scenario would be to extend the domain of the numerical model and fully implement the intertidal area in the model bathymetry. In this way, the water flux, the sediment flux and the sediment trapping efficiency of the Dollard are enlarged. However, such a model modification requires more time than is available within the scope of this project. Therefore, an alternative and simpler method was chosen.

To apply the model to simulate the process of new intertidal areas trapping sediment without making large modifications to the model grid and set-up, a simpler approach was adopted. This model scenario is meant to be illustrative of how a new intertidal area could contribute to sediment trapping and reduction of concentrations in the estuary. All sediment that is deposited on the bed in a defined area within the Dollard is extracted instantaneously (every computational time-step), and removed from the computational domain, as summarized in Table 6.1. The area for sediment trapping in this model scenario is shown in red in Figure 6.2 and was chosen by examining the bathymetry of the Dollard area.

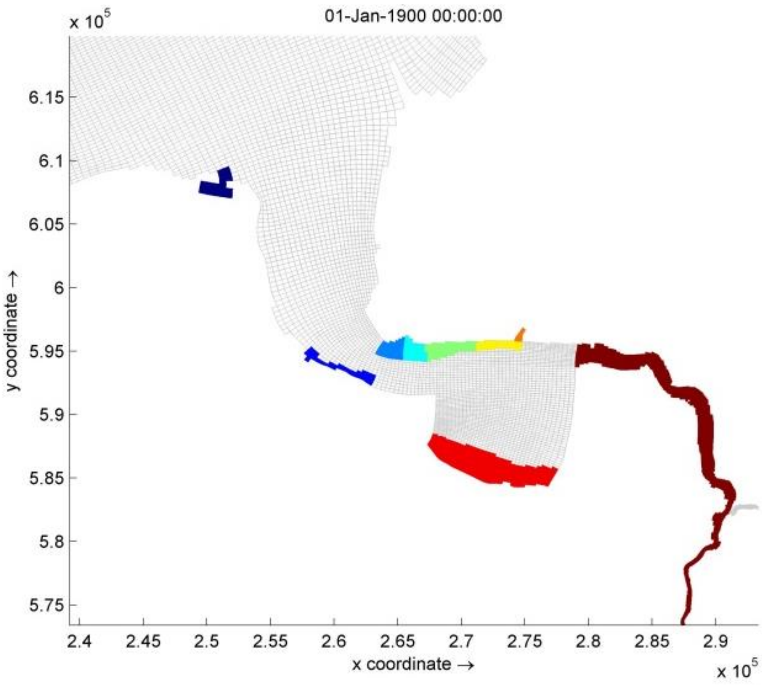


Figure 6.2 The area tested in the adaptive poldering alternative (in red): The other colours are the sediment dredging areas (in the 2012 baseline model). The standard sediment dredging areas used for the baseline model are shown on the right, with each area having a different colour.

Table 6.1 Dollard sediment extraction alternatives for the scenario 'Adaptive poldering'

Alternative	Ports	Extraction	Bathymetry	Frequency of dredging
Baseline	Yes	No	2005	weekly
Alt 1	Yes	Yes	2005	every minute

6.2 Results

6.2.1 SPM fields

The amount of sediment extracted from the Dollard in this defined area is 0.12 million tons/year. This is the amount of sediment that was deposited on the bed in the defined 'inter-tidal' (sediment trapping) area. The computed reduction in surface suspended sediment as a result of sediment extraction is low (reduction ~10 mg/l near-surface, with no effects seaward of Eemshaven; see Figure 6.3). The near-bed concentrations show a larger difference ~100 mg/L in the Dollard with lesser effects throughout the rest of the estuary (see Figure 6.4).

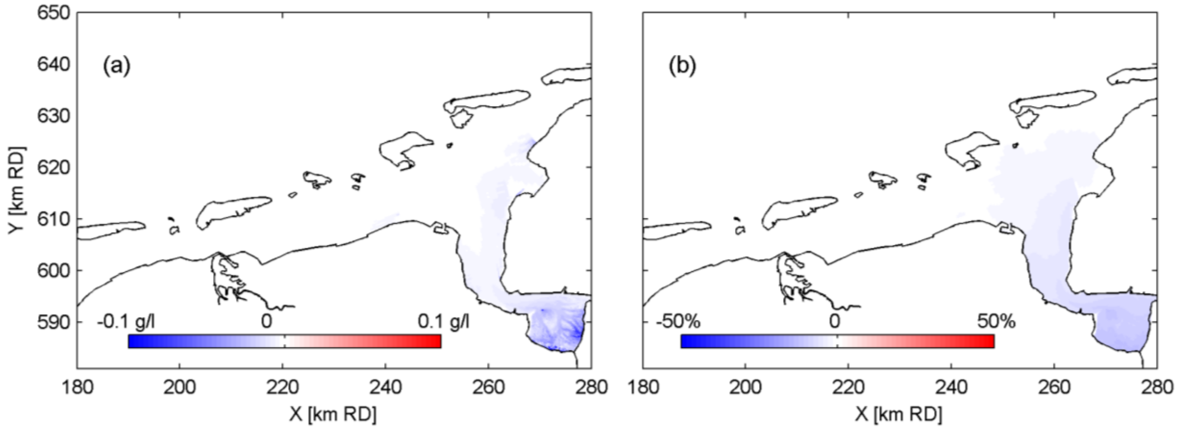


Figure 6.3 Absolute (a, in g/) and relative (b, in %) difference in yearly averaged near surface suspended sediment concentration relative to the baseline scenario for sediment extraction Alt 1 (Alt1 -baseline)

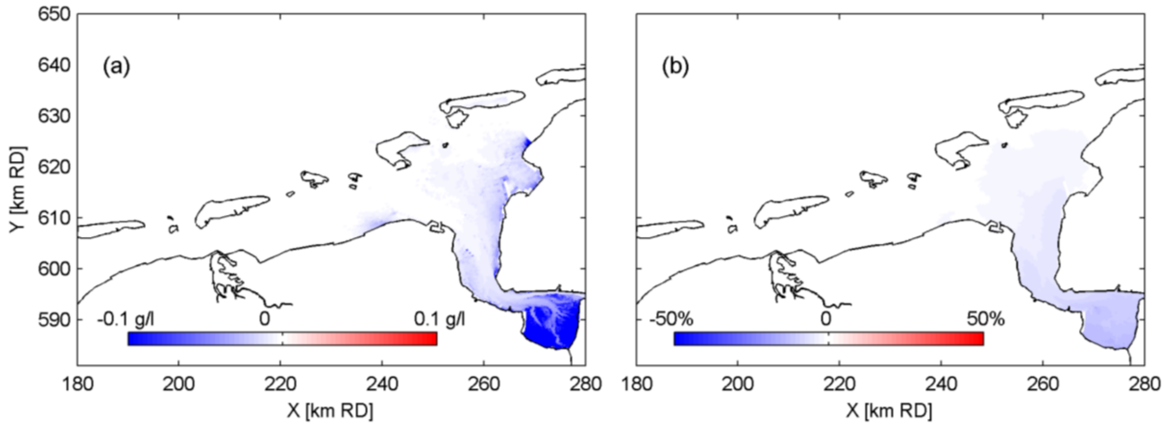


Figure 6.4 Absolute (a, in g/) and relative (b, in %) difference in yearly averaged near bed suspended sediment concentration relative to the baseline scenario for sediment extraction Alt 1 (Alt1 -baseline)

6.2.2 Port siltation

As was shown in the previous section, the largest effect of these extraction scenarios is in the Dollard itself, but this is limited to a decrease of ~10% relative to the baseline. The reduction in suspended sediment concentrations throughout the rest of the estuary is less. This result is also reflected in the fluxes into the ports where changes < 15 % occur (Table 6.2). Therefore, extracting sediment from the Dollard in the way executed here influences the sediment concentrations in the Dollard itself, but does not lead to much lower port siltation rates. This conclusion may be the result of the numerical implementation, which will be evaluated in section 6.3.

Table 6.2 Sediment fluxes (in million tons/year), estimated from dredging requirements, and computed for the baseline simulation and the 'adaptive poldering' scenario

Port	Estimated	baseline	Alt. 1
Eemshaven	0.5	0.46	0.45
Delfzijl	0.8	0.82	0.71
Emden area	1.6	0.59	0.53

6.2.3 Average SPM concentrations per area

The largest effect, though relatively small, of sediment extraction can be seen in and around the Dollard itself. Sediment dredged from the Dollard in the baseline run used to be disposed in D2 (Figure 6.5) in Area 8, which no longer occurs in the extraction scenario. Sediment dredged from the Port of Delfzijl is still disposed in D2 (albeit 10% lower than in the baseline simulation, see Table 6.2).

The range of differences in near bed suspended sediment concentrations are between 1 and 179 mg/L for the extraction scenario, with the largest differences occurring in Area 10 (Figure 6.6). This is in line with expectations, because sediment is extracted from area 10. Near the water surface, the predicted effect is a reduction in SSC of 28 mg/l. The maximum reduction is at the landward end of the Dollard.

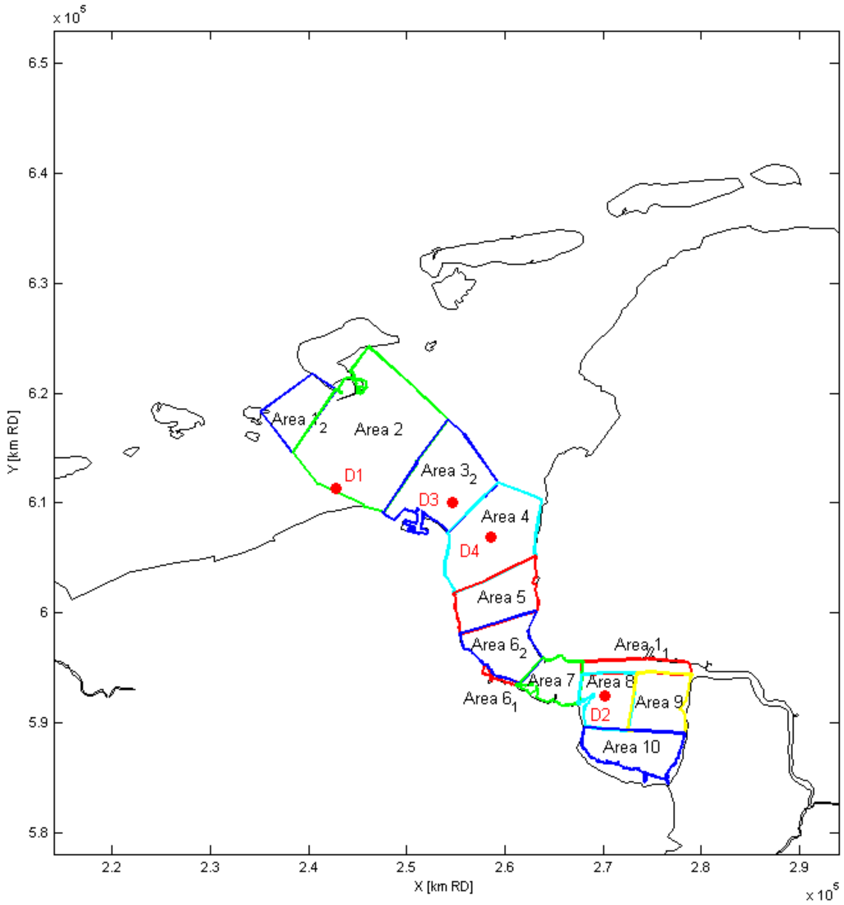
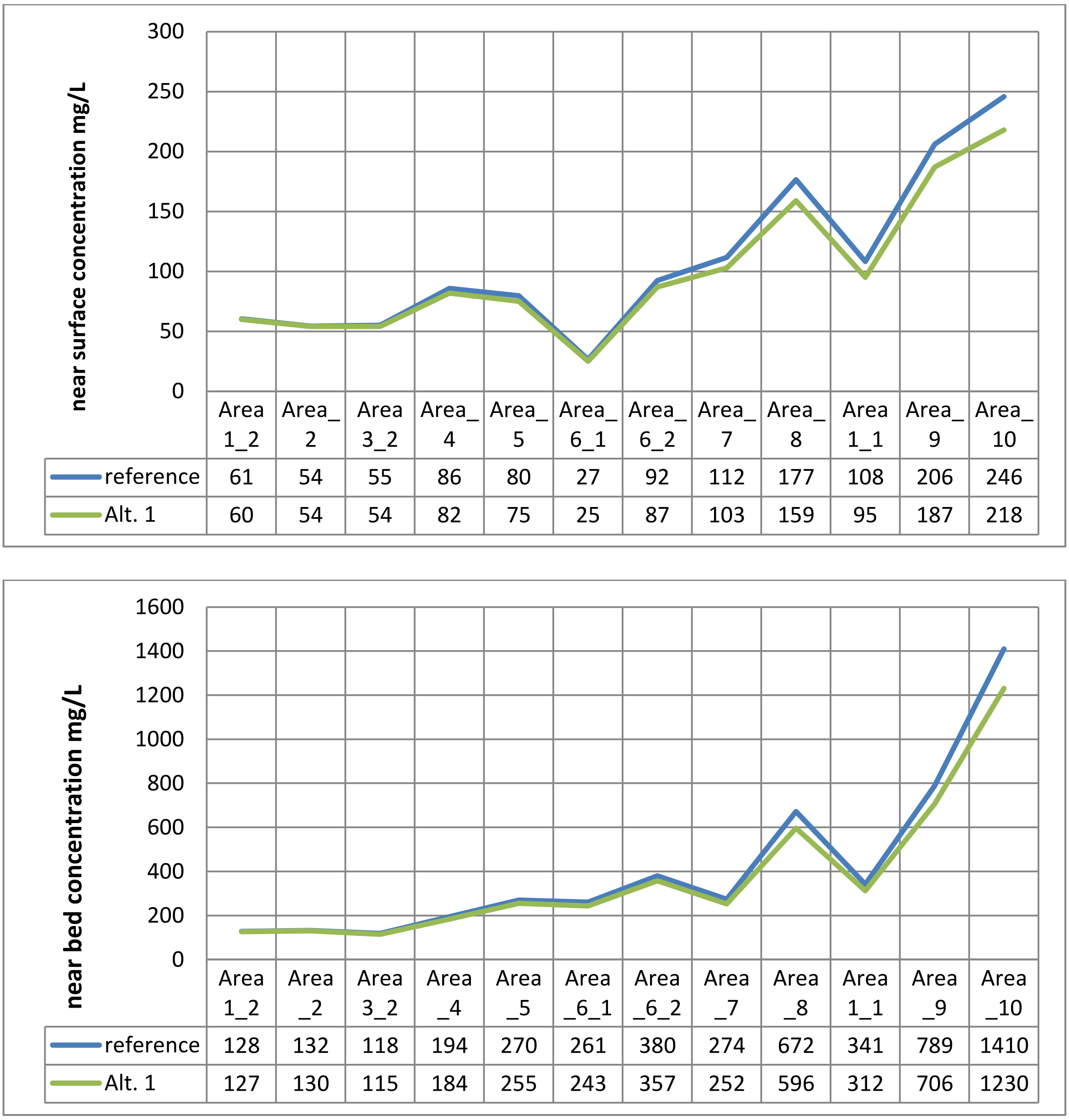


Figure 6.5 Definition of areas used to spatially average the suspended sediment concentration and existing disposal locations (D1-D4, in red). In the baseline scenario, sediment from Eemshaven is disposed in D1, sediment from the Port of Delfzijl and the Dollard is disposed in D2, sediment from the Emden area is disposed in D3 and D4.



	Area 1_2	Area_2	Area 3_2	Area_4	Area_5	Area_6_1	Area_6_2	Area_7	Area_8	Area 1_1	Area_9	Area_10
reference	61	54	55	86	80	27	92	112	177	108	206	246
Alt. 1	60	54	54	82	75	25	87	103	159	95	187	218

	Area 1_2	Area _2	Area 3_2	Area _4	Area _5	Area _6_1	Area _6_2	Area _7	Area _8	Area 1_1	Area _9	Area _10
reference	128	132	118	194	270	261	380	274	672	341	789	1410
Alt. 1	127	130	115	184	255	243	357	252	596	312	706	1230

Figure 6.6 Surface (upper panel) and near bed (bottom panel) suspended sediment concentrations for the studied alternative and the baseline model. Concentrations are yearly averaged values, and spatially averaged per area. The areas progress up estuary.

6.3 Model applicability

The scenario presented in this chapter, the creation of new intertidal area, is not one that can be easily implemented in the model. An additional sediment sink in the Dollard was implemented in the model in a simplified way, in which sediment was removed from a defined area in the Dollard as soon as it accumulated so the model bed always remained empty. To what extent this model scenario represents a realistic sediment sink, depends on the quantities. For the purpose of model applicability, the representation of the sink is the main discussion point.

Using the same methodology as in section 6.1, the extracted amount of sediment can be related to the size of an intertidal area assuming a trapping efficiency, tidal range, and sediment concentration. The simulated extraction (0.12 million tons/year, see section 6.2.1). then corresponds to an intertidal area of 0.5 to 1 km^2. Therefore the estimated impact of a man-made intertidal area such as in Figure 6.1 will be much larger, with annual sediment deposition rates of probably one to several million ton/year.

The effectiveness of a sediment sink decreases in time. The shape of the intertidal area evolves towards equilibrium conditions which lead to lower net sedimentation rates. The average vertical accretion rate in the man-made intertidal area described in section 6.1 (with a size of10 km^2 and a sediment influx of 1.8 million tons/year) is 36 cm/year (dry density of 500 kg/m^3, typical for relatively fresh mud deposits). Such an intertidal area will therefore silt up rapidly. The effect will then be of short duration (depending on the initial depth), but without removal of mud deposits typically 5-10 years (5 to 10 times 0.36 m/year is 1.8 to 3.6 m, which is a typical initial depth).

The amount of siltation in such an intertidal area increases with area size, because the tidal volume (and hence the sediment flux) increases almost linearly with the size of the area. In most of the intertidal area, the siltation rates in a large area will be comparable with a small area. In a large intertidal area, tidal channels will develop with fairly high flow velocities, where siltation does not take place. Hence, a large intertidal area may be slightly less effective than a small intertidal area. On the other hand, a large intertidal area has a larger residence time and may therefore be a more effective sediment trap. Determining the efficiency of such sediment intertidal areas (and therefore siltation rates and period of infilling) requires further research. The larger the intertidal area available for siltation, the larger the reduction of SSC in the Ems estuary will be, because the sediment transport towards the intertidal area increases with tidal volume (and hence size of the area).

Although it can be debated how the area size influences sediment extraction rates and how the size determines the extraction masses, the simulation does provide information on the down-estuary effects of extraction and extending the floodplains. The reduction in suspended sediment concentration remains largely confined to the Dollard: the most seaward area substantially influenced (>5% reduction near the bed) is area 6_1 (close to Delfzijl). Although this confinement is partly related to the low extraction rate, it does suggest that extraction from the Dollard has a more local impact than the scenarios considered earlier (chapters 4-5). It should also be borne in mind that in reality this sediment sink will also be a source of sediment resuspension at times (e.g. during storms), which may then be redistributed throughout the Dollard.

6.4 Conclusions

- Creating a large intertidal area (such as in Figure 6.1) will probably be lead to a large extraction of sediment from the system, and therefore to a large reduction in suspended sediment concentration. Such a large polder could not be modelled within the scope of the project.
- Modelling a much smaller sediment sink in the Dollard, the suspended sediment concentrations in the Dollard and surrounding estuary were reduced up to several 10 mg/l near the surface and over 100 mg/l near the bed.
- The reduction in suspended sediment concentrations throughout the rest of the estuary is less (decrease of ~10% relative to the baseline).
- Therefore only minor changes occur in the fluxes into the ports.

- These scenarios show what part of the Ems estuary is impacted by a relatively small sediment extraction in the Dollard (like extending the floodplain area) and how that impacts the suspended sediment dynamics in the Ems Estuary.
- The amount of sediment extracted in this model scenario corresponds to a polder of about 0.5 – 1 km^2, trapping sediment for a period of 5 to 10 years. For relatively small polders (several km^2), sediment extraction rates will probably increase nearly linear with area size. The suspended sediment concentrations will decrease, but not linearly as with the sediment sink, and can also not be predicted straightforwardly.
- Determining siltation rates and consequently infilling times of larger polders would require larger modifications to the existing model.

7 Restoration of channel depth

7.1 Scenario definition

This scenario is to restore the channels of the Oost Friesche Gaatje, Doekegat, and Emden fairway towards their original depths of 1949.

Since 1949, the tidal channels in the Ems Estuary have been deepened to provide access to the various ports in the Ems Estuary (see Figure 5.1). There are strong indications that deepening of the access channels to the ports have led to more import of fine sediments, and therefore a larger turbidity (report 7). The aim of this chapter is to determine the potential impact of shallower tidal channels on the turbidity of the Ems Estuary.

First, a brief overview is given of the main historic morphologic changes in channel depth. Based on this historic analysis, three alternatives are defined which, in strongly simplified form, represent a raising of the bed topography to previous bed levels.

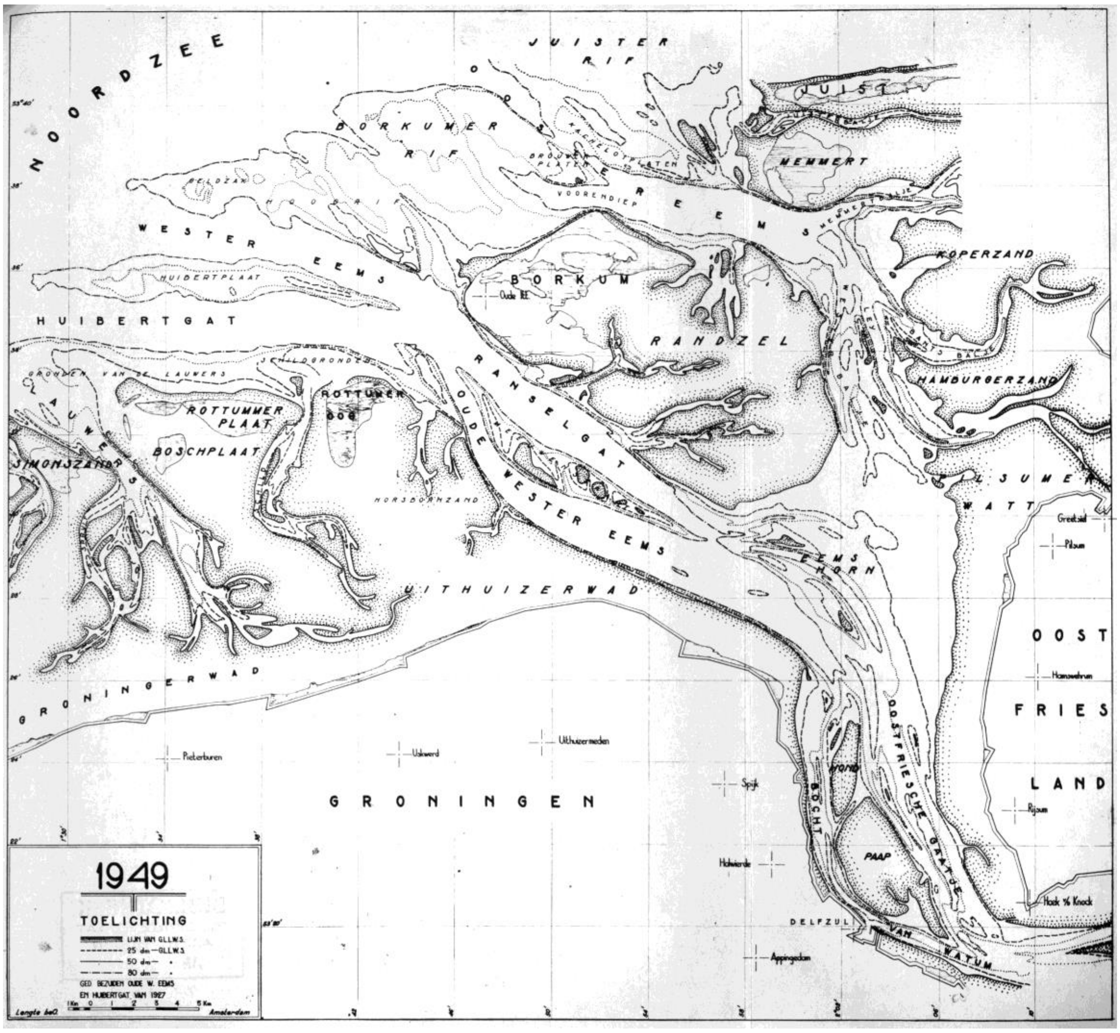


Figure 7.1 Map of the Ems Estuary, from Gerritsen (1952). Depth contours are in GLLWS, which is 2.03 m below NAP.

In 1949, the depth of the Oost Friesche Gaatje was typically between 7 and 10 m below NAP (see Figure 7.1), and locally deeper than 10 m. The deepest parts of the present-day Oost Friesche Gaatje (Figure 7.2) are below -15 m NAP, whereas the sill connecting the Oost Friesche Gaatje with the oude Wester Eems / Ranselgat is typically 12 m below NAP. These bathymetric changes (from 1949 to present) are caused by:

- Morphodynamic processes. The Oost Friesche Gaatje has become more dominant compared to the Bocht van Watum;
- Dredging for ship access. The shallowest sections of tidal channels are typically sills, which block navigation. The sills are therefore dredged for navigation purposes; and
- Sand mining. Sand was and still is mined from the Ems Estuary. Probably, the irregular, shallow sections in the Oost Friesche Gaatje are the result of sand mining.

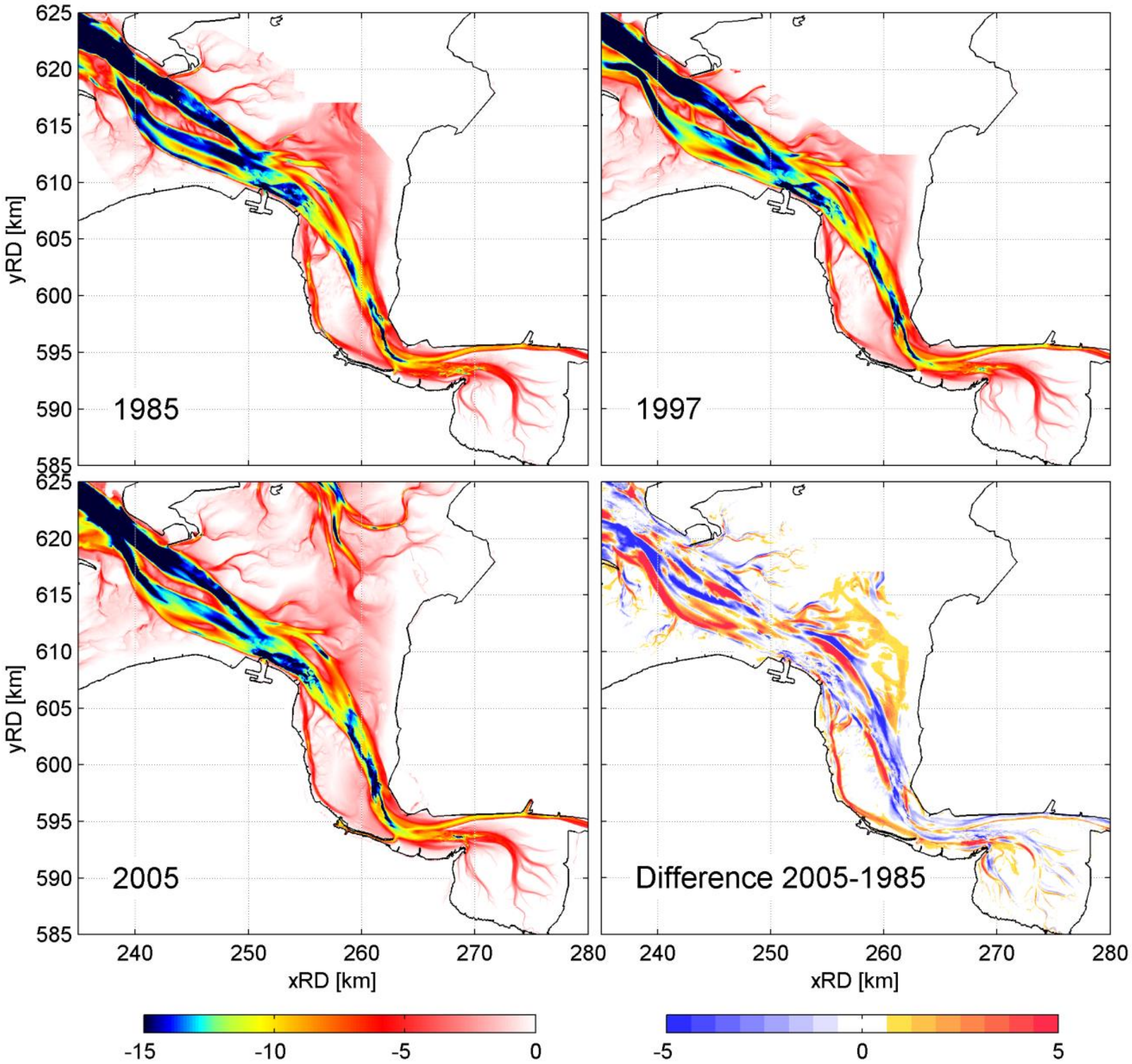


Figure 7.2 Bathymetry of the Ems Estuary (in meters) in 1985, 1997 and 2005. Scale on left is absolute depth relative to NAP. Scale on right is the difference between 2005-1985.

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 as a result of channel deepening. Channel deepening affects the tidal range and estuarine circulation. An increasing tidal range (difference between low water and high water) frequently leads to higher turbidity levels (Uncles, 2002, report 7). Estuarine circulation is a salinity driven circulation pattern with up-estuary directed residual currents near the bed and down-estuary directed residual currents near the surface. The sediment concentration is higher near the bed, and therefore estuarine circulation may generate up-estuary residual sediment transport.

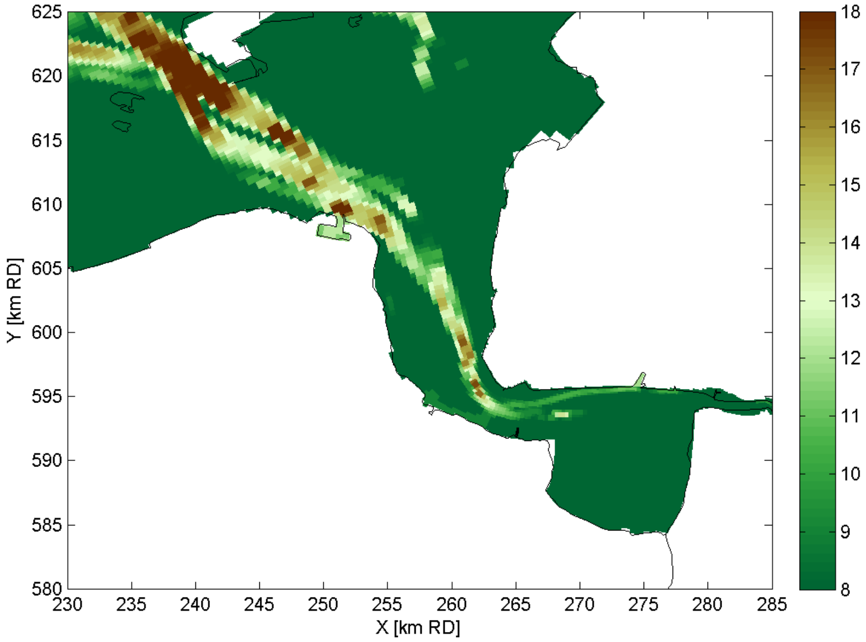


Figure 7.3 Depth of the baseline model in 2005 (in meters)

Three bathymetric alternatives are defined which represent a stepwise re-adjustment of different parts of the Oost Friesche Gaatje, Doekegat, and Emden fairway towards the depth of that part of the estuary around 1949.

It is expected that shallowing of the channels will reduce this estuarine circulation and decrease the tidal range, and consequently lead to lower suspended sediment concentrations in the estuary. Three alternatives were defined to simulate the effect of channel restoration (shallowing) on suspended sediment concentrations (summarised in Table 7.1 below).

- The first scenario (Alt 1, Figure 7.4) is a rise of the bed level (shallowing) in the area which experiences the larges siltation rates (the Emden Navigation channel). Before large-scale engineering works started, the depth of this channel was probably around 8 m below NAP.
- The second scenario (Alt 2, Figure 7.5) is a rise of the bed levels (shallowing) on the sills where tidal channels connect. This is where most sediment was removed during the initial deepening, and where maintenance dredging is required.
- The third scenario (Alt 3, Figure 7.6) is a combination of Alt1 and Alt 2.

Table 7.1 Channel restoration alternatives

Alternative	Ports	Extraction	Bathymetry
Baseline (Figure 7.3)	Yes	No	2005
Alt 1 (Figure 7.4)	Yes	No	2005 + raising of the bed level in the Emden Navigation channel to -8 m
Alt 2 (Figure 7.5)	Yes	No	2005 + raising of the bed level in the Oost Friesche Gaatje with 1 m and in the Doekegat with 2m
Alt 3 (Figure 7.6)	Yes	No	2005 + raising of the in bed level in the Emden Navigation channel to -8 m and shallowing in the Oost Friesche Gaatje by 1 m and in the Doekegat by 2 m

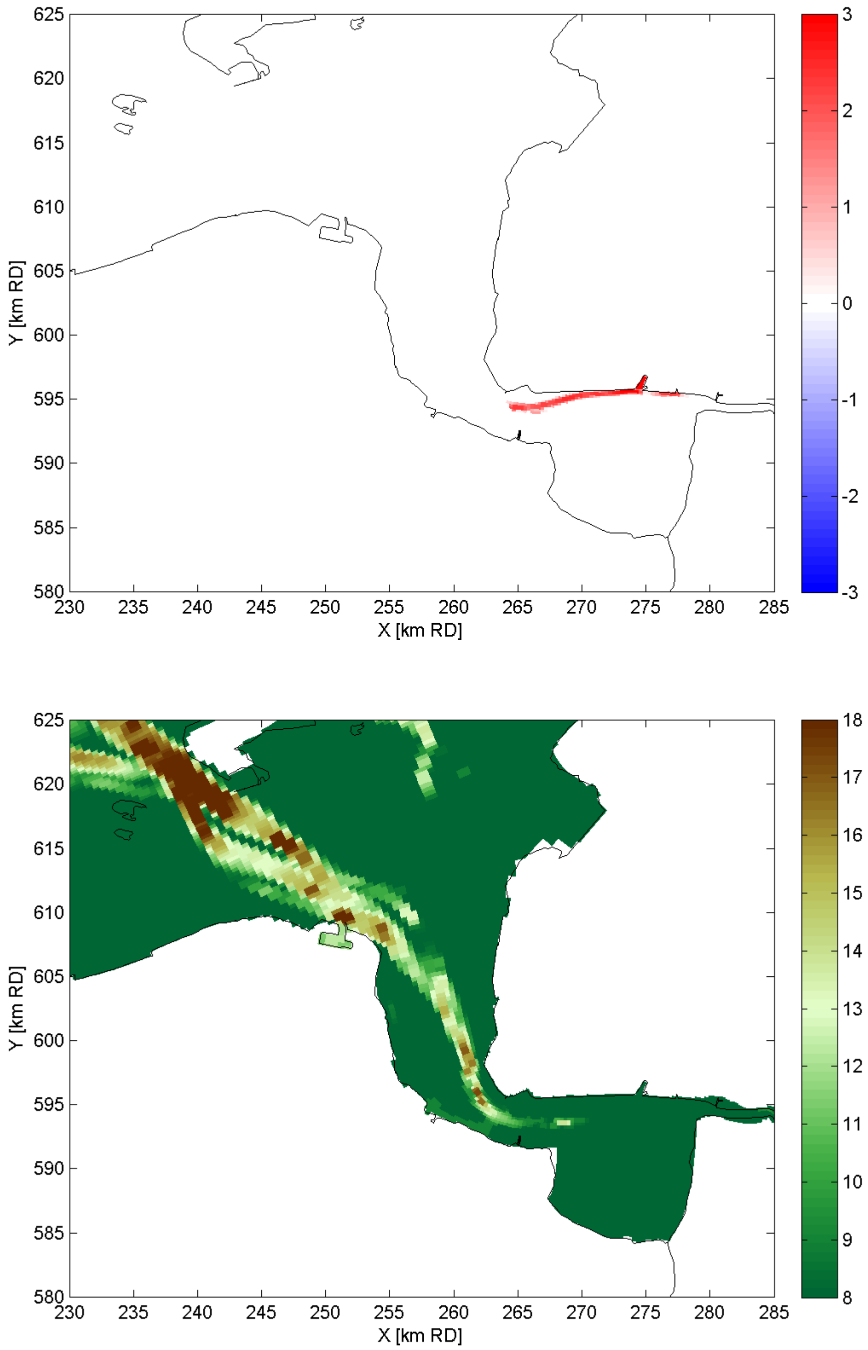


Figure 7.4 Raising of the bed level in the Emden Navigation channel to -8 m: difference compared to the 2005 bathymetry (top) and resulting bed level (below) –Alt 1. Scales are in meters.

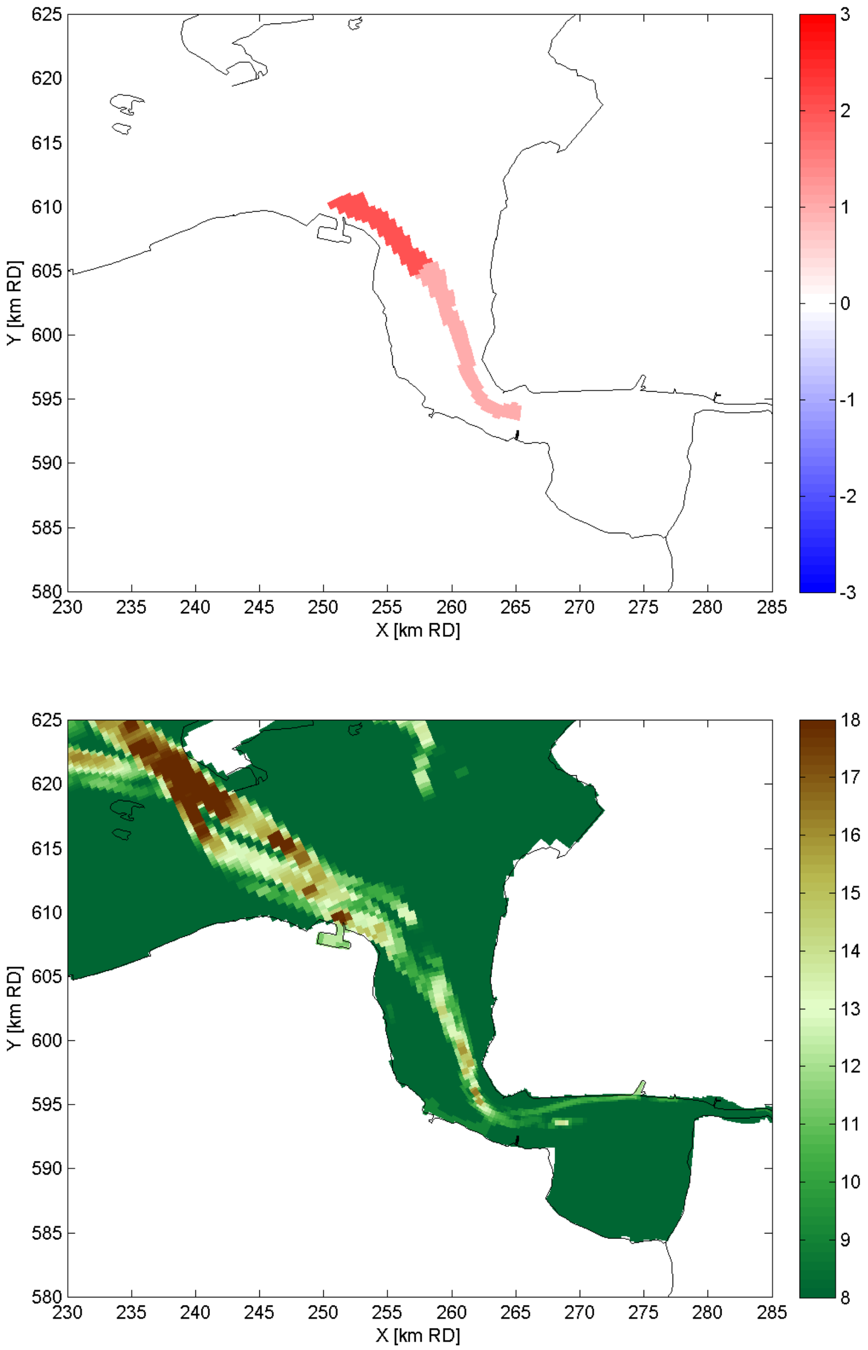
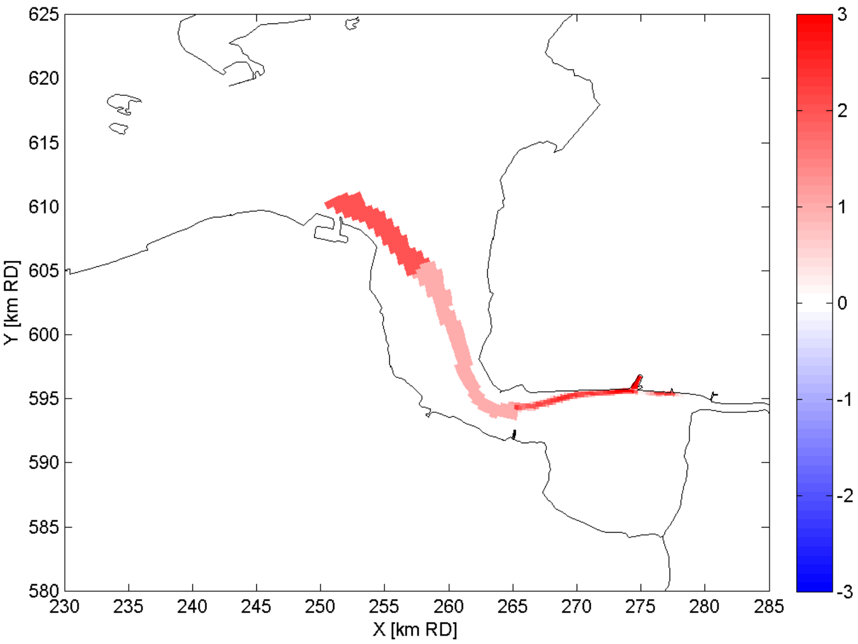


Figure 7.5 Raising of the bed level in the Oost Friesche Gaatje by 1 m and in the Doekegat by 2m: difference compared to the 2005 bathymetry (top) and resulting bed level (below) – Alt 2. Scales are in meters.



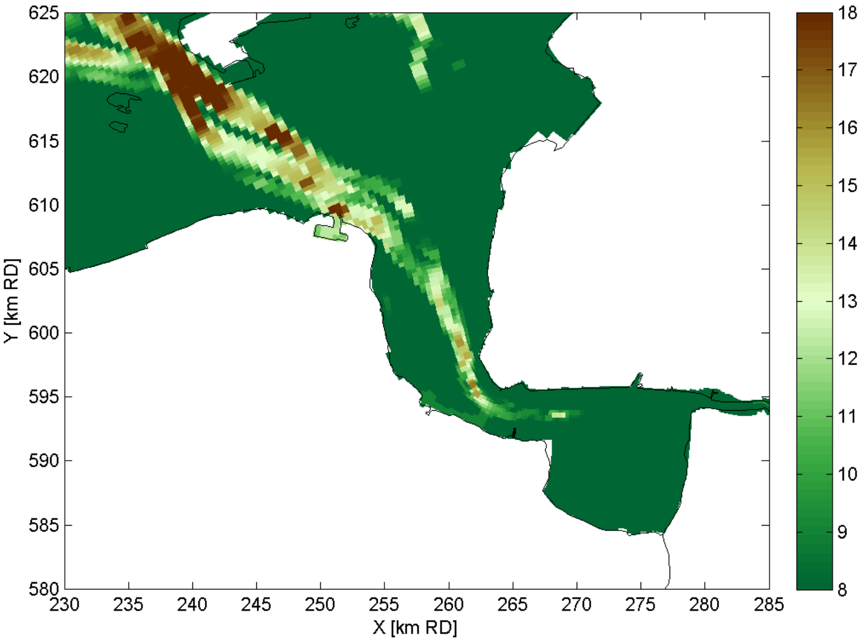


Figure 7.6 Raising of the bed level in the Emden Navigation channel to -8 m and shallowing in the Oost Friesche Gaatje by 1 m and in the Doekegat by 2 m (combination of Figure 7.4 and Figure 7.5): difference compared to the 2005 bathymetry (top) and resulting bed level (below) – Alt 3. Scales are in meters.

7.2 Results

7.2.1 SPM fields

Restoration of the bed level in the Emden Navigation channel to -8 m has minor effects on suspended sediment concentrations (Figure 7.7). Sediment concentrations were reduced in the inner Dollard but increased west of the Oost Friesche Gaatje by ~ 20%.
Raising the bed levels further seaward (1 m in the Oost Friesche Gaatje and 2 m and in the Doekegat) has a more pronounced effect. The suspended sediment concentrations change with 20-30% (Figure 7.8), decreasing the suspended sediment concentrations in the Dollard area but increasing the suspended sediment concentrations in the outer estuary.
The combined effect of both scenarios (Figure 7.9) is dominated by the effect of Alt 2, because the impact of Alt 1 is relatively small.

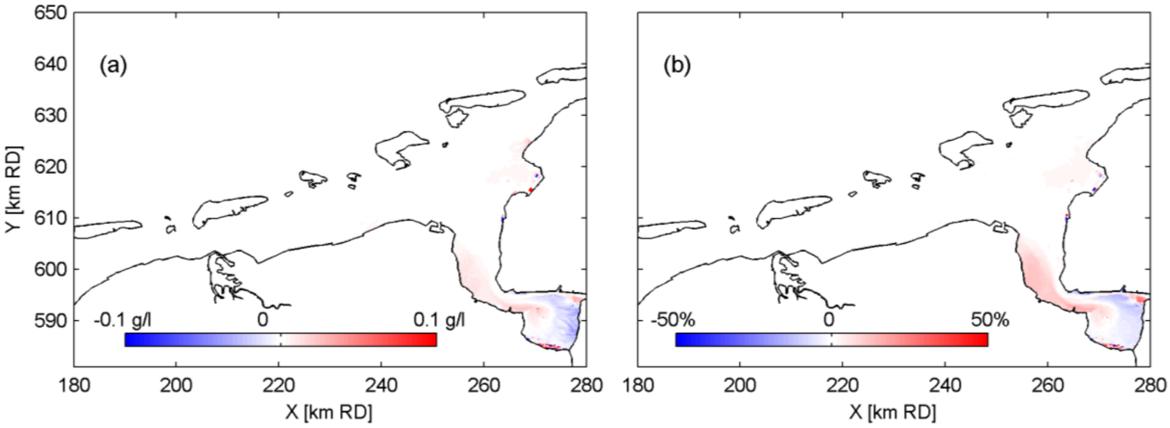


Figure 7.7 Absolute (a, in g/) and relative (b, in %) difference in yearly averaged surface suspended sediment concentration relative to the baseline scenario for channel restoration scenario 1 (Alt1 - baseline)

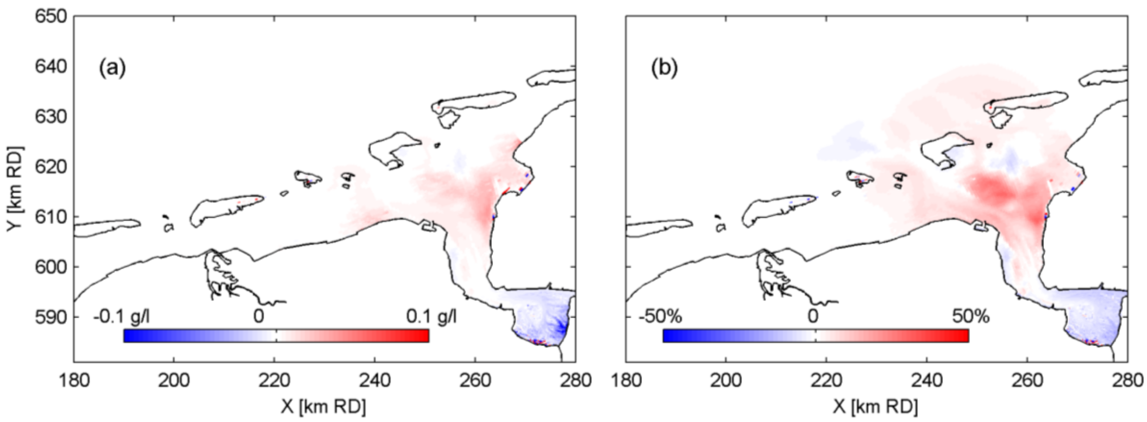


Figure 7.8 Absolute (a, in g/) and relative (b, in %) difference in yearly averaged surface suspended sediment concentration relative to the baseline scenario for channel restoration scenario 2 (Alt2 - baseline)

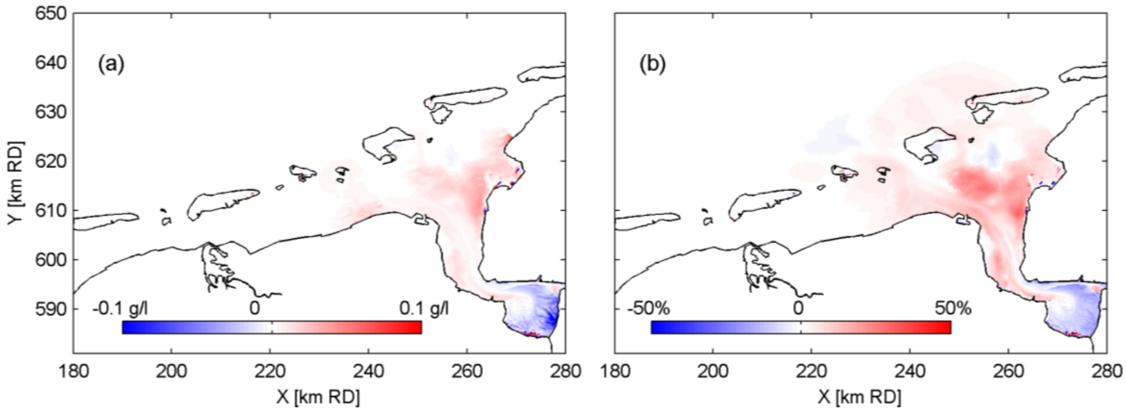


Figure 7.9 Absolute (a, in g/) and relative (b, in %) difference in yearly averaged surface suspended sediment concentration relative to the baseline scenario for channel restoration scenario 3 (Alt3 - baseline)

7.2.2 Port siltation

Shallowing of the Emden Navigation channel (Alt 1) has only minor relative effects on the fluxes into Eemshaven but slightly more effect on Delfzijl where the flux increased (Table 7.2) This increase in port siltation is the direct result of a slight local increase in suspended sediment concentrations (see the previous section). For Alt 1, the suspended sediment concentration increases near Delfzijl (Figure 7.7), and therefore the port siltation increases. Port siltation in Emden area is also strongly reduced (from 0.59 to 0.41 Mt/y). Near Eemshaven, the sediment concentration mainly increases for Alt 2, and therefore port siltation rates increase for this scenario. The largest influence is on the port of Emden and its navigation channel, where the siltation rate is 30% smaller. Combined with shallower channels in the outer estuary, siltation here is 40% smaller. The siltation rates in all three areas combined changes only slightly.

Table 7.2 Sediment fluxes (in million tons/year), estimated from dredging requirements, and computed for the baseline simulation and the channel restoration alternatives

Port	Estimated	baseline	Alt. 1	Alt. 2	Alt. 3
Eemshaven	0.5	0.46	0.46	0.48	0.48
Delfzijl	0.8	0.82	0.92	0.77	0.85
Emden area	1.6	0.59	0.41	0.50	0.36

7.2.3 Average SPM concentrations per area

The change in suspended sediment concentrations (Figure 7.11) per area (see Figure 7.10 for area definition) is less than the spatial patterns (Figure 7.7 to Figure 7.9) suggest. This is because within several of the 12 predefined domains, local increases in suspended sediment concentrations are balanced by local decreases.

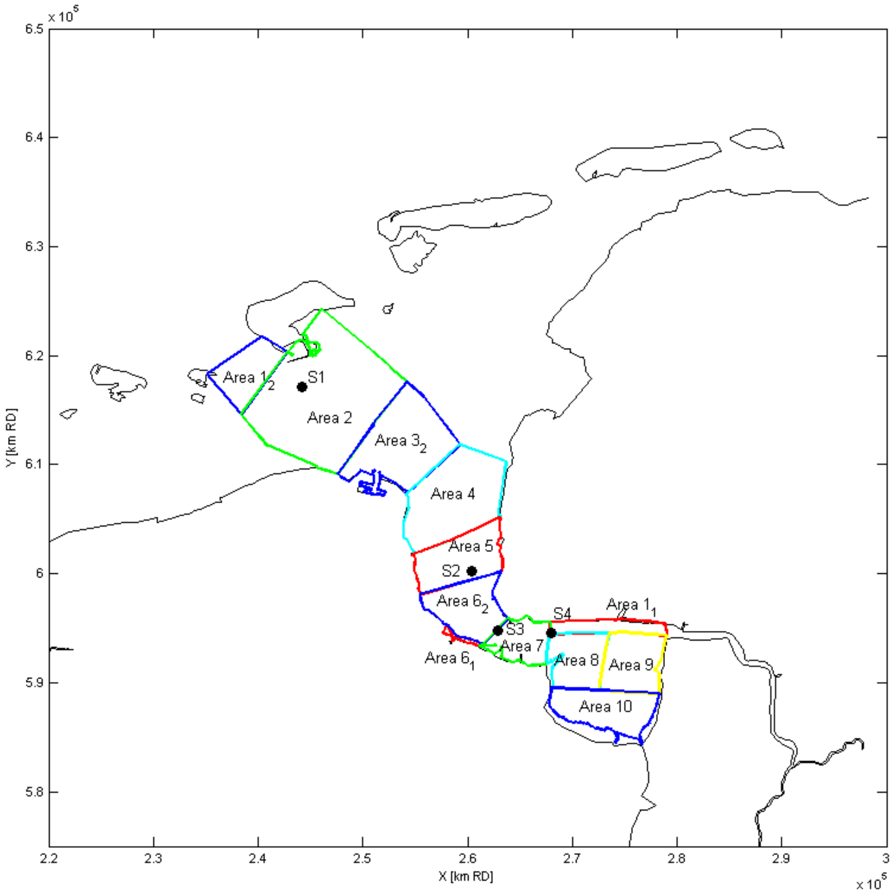
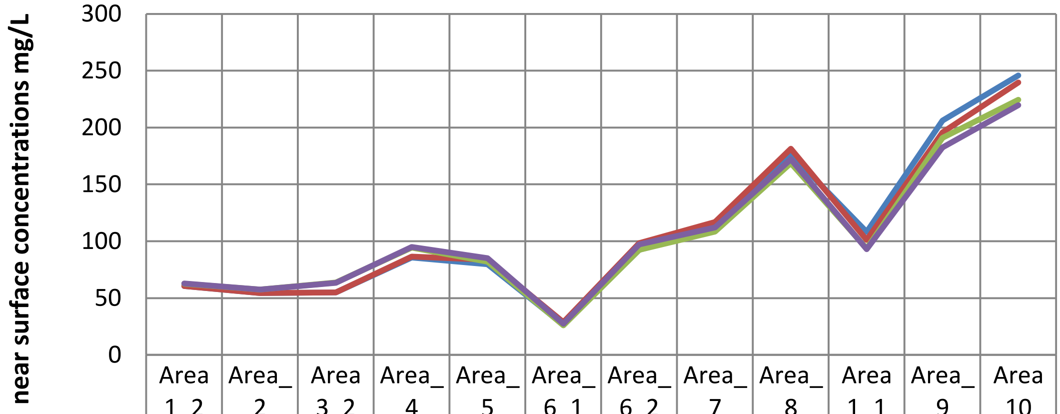


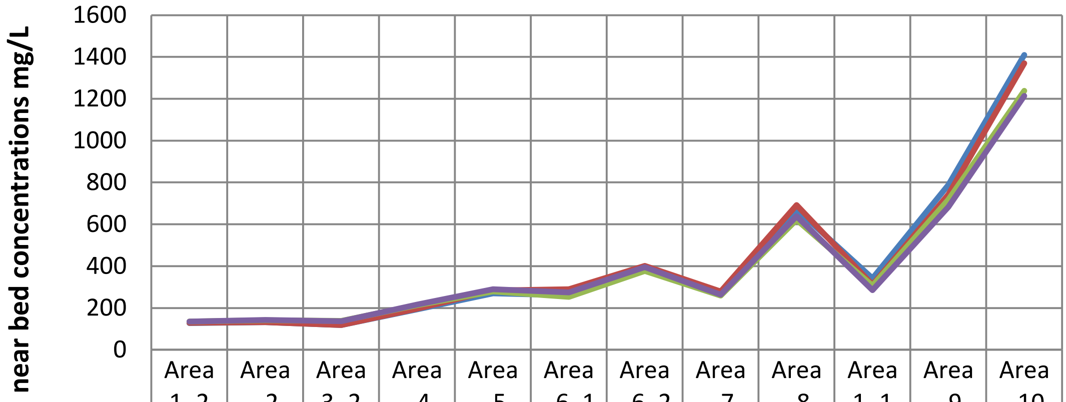
Figure 7.10 Definition of areas used to spatially average the suspended sediment concentration and locations S1-S4 used to the compute residual flow velocity profiles

The reduction in suspended sediment concentration in the Dollard is largest in the most landward area (Area 10). Near the surface, the yearly averaged sediment concentration decreases with 6, 22, and 26 mg/l for Alternatives 1, 2, and 3 (resp.). This is equivalent to 2, 9, and 11% reduction. Near the bed, the absolute decrease is slightly larger because the sediment concentration levels are larger (40, 173, and 197 mg/l) but also the relative decrease is larger (3, 12 and 14% reduction) which is to be expected as the channel is made shallower and so the vertical concentration gradient is also reduced.

Between Area 2 and 6, the sediment concentration increases. The largest absolute increase in suspended sediment concentration is in Area 4: 9 mg/l (near surface) – 22 mg/l (near-bed) for the combined scenario (Alt 3). This is 10-11%. For Alternative 2, the largest increase occurs slightly more seaward (Area 3_2), with an increase of 9 mg/l (near surface) – 20 mg/l (near-bed). In relative terms this is equivalent to an increase in suspended sediment concentrations of 16-17%.



	Area 1_2	Area_2	Area 3_2	Area_4	Area_5	Area_6_1	Area_6_2	Area_7	Area_8	Area 1_1	Area_9	Area 10
reference	61	54	55	86	80	27	92	112	177	108	206	246
Alt. 1	61	55	55	87	84	29	98	117	181	101	196	240
Alt. 2	63	58	64	94	82	26	92	108	169	94	191	224
Alt. 3	63	58	63	95	85	27	97	112	172	93	183	220



	Area 1_2	Area _2	Area 3_2	Area _4	Area _5	Area _6_1	Area _6_2	Area _7	Area _8	Area 1_1	Area _9	Area _10
reference	128	132	118	194	270	261	380	274	672	341	789	1410
Alt. 1	129	133	118	197	284	290	401	278	692	311	742	1370
Alt. 2	135	142	138	213	279	252	378	259	622	306	718	1237
Alt. 3	135	142	137	216	290	275	395	263	639	284	682	1213

Figure 7.11 Surface (upper panel) and near bed (bottom panel) suspended sediment concentrations for the studied alternatives and the baseline model. Concentrations are yearly averaged values, and spatially averaged per area. The areas progress up estuary.

7.3 Model applicability

The computed scenarios quantitatively estimate the response in estuarine suspended sediment concentration on a change in channel depth. How realistic these estimates are, is determined by (1) the accuracy of the computed sediment transport mechanisms, and (2) by the way in which the change in channel depth is modelled,

7.3.1 Modelled processes

Sediment redistribution in the Ems Estuary is determined by a number of processes redistributing sediment or transporting sediment in a preferential direction. Residual transport of sediment can be generated by residual flows, asymmetries in the flow, and by sink and source terms.

Hydrodynamics

Experiments with different bed levels and effect of salinity on suspended sediment transport (report 7) revealed that an important mechanism transporting the sediment up-estuary is estuarine circulation. Estuarine circulation is strongly influenced by the water depth: the strength of the near-bed up-estuary current increases with the water depth cubed h^3 (according to the formulation of Hansen and Rattray, 1965; see also report 7). This depth-dependency is reproduced by the model. In the outer estuary, the estuarine circulation is weakest for alternative 2 (see Figure 7.12). This is in line with the shallower tidal channels in this part of the estuary for that scenario. In Alternative 1 and 3 the navigation channel to the port of Emden was shallower, and as a result the estuarine circulation no longer generates a net up-estuary residual flow near the bed. The effect of the channel depth on the residual flow is therefore in line with expectations.

Sediment transport

The effect of the hydrodynamics on sediment dynamics depends on the accuracy of the sediment transport model. In the outer estuary, observed suspended sediment concentrations are in line with the model output (tidal variation and spring-neap variation in sediment concentrations, vertical variation in the sediment concentration, as well as the along-estuary concentration gradient; see report 4). With the available information the effect of estuarine circulation can therefore be reproduced by the model. Results should be carefully interpreted, because residual transport by estuarine circulation is a small net effect resulting from the difference between 2 large and opposing sediment transports (the ebb and the flood). A small error in either flood or ebb transport leads to a relatively large error in the residual transport. Most of the computed results are, however, intuitive: shallower channels decrease estuarine circulation and therefore up-estuary transport. Shallower channels will therefore lead to a less turbid Dollard.

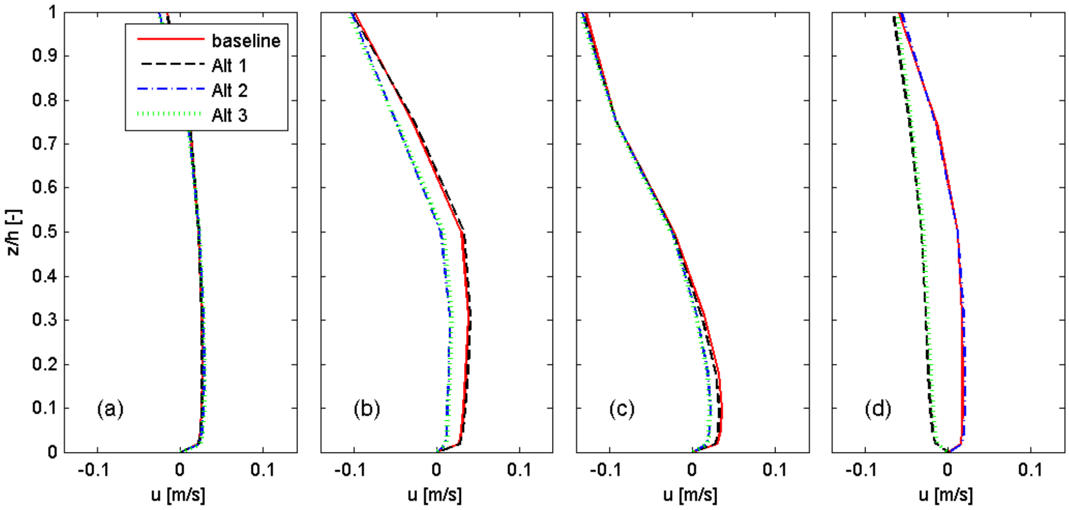


Figure 7.12 Yearly averaged residual flow velocity profiles computed at locations s1 (a), s2 (b), s3 (c), and s4 (d), for the baseline simulation and for Alternatives 1, 2 and 3. Tidal averaging has been done with a dimensionless y-scale (the vertical level z divided by water depth h).

The sediment transport processes in the Emden fairway are not properly represented in the model (see report 5). Therefore the changes in sediment transport processes (port siltation and suspended sediment concentration) computed with alternative 1 (raising the bed level in the Emden Fairway) should be interpreted with care (and especially near Emden for all bed level alternatives). Nevertheless, the hydrodynamic changes do point to an important transition, independent of any shortcomings in the sediment transport model. By raising the bed levels in the Emden fairway, the vertical structure of the currents changes substantially (Figure 7.12d). Historically, the residual flow was outward-directed (alternative 1 and 3), promoting seaward transport of sediment. Upon deepening, the near-bed flow is directed up-estuary (because of estuarine circulation). Such a depth-dependence of residual flow patterns is in line with expectations (Hansen and Rattray, 1965; see also report 7 for details). Since the sediment concentration is generally higher close to the bed, such a residual flow pattern promotes import of sediment. This may be an explanation for the observed historic increase in siltation rates: since the mid-40's the amount of sediment accumulating in the lower Ems River and the Emden fairway is increasing. Although this is partly caused by the deepening of the lower Ems River itself (report 7), the historic deepening of the Emden fairway may have also played an important role.

7.3.2 Implementation of bathymetric changes

The effect of shallower channels on estuarine sediment dynamics not only depends on the representation of sediment transport processes, but also on the implementation. The computed effect of raising the bed in the Doekegat, the Oost Friesche Gaatje, and the Emden fairway (alternative 3) is smaller (<25%) than the effect of the bathymetric changes that have occurred in the Ems Estuary (excluding changes in the lower Ems River) between 1985 and 2005 (up to change in suspended sediment concentration, see e.g. Figure 4.9 in report 7). Even though, the changes in local bed level are more pronounced in each of the three scenarios simulated here than the actual changes that occurred from 1985 to 2005 as a uniform modification was applied over the channel area. Apparently, a local intervention (such as simulated in Alternatives 1 – 3) has a small impact compared to estuary-wide changes (which were simulated in report 7).

7.4 Conclusions

The main conclusions of the scenarios related to restoration of the channels in the Ems estuary are that

- Raising of the bed levels in the Oost Friesche Gaatje and in the Doekegat resulted in spatially varying increases and decreases in suspended sediment concentrations by 20-30% locally.
- Restoration of the bed level in the Emden Navigation channel to -8 m had minor effects on computed suspended sediment concentrations. This may be partly the result of the complex processes in that part of the estuary, which are not all understood (and can therefore not be adequately modelled).
- Results of the different channel restoration scenarios have similar effects on the near-surface concentrations as on the near-bed surface concentrations with a slightly larger effect near-bed in the Dollard.
- Raising the bed levels of the Emden Navigation channel had only minor effects on siltation in the ports of Eemshaven and Delfzijl, but results in a substantial siltation decrease in the port and approach channel of Emden.
- Raising of the bed levels in the Oost Friesche Gaatje and in the Doekegat leads to a slight increase in the sediment fluxes into Eemshaven but to a decrease for Delfzijl and Emden area. Additionally, the fairway changes from sediment importing to exporting.

8 Implications for net primary production

8.1 Introduction

From the scenarios aiming to reduce suspended sediment concentration, two contrasting scenarios (based on the sediment model results) were further analysed with respect to their effect on primary production.These two scenarios were:

1. North Sea sediment disposal (described in Chapter 4 as alternative 2) at Location 6 (see Figure 4.1) and
2. Restoration of channel depth (described in Chapter 7) in the Emden Navigation channel, Oost Friesche Gaatje and in the Doekegat (Alt3 in Table 7.1; Figure 7.6). This scenario represents the 2005 situation + raising of the bed level in the Emden Navigation channel to -8 m and shallowing in the Oost Friesche Gaatje by 1 m and in the Doekegat by 2 m.

This analysis was made by applying the suspended sediment concentrations from the sediment model to the water quality and primary production model described in detail in report 6 of this series. In short, this model uses output from a 3D hydrodynamic model for transport and dispersion. Suspended sediment concentrations, calculated with the sediment model (used in chapters 4 to 7) were used as input in order to calculate light availability for phytoplankton and microphytobenthos.
As a step in the calibration of the model for 2012, the suspended sediment concentrations from the sediment model were adjusted so that light conditions were calculated correctly in the water quality and primary production model. This was done in three steps (see for more details report 6):

1 A minimum level of extinction due to suspended sediment was set to the Ems river and part of the intertidal area in the Dollard. This was necessary to prevent excessive growth of phytoplankton in those areas and subsequent transport to deeper parts of the estuary.
2 Over the whole model grid, suspended sediment concentration from the sediment model was lowered by a factor two in order to attain a better fit of the model to observations of light extinction coefficient.
3 Suspended sediment concentrations were redistributed in time to better fit the observed suspended sediment and light extinction.

The third step of the calibration was left out for all scenario runs including the reference run. This was done because for the scenario's not only the average change of sediment concentration is important, but it is also important in which time of the year the changes occur. For example, a reduction of SPM in winter will not have a great effect on primary production because of low light availability and temperature, while a reduction in summer will result in enhanced production. .
Model analysis (report 7) has shown that primary production by phytoplankton is very sensitive to changes in suspended sediment fields. This is due to the strong light limitation in virtually the whole estuary, which is in agreement with earlier studies (e.g. Colijn & Cadee, 2003), and is a direct consequence of the high turbidity. Therefore, the sensitivity of simulated primary production to suspended sediments causes a very strong response of phytoplankton to any scenarios affecting suspended sediment concentrations, which can be expected (report 7). A direct consequence of this sensitivity is that any discrepancies in the simulated suspended sediment concentration will be clearly visible in primary production and

phytoplankton biomass, and therefore also in chlorophyll-a. For that reason, the relative change in calculated primary production as a response to changing suspended sediment concentration is more reliable than the absolute value of primary production.

On the basis of the suspended sediment concentrations calculated by the sediment model the following implications for primary production are to be expected.

- The “North Sea sediment disposal” (Chapter 4) scenario decreased the near-surface suspended sediment concentration south of Eemshaven up to 50% and more at some locations. The reduction was most pronounced in the Dollard. North of Eemshaven, suspended sediment concentrations did not decrease, but rather increased slightly. On the basis of the sensitivity analysis in report 7 it can be expected that total primary production in the estuary will show a strong increase in pelagic primary production, especially in the inner parts. Benthic primary production is not expected to increase strongly upon the reduction of turbidity, and even a negative effect could be expected at some places due to competition for nutrients with phytoplankton.
- The “Restoration of channel depth” (Chapter 7) scenario did not have a large effect on suspended sediment concentration in the estuary. Near-surface concentrations were reduced with a few per cent in the Dollard, and a slight increase was observed towards the North Sea. In principle, shallowing could have a positive effect on primary production because of a smaller mixing depth, and therefore a higher light availability in the area which is shallower. However, since this area is relatively small, this effect can not be expected to be large. Therefore, it is not expected that this scenario affects pelagic primary production significantly over the whole estuary.

In the next paragraphs, the actual simulation results of both scenarios are presented.

8.2 Results

The effect of the scenarios is evaluated with respect to factors important for primary production. The expected changes in suspended matter have effect on the light extinction coefficient in the water column, which in turn affects light availability and therefore phytoplankton biomass (chlorophyll-a) and primary production.

The results are shown as time series of daily averages (so variation due to tide is not shown here) and box plots with “notches”. Notches are placed in such a way, that when notches of two series do not overlap, this is a strong indication that the series are significantly different from eachother.

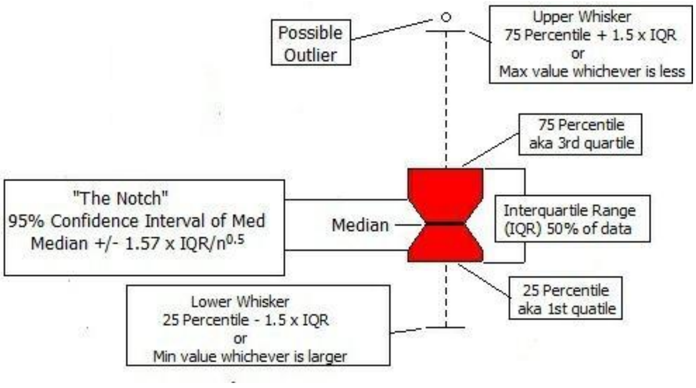


Figure 8.1 Explanation of a notched boxplot (image from https://sites.google.com/site/davidsstatistics/home/notched-box-plots).

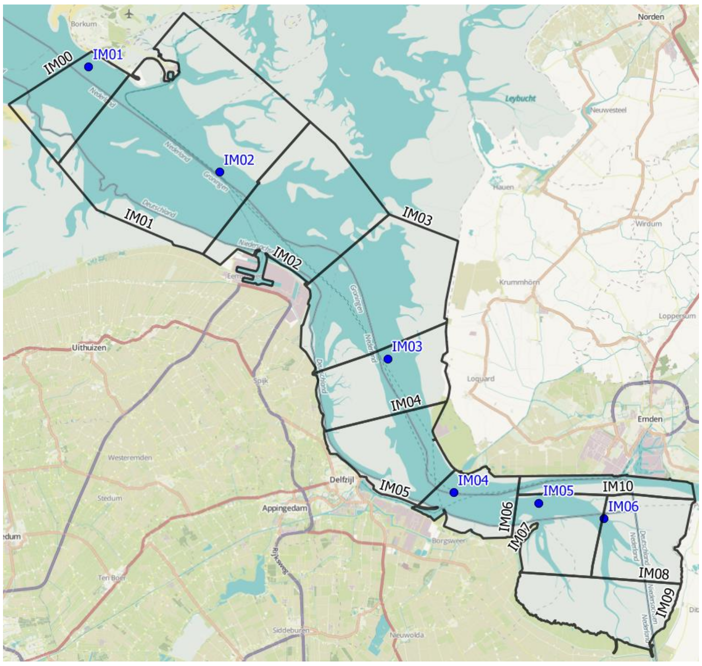


Figure 8.2 Map of IMARES monitoring points (blue) and areas. Background map is OSM Humanitarian (retrieved June 2015).

Extinction coefficient

The extinction coefficient was reduced during the whole year for the **offshore dumping** scenario at stations 2 – 6. The largest decrease was seen in the stations close to the Dollard (Figure 8.3). At the most seaward station (1) no effect was seen. This may be explained by the fact that the positive effect of not dumping in the Dollard (the “old” dumping site) is probably compensated by the increase of turbidity at the “new” dumping site offshore. This is consistent with the results from the sediment model where the largest reduction of suspended sediment concentration was also seen in the Dollard (Figure 4.4) and an increase of suspended matter at the “new” North Sea dumping site. The **shallowing** scenario led to a slightly higher extinction coefficient during the whole year.

Summer values of extinction coefficient were significantly reduced after relocation of the dumping location from the Dollard to the North Sea, and therefore led to a better light availability for phytoplankton. This effect increased towards the Dollard. The shallowing scenario did not result in any significant reduction of summer extinction coefficients at any of the stations (Figure 8.4). The small increase observed from the time series is reflected in slightly higher extinction coefficient in summer, but is only significantly at station 3 (Figure 8.4).

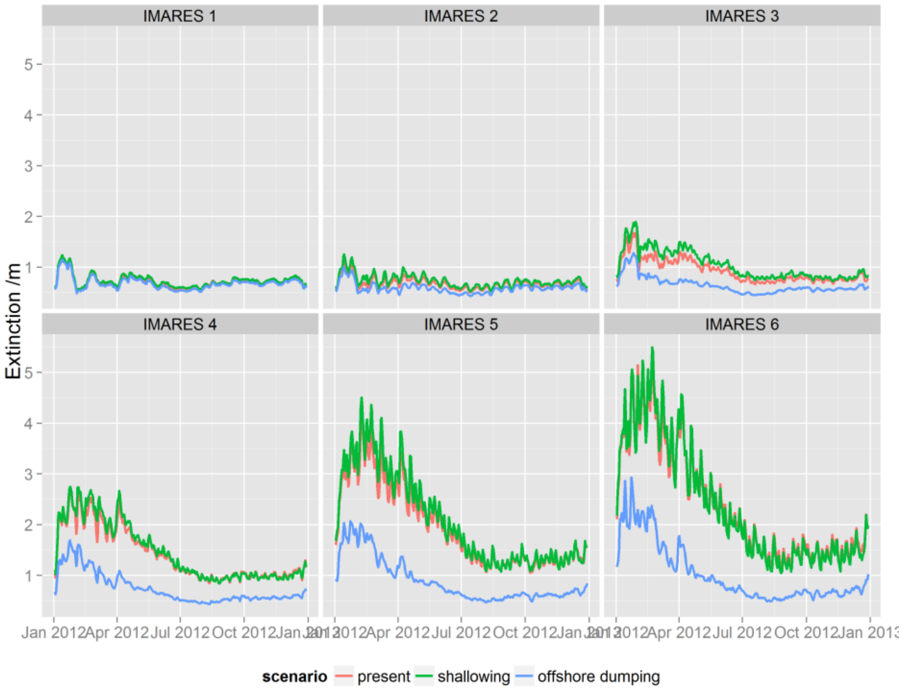


Figure 8.3 Time lapse of daily averaged extinction coefficient (/m) at the IMARES monitoring stations 1 – 6. In spring, when light is important for the phytoplankton spring bloom and in summer, only the offshore dumping scenario leads to a lower extinction coefficient at these stations.

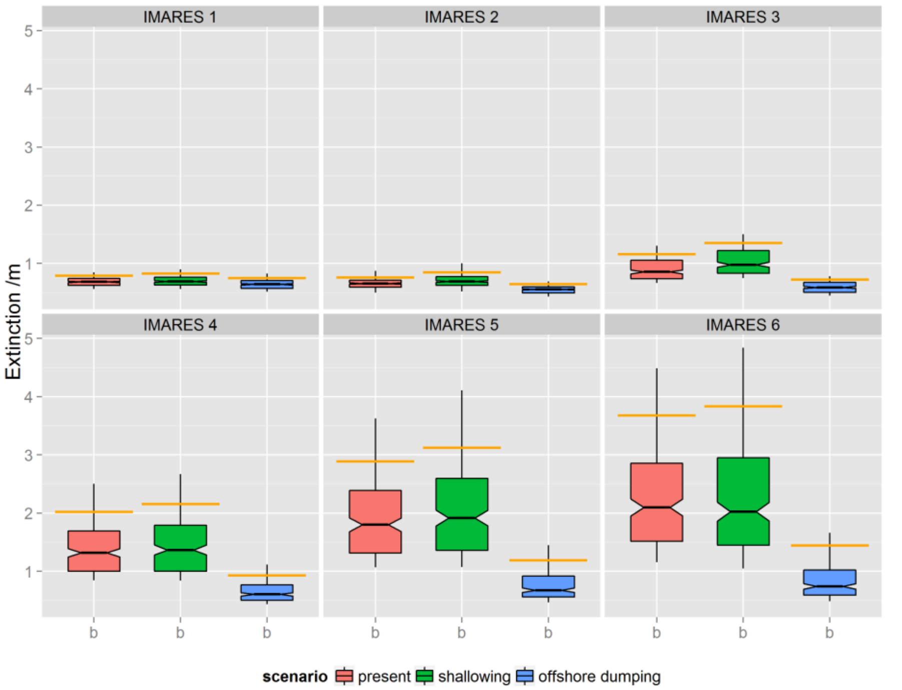


Figure 8.4 Boxplot with notches and 90 percentile (orange) of summer (March – September) extinction coefficient (daily average) at the IMARES monitoring stations 1 – 6. Offshore dumping led to a significant reduction of extinction coefficient, while the changes of extinction coefficient due to shallowing were not significant. (When notches do not overlap between series, this is a strong indication that values differ significantly from eachother)

Chlorophyll-a

Chlorophyll-a, a proxy for phytoplankton biomass, is higher in the **offshore dumping** scenario as compared to the current situation during the growth season (roughly from March – September), while chlorophyll-a in the **shallowing** scenario did not differ much from the current situation. This is also reflected in the boxplots, showing a significant increase in chlorophyll-a at stations 2 – 6 for the offshore dumping scenario, but no significant effect due to the shallowing scenario. This is in line with the findings for suspended sediment and extinction.
The boxplots also show 90-percentile values of chlorophyll-a concentration during summer. In the Water Framework Directive, this value should not exceed 18 ug/l in the inner part of the Ems estuary and 21 ug/l in the outer estuary in order to achieve “good” ecological status. Although the meaning of this indicator is questioned (e.g. Germany does not use this indicator in the Ems estuary), it is at this moment still an operational limit in the Dutch WFD process. Only at station 6, this threshold is exceeded slightly (22 ug/l) in the offshore dumping scenario. Since the model is still overpredicting the chlorophyll-a concentration during summer in the Dollard (PP Setup report # 6), the risk of exceeding the limit chlorophyll-a is small.

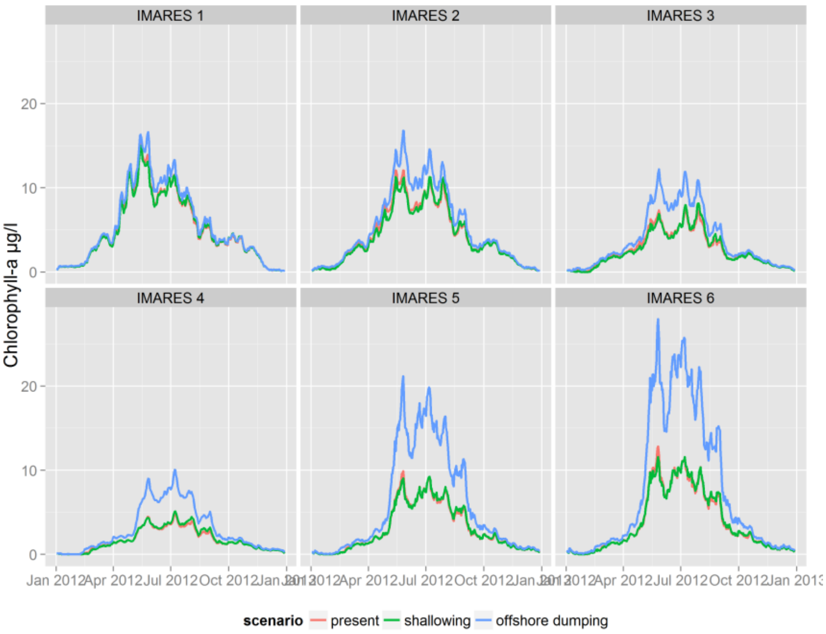


Figure 8.5 Time lapse of daily averaged chlorophyll-a concentration (in ug/l) at the IMARES monitoring stations 1 – 6. In spring, when light is important for the phytoplankton spring bloom and in summer, only the offshore dumping scenario leads to a lower extinction coefficient at these stations.

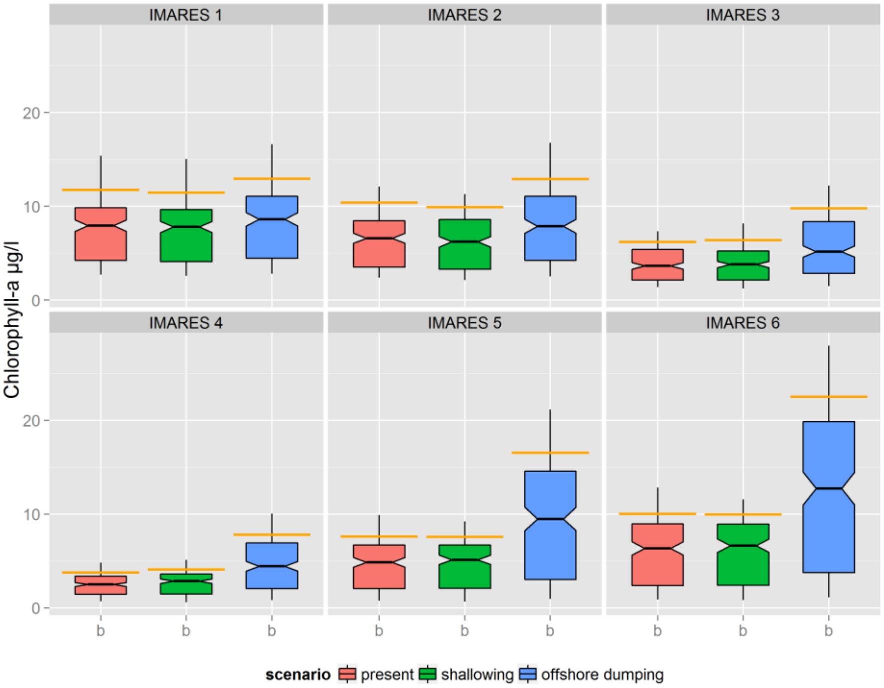
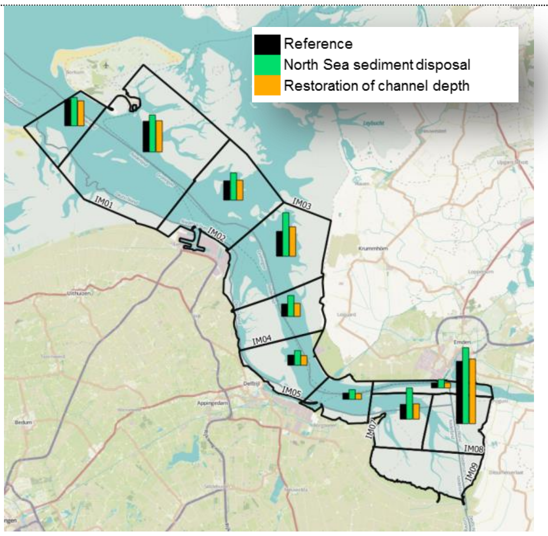


Figure 8.6 Boxplot with notches and 90 percentile (orange) of summer (March – September) chlorophyll-a concentration (ug/l) (daily average) at the IMARES monitoring stations 1 – 6. Offshore dumping led to a significant reduction of extinction coefficient, while the changes of extinction coefficient due to shallowing were not significant. (When notches do not overlap between series, this is a strong indication that values differ significantly from eachother)

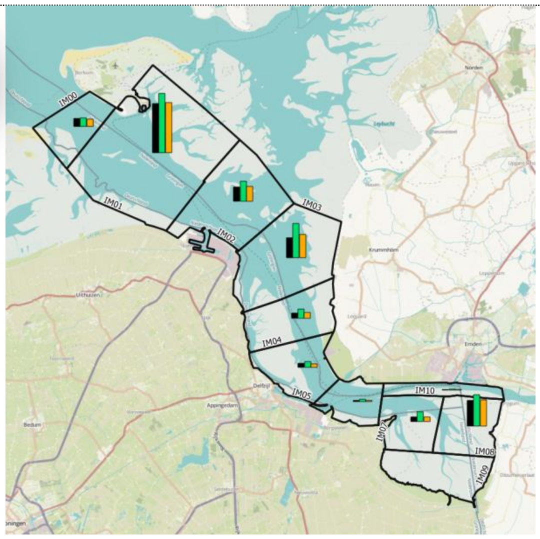
8.2.1 Pelagic primary production

North Sea sediment disposal has a strong effect on net pelagic primary production (Figure 8.7). Over the whole estuary, pelagic primary production increases by 10 tonnes C/y (from 27 to 37 tonnes C/y). This increase is mostly attributed to areas IM01-IM03 in the outer estuary and IM07 - IM09 in the Dollard (Table 8.1). The relative increase in pelagic primary production over the whole estuary is 38%, and is highest in the area IM07, followed by IM03 and IM09 (Table 8.1).

The **restoration of channel depth** scenario has in general little effect on pelagic primary production (Figure 8.7). In total, an increase of 5 % is obtained, with the strongest relative increase in IM03 and the the Dollard. These are areas where suspended sediment decreased, and where a large part consists of shallow intertidal areas. The strongest decrease in primary production is 4 % in subarea IM00 and IM05 (Table 8.1). The decrease in IM00 is explained by the increased SPM concentrations in this area. The absolute decrease of primary production in IM05 is very small. Overall, the small effects of this scenario can be explained by the small changes in suspended sediment concentrations that are calculated (paragraph 7.2.1).



Surface specific pelagic net Primary production expressed in in gram carbon per square meter per year for each "IMARES area". Since the net production in shallow water is higher than in deep water, the production reflects the proportion of the area covered with tidal flats.



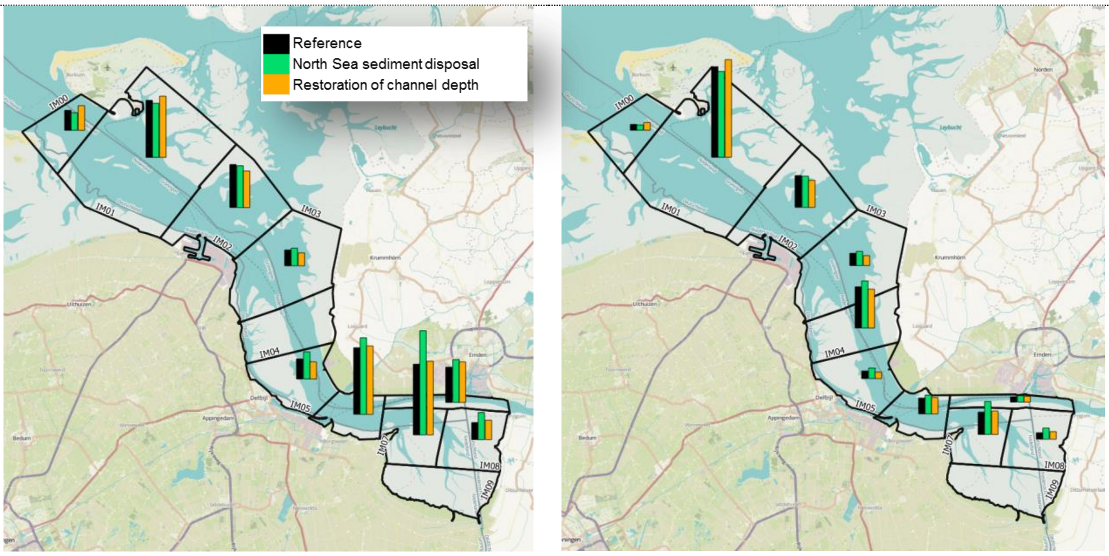
Total specific pelagic net Primary production expressed in in tonnes carbon per year for each "IMARES area". The total net production is, besides the proportion of tidal flats also dependent on the size of the area.

Figure 8.7 Area-specific and total pelagic primary production for defined areas in the Ems estuary estuary for the reference situation and two scenarios: the North Sea sediment disposal and Restoration of channel depth. These scenarios and their effect on suspended sediment concentrations are further described in chapters 4 and 7. Background map mud flats: © OpenStreetMap Humanitarian.

Table 8.1 Pelagic primary production in tonnes carbon per year for defined areas in the Ems estuary estuary for the reference situation and two scenarios: the North Sea sediment disposal and Restoration of channel depth. The absolute difference is shown as a blue (increase) or red (decrease) bar, and the relative change in % per area and in total is also indicated. The exact scenarios and their effect on suspended sediment concentrations are described in chapters 4 and 7. All scales of bars are common for this table.

thousands of tonnes C/y	Reference Total net PP	North Sea sediment disposal Total net PP	absolute difference	% difference	Restoration of channel depth Total net PP	difference	%
IM00	1.8	1.9		8%	1.7		-3%
IM01	10.7	12.7		19%	11.0		2%
IM02	3.1	4.2		39%	3.2		4%
IM03	3.9	6.6		70%	5.0		28%
IM04	1.0	1.7		62%	1.1		7%
IM05	0.8	1.2		48%	0.8		-3%
IM06	0.3	0.5		64%	0.3		0%
IM07	1.0	2.1		113%	1.1		8%
IM08	4.9	6.1		24%	5.1		4%
IM09	1.8	3.1		75%	1.9		8%
IM10	0.2	0.3		66%	0.2		5%
sum	**29**	**40**	**11**	37%	**31**	**1.9**	6%

8.2.2 Benthic primary production



Benthic net PP in gC/m2/y (see *Figure 8.7* for explanation of units)

Total benthic net PP in tonnes C/y (see *Figure 8.7* for explanation of units)

Figure 8.8 Area-specific and total benthic primary production for defined areas in the Ems estuary estuary for the reference situation and two scenarios: the North Sea sediment disposal and Restoration of channel depth. These scenarios and their effect on suspended sediment concentrations are further described in chapters 4 and 7.

Table 8.2 Total benthic primary production for defined areas in the Ems estuary estuary for the reference situation and two scenarios: the North Sea sediment disposal and Restoration of channel depth. These scenarios and their effect on suspended sediment concentrations are further described in chapters 4 and 7. All scales of bars and colours are common for this table.

	Reference	**North Sea sediment disposal**			**Restoration of channel depth**		
thousands of tonnes C/y	Total net PP	Total net PP	absolute difference	% difference	Total net PP	difference	%
IM00	1.4	1.3		-9%	1.7		22%
IM01	19.5	18.4		-6%	19.8		2%
IM02	5.8	5.7		-2%	5.0		-14%
IM03	2.9	3.1		6%	2.2		-24%
IM04	8.7	10.6		22%	8.0		-8%
IM05	1.5	1.9		28%	1.3		-12%
IM06	3.5	4.3		23%	3.6		3%
IM07	4.4	7.0		58%	4.7		6%
IM08	1.1	2.2		100%	1.4		24%
IM09	2.6	3.8		50%	2.9		13%
IM10	0.6	0.9		48%	0.8		24%
sum	**52**	**59**	**7**	14%	**51**	**-0.7**	-1%

Over the whole estuary, **North Sea sediment disposal** increases benthic primary production by 14 % (Table 8.2). The effect on benthic primary production differs between the different areas. In the Dollard and middle reaches, an increase is observed, while benthic primary production is reduced in the outer parts (Figure 8.8). The differences in benthic primary production in the due to North Sea sediment disposal can be explained by the following processes

- Due to the reduction in turbidity, the area suitable for benthic diatom growth (i.e. the area where enough light is available at the sediment surface) expands slightly. Since nutrients are not limiting in the inner part of the estuary, all extra available area will be populated by benthic diatoms, and will thus contribute to an increase in production.
-
-
- It can be expected that the increased growth of pelagic and benthic algae will deplete the nutrients more often as compared to the present situation and thus reduced nutrient availability, although this is not very clear from the limiting factors plot (Figure 8.108.3). The reduction of benthic production in the outer parts of the estuary is explained by this lower nutrient availability due to increased production in the inner parts of the estuary. (Figure 8.11).

The **restoration of channel depth** has in general little effect on total benthic primary production. Integrated over the whole estuary, there is a 1 % increase of total benthic primary production (Table 8.2). Like in the North Sea sediment disposal scenario, production increases somewhat in the Dollard, but decreases in the middle reaches and increases again in the most seaward areas (Figure 8.8). In this scenario, the increased production cannot be explained by decreased turbidity and thus extended suitable areas for benthic production. However, iin the Dollard, the average depth is slightly decreased in intertidal areas. The increase in benthic production can be explained by the fact that due to the shallower conditions (Figure **8.9**) a larger area comes available where benthic primary production is possible.

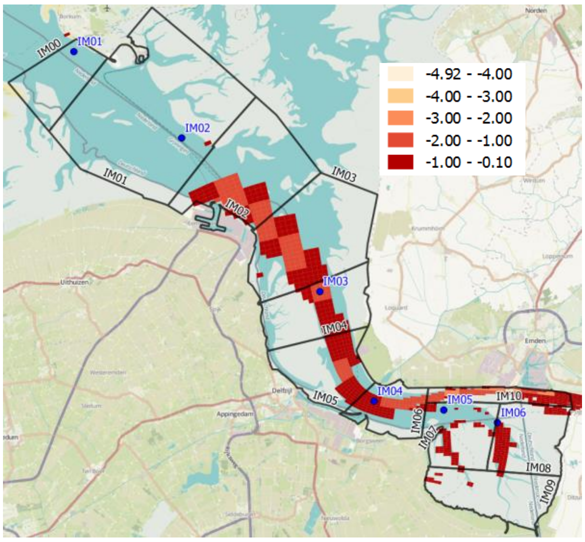


Figure 8.9 Representative example of depth (from water surface to bottom) change (negative value means shallower; only shallowing of 10 cm and more are shown) in the Shallowing scenario at day 100 of the simulation (10th April 2012) projected on the water quality and primary production grid cells.

8.2.3 Total (pelagic plus benthic) primary production

Total production is calculated as the sum of benthic and pelagic production. Over the sum of the areas, total production increases in the **North Sea sediment disposal** scenario by 17 % (Table 8.3). The relative increase is highest in the Dollard (IM07), but increases are also substantial in the middle part of the estuary. The effect becomes smaller towards the North Sea, and there is no effect on total primary production in the area closest to the North Sea.

The total production did not change (only 2 % increase) substantially in the **Restoration of channel depth** scenario, although the effect differed between the different areas (Table 8.3). The general pattern in production change was mainly caused by changes in benthic production.

Table 8.33 Total (pelagic plus benthic) primary production for defined areas in the Ems estuary for the reference situation and two scenarios: the North Sea sediment disposal and restoration of channel depth. The scenarios and their effect on suspended sediment concentrations are further described in chapters 4 and 7. All scales of bars and colours are common for this table.

	Reference	North Sea sediment disposal			Restoration of channel depth		
thousands of tonnes C/y	Total net PP	Total net PP	absolute difference	% difference	Total net PP	difference	%
IM00	3.2	3.2		1%	3.4		8%
IM01	30.2	31.1		3%	30.8		2%
IM02	8.9	10.0		12%	8.2		-8%
IM03	6.8	9.7		43%	7.2		6%
IM04	9.7	12.3		27%	9.1		-6%
IM05	2.3	3.0		35%	2.1		-9%
IM06	3.8	4.8		26%	3.9		2%
IM07	5.4	9.1		68%	5.7		6%
IM08	6.0	8.3		38%	6.5		8%
IM09	4.3	7.0		60%	4.8		11%
IM10	0.8	1.2		52%	0.9		19%
sum	**81**	**100**	**18**	22%	**83**	**1.2**	2%

8.2.4 Limiting factors

From previous analysis it is known that pelagic primary production in the Ems estuary is in general light-limited (report 7 and Figure 8.10). Only in the Dollard area IM08, nutrient limitation occurs during summer in the reference situation (Figure 8.11). Since primary production in this area is probably overestimated by the model, it is not clear whether this nutrient limitation really occurs in nature

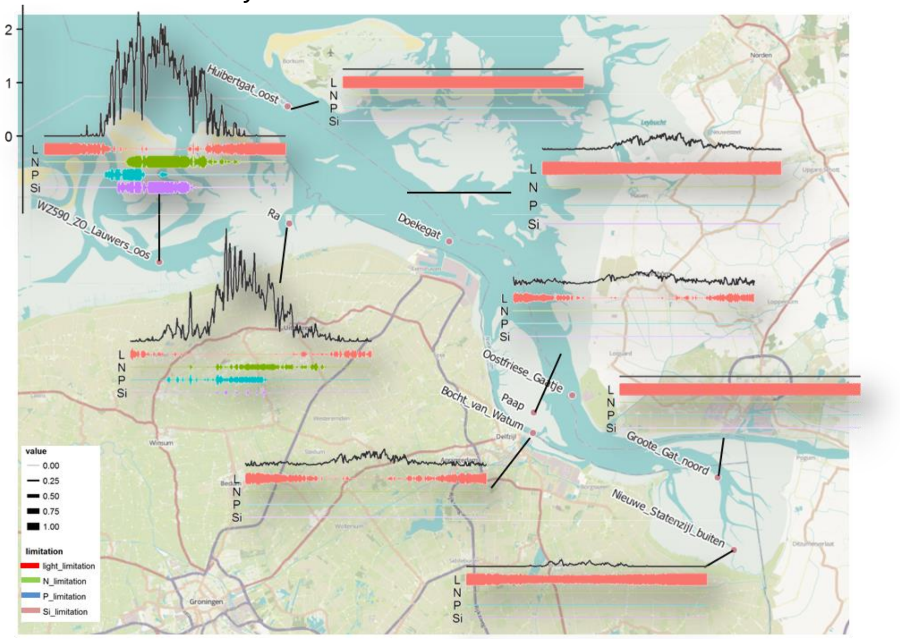


Figure 8.10 Net pelagic primary production (black line) and limiting factors (colored lines varying in thickness) as simulated for 2012 for some stations in the Ems Estuary. Shallow stations often have relatively high production, while deep stations do not show any net primary production. Towards the outer and western part of the estuary, nutrient limitation increases during summer (figure reproduced from the model setup report #7).

The **North Sea sediment disposal** scenario causes a considerable reduction in turbidity. In a strong light-limited system, this causes an increase in primary production and possibly a shift in limiting factors. Indeed, the scenario resulted in an increase of primary production (Figure 8.7), but no shift of the dominant limiting factor could be observed (Figure 8.11).

For the **restoration of channel depth** scenario, no change in limiting factors is simulated. This is also expected, since the change in primary production is less than 20 % in most areas. The ample amount of nutrients and the relative small change in primary production do not cause a shift from light to nutrient limitation.

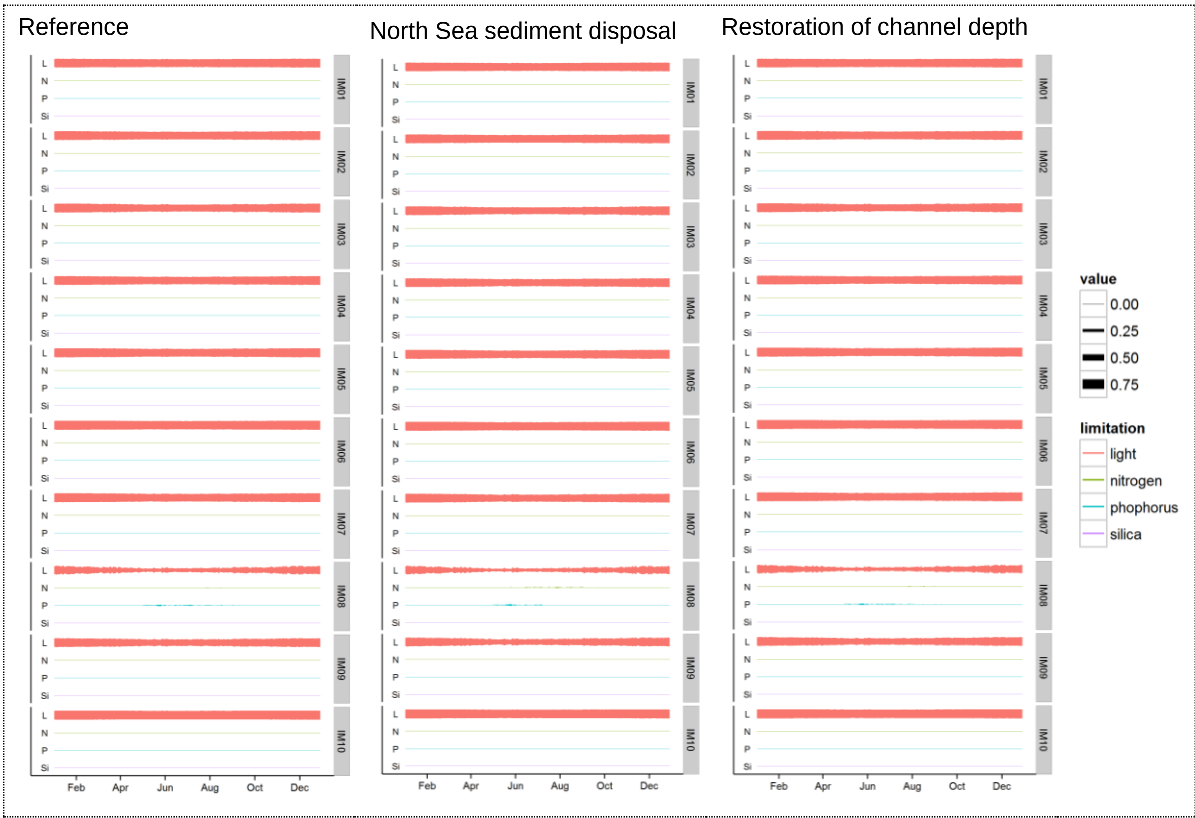


Figure 8.11 Limiting factors for primary production in subareas. 0: no limitation, 1: limitation. Values between 0 and 1 occur because of temporal aggregation (to daily average) and spatial aggregation (to subareas) of grid cells. The thick red line that is observed in almost all areas thus indicate that light is on average limiting for these areas during virtually the whole year.

8.3 Model applicability

The water quality and primary production model, its validation, and limitations are further described in report 6. The results from the current scenario study are dependent on the applicability of this model.

It is important to realize that the water quality and primary production model is the third model in the chain of models. Possible discrepancies in the hydrodynamic and sediment model propagate to the primary production model, affecting the accuracy of the primary production calculation. However, uncertainties do not necessarily add up in this model chain, and uncertainties in e.g. the hydrodynamics do not always have strong consequences for the calculation of primary production or other water quality variables.

The primary production model calculates primary production based on temperature and the availability of light and nutrients, while transport and dispersal of algae and substances is calculated based on the hydrodynamic flow fields. In principle, all key processes that play a role to describe the temporal and spatial variation of primary production and nutrients are included, and a great effort has been put in calibration and validation of the model. However, there are still some flaws in the model results that urge to a critical look at the model results for the current scenarios. However, as the processes used in the model are rather generic, the relative change of variables in scenarios should give a rather robust indication of the expected relative changes in the two scenarios.

In detail, the following processes contribute to the simulation of primary production.

- Transport and dispersion is taken from the hydrodynamic model, and aggregated for use in the primary production model. The effect of aggregation is tested by recalculating the salinity. Vertically, the model is aggregated to one layer (2D) in the vertical and aggregated in the horizontal in order to reduce calculation time. The aggregation did not influence the salinity calculation in the estuary significantly.
- Suspended sediment concentrations were taken from the sediment model and were recalibrated for use in water quality models. Their actual concentrations were reduced for the 2012 year run to create a better match with measured extinction. Extinction of light in the water column is calculated in the water quality and primary production model and takes into account extinction by suspended sediment, phytoplankton, dead organic material and dissolved organic material. The total availability of light for phytoplankton primary production is then a function of extinction and mixing depth. After calibration of suspended sediment concentration, modelled extinction showed an overall reasonable fit and is therefore considered suitable for scenario studies (report 6).
- Calculation of primary production is based on observed temperature, modelled underwater light and nutrient availability and a combination of generic and tailor made relationships that describe the growth response of phytoplankton and phytobenthos. For phytoplankton, this process has been extensively tested in many different environments (Los, Villars, & Van der Tol, 2008, Blauw et al., 2008). Overall, average modelled phytoplankton biomass (chlorophyll *a*) showed no bias compared to measured chl *a.* Primary production, integrated over the areas presented in this chapter, was in the same order of magnitude as measured primary production, but approximately 15 % lower (report 6).
- Availability of nutrients is calculated based on loads from the river Ems, boundaries, hydrodynamics and processes in the water and sediment. There is interaction with a layered sediment where dead organic material is mineralized. The general fit of the model to measured concentrations is reasonable to good. The model also reproduces nicely the increase of phosphate in the Dollard and outer Ems during summer in 2012, caused by redelivery from the sediment.

Benthic algae biomass and production showed to be more challenging and processes might be too simple in the model. Modelled microphytobenthos biomass was higher than measured microphytobenthos biomass in most locations. The measured benthic primary production was not considered to be accurate enough to be compared to the model (report 9). Therefore, objective validation was not possible. Instead, parameters were chosen so that the benthic primary production was in the same order of magnitude of pelagic primary production in the estuary. It was concluded that in that way the model simulates the average biomass and primary production of benthic diatoms in the right order of magnitude.
Summarizing, the model describes well enough the relation sediment – extinction – pelagic primary production and contains enough detail to be used for the type of scenarios applied in the current study. The model is less suitable to be used in scenario studies focussed on benthic primary production. In part of the model grid, most notably in the shallow Dollard area IM08, the model results deviate from expected values. Potentially, the model could also be used for scenarios in which nutrient loads from the river Ems or other sources are reduced. Nutrient concentrations are well predicted with the current model, and great detail is included to cover e.g. also the phosphorus redelivery from the sediment correctly.

8.4 Conclusions

The scenario results were in general similar to what could be expected based on earlier sensitivity analysis (report 7). The large effect of **North Sea sediment disposal** on suspended sediment concentrations caused a large increase (+38%) in pelagic net primary production. This effect was largest in the Dollard, and could be attributed to increased underwater light availability. However, light remains limiting for primary production. Benthic primary production also increased (in total 11%) and most of the increase occurred in the Dollard. The increase of benthic primary production in the Dollard, can be explained by a slight extension of suitable area for benthic primary production due to reduced turbidity. On the other hand, there was a slight decrease in benthic primary production in the seaward part of the estuary. This is caused by increased competition for available nutrients in this area, although the frequency of nutrient limitation does not increase. Overall, the decrease in suspended sediment and increase in light availability increased total primary production, but the balance in pelagic to benthic primary production increased in favour of pelagic primary production.

Restoration of channel depth has a much smaller effect on suspended sediment concentrations and, consequently, pelagic net primary production was only moderately (+5%) increased in the area. The increase was significant in the Dollard, which could be expected based on the suspended sediment concentrations and in IM03. Benthic primary production was hardly influenced (+1 %) in total, but the variation between the different regions was substantial. In the Dollard, benthic production increased, while in the outer regions, the benthic primary production decreased by 15 – 20 %. This result might be a direct effect of the change in bathymetry and tidal range, and therefore the area of drying mudflats, where benthic primary production occurs.

9 Discussion

Under the Water Framework Directive, good ecological status must be achieved in coastal waters. To improve the ecological status of the Ems Estuary, measures to reduce turbidity and increase primary production in the estuary are being investigated. To investigate the effectiveness of possible measures, numerical models developed under the project 'Research of mud dynamics in the Ems Estuary' have been used for scenario analysis to assess a number of measures. Three main indicators were computed from the results of model simulations to allow comparison of the effectiveness of these scenarios. The change in these indicators is a direct indication of how turbidity levels and spatial distribution within the estuary will be influenced by mitigation scenarios. The influence of different scenarios is compared to a baseline model for the year 2012, described in report 7 and summarized in Chapter 2 of this report.

This chapter provides an overall discussion of the results of the model analyses and model applicability presented in the previous chapters. The discussion focuses on turbidity and primary production results from the model simulations.

9.1 Turbidity

Four main scenarios were evaluated with respect to reducing the turbidity (suspended sediment concentrations) in the Ems Estuary.

1. <u>Disposal of dredged sediment in the North Sea</u>

The first scenario evaluated was the effect of disposing dredged sediments further offshore between the Wadden Sea and the North Sea or even in the North Sea, instead of within the Ems Estuary. Four different alternatives were considered, comprising different disposal locations. The costs of dredging (per m^3 of dredged material) increases with the sailing distance to disposal locations. However, the further offshore the sediments are disposed, the lower the sediment concentration in the Ems Estuary becomes and thus the lower the port siltation rates are.
The accuracy of the siltation rates are determined by the estuarine sediment concentration (report 5) and hydrodynamics (report 4). The baseline model reproduces present-day siltation rates (based on dredging quantities) in the ports of Delfzijl and Eemshaven, which indicates the horizontal transport of sediment and trapping in the ports are well captured by the model so for these two ports there is confidence that the model can react correctly to a change in sediment availability. Siltation is however underestimated in the port of Emden and approach channel, because the sediment concentration in the Emden fairway is too low. In terms of the overall estuarine concentrations, this underestimation is partly compensated for by disposing all sediment from Delfzijl (in reality not all dredged sediment is disposed; most is agitated and thereby flows out of the port into the estuary) but means that any specific changes to the dredging and dumping in the port of Emden will not fully capture the local effects. Therefore, the physics governing siltation in these ports is sufficiently represented by the model. The sediment dynamics in the approach channel to Emden and in the lower Ems River are not well reproduced by the model, and therefore any impact of dredging scenarios on this area should be carefully interpreted. Furthermore, not all disposal locations in the baseline simulation are on the exact position they are in reality, but with the focus on long-term impacts of disposal, such details have little impact on the large-scale sediment distribution.
In addition, the correct representation of the residual transport of sediment and sediment spreading, which is well captured by the model, is also important when determining the

impact of disposing offshore. The computed residual transport is difficult to verify, though residual transport is caused by asymmetries (which are reproduced by the model) and by sediment sinks. The residual transport resulting from natural sediment sinks is underestimated but residual transport from man-made sinks (ports) is reproduced and as these are the largest sinks in the estuary a large proportion of the residual transport is inherently captured and so the changes as a result of disposing offshore will also be reflected in the residual transport of sediment up-estuary.

2. Sediment extraction from ports (and disposal on land)

The second scenario evaluated was the effect of extracting sediment from the ports (and disposing this on land) instead of disposing the dredged material within the estuary. Four different alternatives were considered, comprising extraction from the ports of Eemshaven, Delfzijl and Emden individually, as well as combined extraction from all three ports. The reduction in suspended sediment concentration in the estuary as a result of extraction from the three ports individually and all ports simultaneously is largest in the areas where the dredged sediments were formerly disposed. Extraction of Eemshaven sediment has the largest effect just offshore, extraction of Delfzijl sediment has the largest effect in the Dollard where sediment was disposed and extraction of sediment from Emden area has an effect spread more widely throughout the estuary as disposal occurred in two large mid-estuary areas in the baseline model. As described for the scenarios of disposing sediment in the North Sea, the ability of the model to simulate siltation rates and horizontal transport of sediment (sediment spreading) correctly will influence the applicability of the results of the sediment extraction scenarios. For example, siltation rates are underestimated in Emden and so the impact of extraction may be larger if siltation rates were initially higher.

3. Creation of intertidal areas

The third scenario evaluated was the effect of creating an intertidal area within the Dollard. This type of scenario may occur if in the future the estuary is extended to create new intertidal areas. This scenario could not be implemented directly in the model given the scope of the study. Instead, a simplified approximation was made by extracting sediment from the Dollard to simulate a situation in which the Dollard acts as a large sediment sink. Suspended sediment concentrations in the Dollard and the surrounding estuary were reduced as a result of the extraction alternative. Outside of the Dollard, concentrations were reduced by 10-20% and therefore only minor changes occurred in the fluxes into the ports. Because of the modelling approach, these results should be considered as preliminary only. The amount of sediment being transported to this additional intertidal area is also influenced by the ability of the model to correctly capture residual transport patterns in the estuary. The residual transport resulting from natural sediment sinks is underestimated but residual transport from man-made sinks (ports) is reproduced. As these are the largest sinks in the estuary a large proportion of the residual transport is inherently captured. As for the effectiveness of the residual transport due to the additional sink in the Dollard, the scenario gives a good indication of the extent of reduction in suspended sediment concentrations but is not fully realistic as in reality sediment from this sink would also be available for resuspension but in the model it is fully extracted.

4. Restoration of channel depth in the Friesche Gaatje and Emden Fairway

The fourth scenario examined was the effect of restoring the channel depths more towards the original pre-dredging depths. Restoration of the bed level in the Emden Navigation channel had minor effects on suspended sediment concentrations compared to the baseline model. Reduction in bed level in the Oost Friesche Gaatje and in the Doekegat resulted in spatially varying increases and decreases of the suspended sediment concentrations in the estuary by 20-30%. The horizontal transport of sediment will be influenced by the restoration of channel depths and as the model reproduces sediment spreading (because the instantaneous depth-averaged currents, as well as the typical current profiles, are sufficiently reproduced and the tidal phase lags are correctly simulated) changes in the spreading of sediment as a result of channel restoration will also be reproduced. Residual transport up-estuary and into the man-made sinks will also be influenced.

<u>Summary</u>
Of all simulated scenarios, extraction from the ports resulted in the largest reduction in SSC and therefore port siltation). The reduction of SSC as a result of offshore sediment disposal is also large. Disposal in the North Sea leads to a reduction as large as extraction (when sediment is no longer transported back into the estuary, offshore disposal is essentially the same as extraction). The computed effects of offshore disposal and extraction are very large. Even though the model can be considered a good model to reproduce suspended sediment concentrations and port siltation, model uncertainties remain and given these uncertainties, more research is needed to further quantify the scenarios in this report. It should further be realised that the simulated effect of *extracting* sediment from the ports (either by offshore disposal or bringing sediment on land) is not the same as the effect of *dredging and disposal* (which is the current practice). An earlier part of this study (report 7) suggests that the effect of dredging and disposal from the ports is mainly a local redistribution of SSC in the estuary, and not so much an increase of average SSC levels (compared to an estuary without ports).

9.2 Primary production
The simulations on which the conclusions are based are done by application of a chain of models, starting with a hydrodynamic model, then a sediment model to simulate sediment concentrations, and finally the water quality and primary production model. The choice of this chain of models has been made to make it possible to simulate changes in primary production as a result of management scenarios that influence morphology (and thus hydrodynamics) or dredging and dumping strategies (and thus distribution of suspended sediment).

The production of pelagic algae has been extensively studied using this type of models (e.g. F. Los & Wijsman, 2007; Los & Blaas, 2010, Smits & Van Beek, 2013, Blauw et al., 2008). The processes used in such models are generic, and could in principle be used in very diverse ecosystems. For the Ems estuary, the only adaptation was done on growth parameters for benthic diatoms. Unlike pelagic algae, benthic diatoms are not light limited in exposed intertidal areas, which cover a large part of the estuary. Their production is therefore likely to be ultimately limited by another factor. In the model, it appeared that either phosphorus or silica was limiting their growth (report 7). Colijn & De Jonge (1984) concluded that benthic diatoms probably were not limited by nutrients. Moreover, since they only occur on drying mudflats, the change in total area suitable for microphytobenthos growth is probably even more important for the total benthic production in the estuary.

Two of the scenarios for reducing turbidity were also simulated with respect to their impact on increasing primary production. The results of the scenarios are explained by the modelled changes in turbidity in relation to the available resources, light and nutrients. A considerable level of spatial and temporal detail and in processes has been included in the current model in order to cover the details in hydrodynamic processes in this highly variable environment. Results obtained on this detailed level were in the current study aggregated to yearly values and integrated over larger areas. Details in time, space and/or processes, although not shown in the results of this study, may still be very relevant to capture transport, dispersion, and e.g.

sediment-water exchange of substances realistically. The applicability of the current model is good, considering the inputs and processes that are captured.

This type of detailed model applications can be used as a tool for exploring the effects of changes in environmental circumstances in an area. Scenario results will help to construct a general picture of which changes may be expected upon scenarios. The model results in this study must therefore be interpreted together with other knowledge on the Ems Dollard system.

<u>Disposal of dredged sediment in the North Sea</u>
The effects of this scenario was consistent with the a priori expectations (chapter 8.1). The reduced turbidity due to disposal of sediments further offshore between the Wadden Sea and the North Sea caused a clear increase of primary production in the area where turbidity was reduced. Especially the inner parts of the estuary benefitted from reduced turbidity, showing an increase in pelagic primary production. The reason for this is that phytoplankton production is strongly light-limited throughout the estuary. Phytoplankton production is therefore very sensitive to any change in turbidity. The reduction of turbidity did not lead to a shift from light limitation to nutrient limitation. The production of microphytobenthos was only modestly affected by this scenario (in total 14% over the whole estuary). This could be expected, since this group of algae is mainly limited by the availability of suitable areas rather than by the light regime in the watercolumn. In some areas in the inner part of the estuary, a relatively high increase was observed. This was attributed to a higher availability of surface area suitable for benthic diatom growth as a result of clearer waters.

<u>Restoration of channel depth</u>
For the other scenario tested, the restoration of channel depth, only small changes in primary production were seen for both phytoplankton and microphytobenthos. Considering the small change in suspended sediment concentrations, this could be expected. A slight increase of primary production by phytoplankton and phytobenthos was calculated for the inner part of the estuary. In the middle reaches, benthic primary production decreased. This is explained by the change in water level, and therefore availability of suitable habitat for benthic diatoms.

Overall, the qualitative results of the scenarios were as expected considering the results from the sediment model scenarios. To increase primary production in the Ems estuary, sediment disposal in the North Sea is the most effective measure of the two scenarios tested here.

10 Conclusions and recommendations

10.1 Conclusions

A number of potential measures (16 in total) for reducing the turbidity and improving the primary production in the Ems Estuary were identified in stakeholder meetings. By applying evaluation criteria including expected effectiveness, sustainability, realisation costs; societal & political support as well as a number of model criteria, the four most promising measures were selected for further analysis:

1. Disposal of dredged sediment in the North Sea
2. Sediment extraction from ports (and disposal on land)
3. Creation of intertidal area to increase sedimentation (also called ‘adaptive poldering’)
4. Restoration of channel depth in the Friesche Gaatje and Emden Fairway

The effects of the four selected measures in reducing the suspended sediment concentrations could be quantified using the models developed earlier of the project. Three different indicators were used to compare the results of the model scenarios to the baseline model (2012) and quantify the effectiveness:

1. SPM fields
2. Port siltation
3. Average SPM concentration per area

Of the four modelled scenarios, the extraction of sediment and the seaward disposal of sediment were most effective, both reducing turbidity throughout the majority of the estuary. Restoration of channel depth has a smaller effect, reducing the turbidity in the Dollard but increasing turbidity further seaward. Only the effect of a small intertidal area was investigated, and the resulting impact was low. A larger and more realistic simulation would require more adaptations to the model than was feasible within the project scope. Two contrasting scenarios were used to subsequently quantify the effect of the scenarios on primary production: North Sea sediment disposal and restoration of channel depth. Sediment disposal in the North Sea had the largest effect with respect to primary production, with almost a 17% increase in primary production for the whole estuary.

The results presented here are simulated as part of an explorative study on the suspended sediment dynamics and primary production in the Ems Estuary. The results suggest that measures exist which reduce turbidity and increase primairy production. However, the changes are fairly small compared to the required effort. Additional research is needed to further substantiate the results presented in this report. Future lines of improvement are therefore briefly discussed in the next section.

10.2 Recommendations

Models are tools to investigate changes in the suspended sediment dynamics and primary production as a result of modifications in the estuary. The predictive power of such models is, however, limited by inaccuracies in the models arising from required spatial scales, time restrictions, and process definitions (in the model, but also on a fundamental level: not all relevant processes in the estuary are sufficiently understood). In order to better quantify the effect of the various scenarios, it is recommended to

1 Increasing our knowledge on the functioning of the Ems estuary by

- Extending monitoring programmes and collecting more data to support increased understanding of the present-day system functioning and to improve the calibration and validation of the numerical models.
  - Investigating in detail the exchange mechanisms in the Emden fairway, requiring collection and analysis of field data.
  - Setup long-term monitoring stations to measure SSC. Continuous observations can be used to quantify long-term changes in SSC with much shorter timeseries than bi-weekly MWTL observations.
  - Collecting more data on suspended particulate matter, light extinction and pelagic primary production in shallow areas, where net production occurs.
  - Collecting more data on benthic primary production, taking into account the high patchiness of this process.
- Developing multiple models in which measures can be implemented and their effect on suspended sediment dynamics can be predicted. These models should be developed to predict long-term effects, and preferably be based on a range of modelling concepts, from simple sediment balance approaches to idealised modelling to very detailed models with variable focus points (large vertical resolution, large horizontal resolution, full coupling between hydrodynamics and sediment dynamics, or erosion-rate limitation instead of supply-limitation).Using multiple model approaches to compute the impact of scenarios will provides important information on how well scenario effects can be predicted (poor if multiple models reveal widely varying scenario results; good if all models suggest the same outcome).

2 Improving the model chain developed in this study by

- A more direct integration of the water quality model and the sediment transport model results during the calibration phase by using primary production and light extinction as a proxy parameter to calibrate suspended sediment transport models.
- Including biological effects in sediment transport models (biostabilization, bioturbation, and flocculation). Generic relationships describing such relationships do not or only partly exist, and require fundamental work.
- Determining the sensitivity of the applied models to uncertainties in the input parameters by defining multiple calibration parameter sets. Testing the trends in the response of the estuary to a wide range of parameter settings provides valuable insight of the sensitivity of the models to uncertainties in parameter settings.
- Improving the individual models within the effect-chain with suggestions given in reports 4, 5 and 6. The main areas for improvement are (1) the hydrodynamics and sediment dynamics in the Emden fairway, (2) implementation of natural sediment sinks in the sediment model, (3) simulation of pelagic primary production in shallow areas, and (4) simulation of benthic primary production .
- Implementing the exact dredging and disposal strategy, including multiple disposal sites and agitation dredging, modify disposal locations in the baseline model, and improve the time window of disposal.

11 References

Braaksma, J. (2012). 'Rijzend Land' Een regionale opslibbingstrategie voor te laag gelegen polders in de Waddenregio. Afstudeerscriptie Academie van Bouwkunst te Amsterdam. http://www.waddenacademie.nl/fileadmin/inhoud/pdf/06-wadweten/Scripties/Rijzend_Land_Jorryt_Braaksma_boekje_DEF_verkl.pdf

Blauw, Anouk N., Hans F. J. Los, Marinus Bokhorst, and Paul L. A. Erftemeijer (2009). GEM: a generic ecological model for estuaries and coastal waters. Hydrobiologia, 618:175–198.

Booij, N., Ris, R.C. and Holthuijsen, L.H. (1999). A third-generation wave model for coastal regions, Part 1, Model description and validation, Journal of Geophysical Research, Vol. 104, No. C4, p. 7649–7666.

Cleveringa, J. (2008). Ontwikkeling sedimentvolume Eems-Dollard en het Groninger wad: Overzicht van de beschikbare kennis en gegevens. rapport A2269. Alkyon, Marknesse. 47 pp.

Colijn, F.; Cadée, G.H. (2003). Is phytoplankton growth in the Wadden Sea light or nitrogen limited?, in: Philippart, C.J.M. et al. (Ed.) (2003). Structuring Factors of Shallow Marine Coastal Communities, part II. Journal of Sea Research, 49(2): pp. 83-93

Colijn, F.; De Jonge, V.N. (1984). Primary production of microphytobenthos in the Ems estuary. Mar. Ecol. Prog. Ser. 14: 185-196.

Friedrichs, C.T. (2012). Tidal flat morphodynamics: a synthesis. In: Hansom, J.D., Flemming, B.W. (Eds.), Treatise on Estuarine and Coastal Science, vol 3: Estuarine and Coastal Geology and Geomorphology, p. 137–170.

Friedrichs, C.T. and Aubrey, D.G. (1988). Non-linear tidal distortion in shallow well-mixed estuaries: a synthesis. Estuarine, Coastal Shelf Science 27, 521-545.

Gerritsen, 1952. Historisch-hydrografisch onderzoek Eems. Notitie D41, 17 p., Hoorn.

Hansen and Rattray (1965). Gravitational circulation in straits and estuaries. J. Mar. Res. 23: p 104-122.

Holthuijsen, L.H. (2007), Waves in oceanic and coastal waters, Cambridge University Press.

De Jonge, V.N. (1992). Tidal flow and residual flow in the Ems estuary, in: De Jonge, V.N. (1992). Physical processes and dynamics of microphytobenthos in the Ems estuary (The Netherlands). pp. 23-41

De Jonge, V.N., Schuttelaars, H.M., van Beusekom, J.E.E., Talke, S.A., and de Swart, H.E., 2014. The influence of channel deepening on estuarine turbidity levels and dynamics, as exemplified by the Ems estuary. Estuarine, Coastal and Shelf Science 01/2014; DOI:10.1016/j.ecss.2013.12.030.

Kornman, B. A. & De Deckere, E. M. G. T. 1998 Temporal variation in sediment erodibility and suspended sediment dynamics in the Dollard estuary. In Sedimentary Processes in the

Intertidal Zone (Black, K. S., Paterson, D. M. & Cramp, A., eds). Geological Society London Special Publications 139, pp. 231–241.

van der Lee,W.T.B.,2000.Temporal variation of floc size and settling velocity in the Dollard estuary. Continental Shelf Research 20, 1495–1511.

Los, H. F. J., Blaas, M. (2010). Complexity, accuracy and practical applicability of different biogeochemical model versions. Journal of Marine Systems, 81(1-2), 44–74. doi:10.1016/j.jmarsys.2009.12.011

Los, F. J., M. T. Villars, & M. W. M. Van der Tol (2008). A 3- dimensional primary production model (BLOOM/GEM) and its applications to the (southern) North Sea (coupled physical–chemical–ecological model). Journal of Marine Systems, 74: 259-294.

Los, F., & Wijsman, J. (2007). Application of a validated primary production model (BLOOM) as a screening tool for marine, coastal and transitional waters. Journal of Marine Systems, 64(1-4), 201–215. doi:10.1016/j.jmarsys.2006.03.009
Pawlowicz, R., Beardsley, B. and Lentz, S. (2002). Classical tidal harmonic analysis including error estimates in MATLAB using T-TIDE, Computers & Geosciences 28, 929-937.

Postma, H. (1961). Transport and accumulation of suspended matter in the Dutch Wadden Sea. Netherlands Journal of Sea Research 1, p. 148-190.

RHDHV (2013). Maatregelstudie Eems-Dollard, Economie en Ecologie in balans Hydrodynamisch berekeningen en effectbepaling herstel maatregelen Eems-Dollard.

Rijkswaterstaat (2009). Programma Rijkswateren 2010-2015. Uitwerking Waterbeheer, 21e eeuw, Kaderrichtlijn Water en Natura 2000 Beheer- en Ontwikkelplan voor de Rijkswateren 2010-2015 (366 p).

Van Schie, M. en M. Firet (2014). Helder en productief. Structurele ecologische verbetering in het Eems-estuarium: voorstel voor een uitvoeringsagenda.

Schmidt, C, Hoijtink, R., Mulder, H., and van Maren, B. (2014). Plan van Aanpak voor Doorrekenen maatregelen t.b.v. verbetering slibhuishouding Eems-Dollard. Informele notitie d.d. 12 mei 2014.

Smits, J. G. C., & Van Beek, J. K. L. (2013). ECO: A Generic Eutrophication Model Including Comprehensive Sediment-Water Interaction. PloS one, 8(7), e68104. doi:10.1371/journal.pone.0068104

Uncles, R.J., Stephens, J.A., and Smith, R.E. (2002). The dependence of estuarine turbidity on tidal intrusion length, tidal range and residence time. Continental Shelf Research 22p. 1835 – 1856.

Van Kessel, T., Winterwerp, J. C., van Prooijen, B., van Ledden, M., Borst, W., 2011. Modelling the seasonal dynamics of SPM with a simple algorithm for the buffering of fines in a sandy seabed. Cont. Shelf Res. 31, S124–S134. DOI:10.1016/j.csr.2010.04.008

Van Kessel, T. and van Maren, D.S., 2013. Far-Field and Long-Term Dispersion of Released Dredged Material. Proc. of the XXth WODCON conference, 9 p. Van Leussen, W., Cornelisse, J., 1996. The determination of the sizes and settling velocities of estuarine flocs by an underwater video system. Neth. J. Sea Res. 31, 231–241.

Van Veen, J. (1950). Ebb and flood channel systems in the Netherlands tidal waters. Journal of the Royal Dutch Geographical Society, 67, 303:325.