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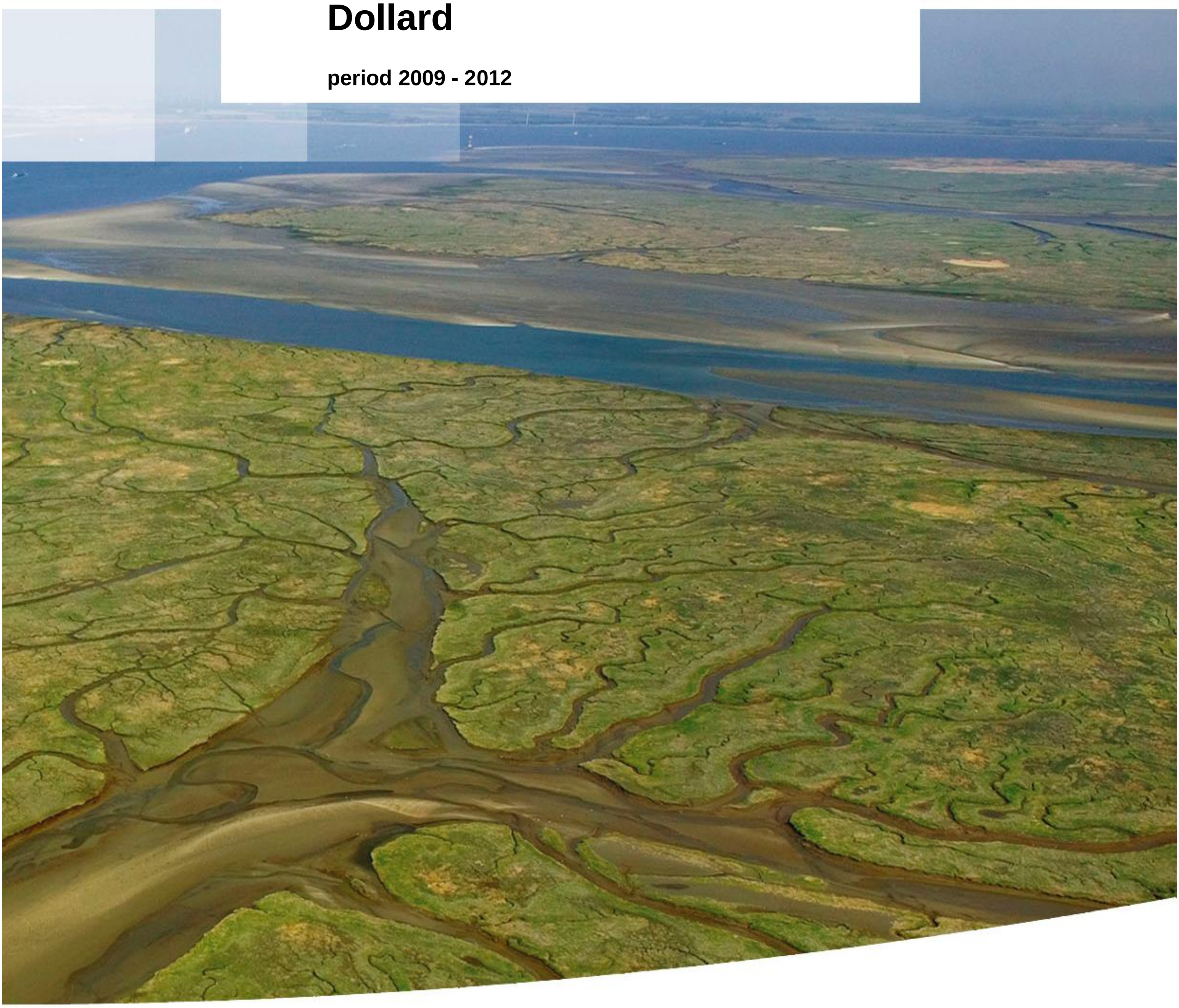
Development and application of effect chain model Ems-Dollard

period 2009 - 2012



Development and application of effect chain model Ems-Dollard

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Summary

This report describes the results of a project on the development and application of an effect chain model of the Ems-Dollard estuary. The project has been carried out in the years 2009-2012 by Deltares in the framework of applied research (KPP).

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Appendices

1 Introduction

This report describes the results of a project on the development and application of an effect chain model of the Ems-Dollard estuary. The project has been carried out in the years 2009-2012 by Deltares in the framework of the applied research contract (KPP) with the Ministry of Infrastructure and Environmental Affairs (I&M) within the theme ‘Healthy Water and Soil Systems under project code GWB16. The project has been supervised by the Waterdienst of Rijkswaterstaat in close cooperation with Rijkswaterstaat Directie Noord-Nederland.

Rijkswaterstaat is responsible for the management of the large water areas in the Netherlands. The Ems-Dollard is a transboundary water body that is managed by Germany and the Netherlands. The main reason for the development of the effect chain model is to have a good basis in order to identify and evaluate possible changes in the Ems-Dollard due to both natural and anthropogenic changes. The implementation and upcoming evaluation of few European Directives made the effect chain model development necessary. The model can give insight in the effects of measures being implemented in the Ems-Dollard, and quantify these effects, thereby contributing to qualitative discussions on future management measures. Also trends in autonomous development (i.e. with no human changes to present layout and use of the estuary) can thus be assessed. Such impact assessments contribute to a sound management of the system according to the European Water Framework Directive.

Measures primarily affect the physical parameters of the estuarine environment, in particular the currents and the silt concentration. It is the intention of this study to enable the quantification of the effects of the changes in these parameters via the under water light climate on the primary production (phytoplankton) and subsequently on higher levels of the estuarine food chain (invertebrates, fish and birds; schematized in Figure 1.1) by means of an integrated effect chain model.

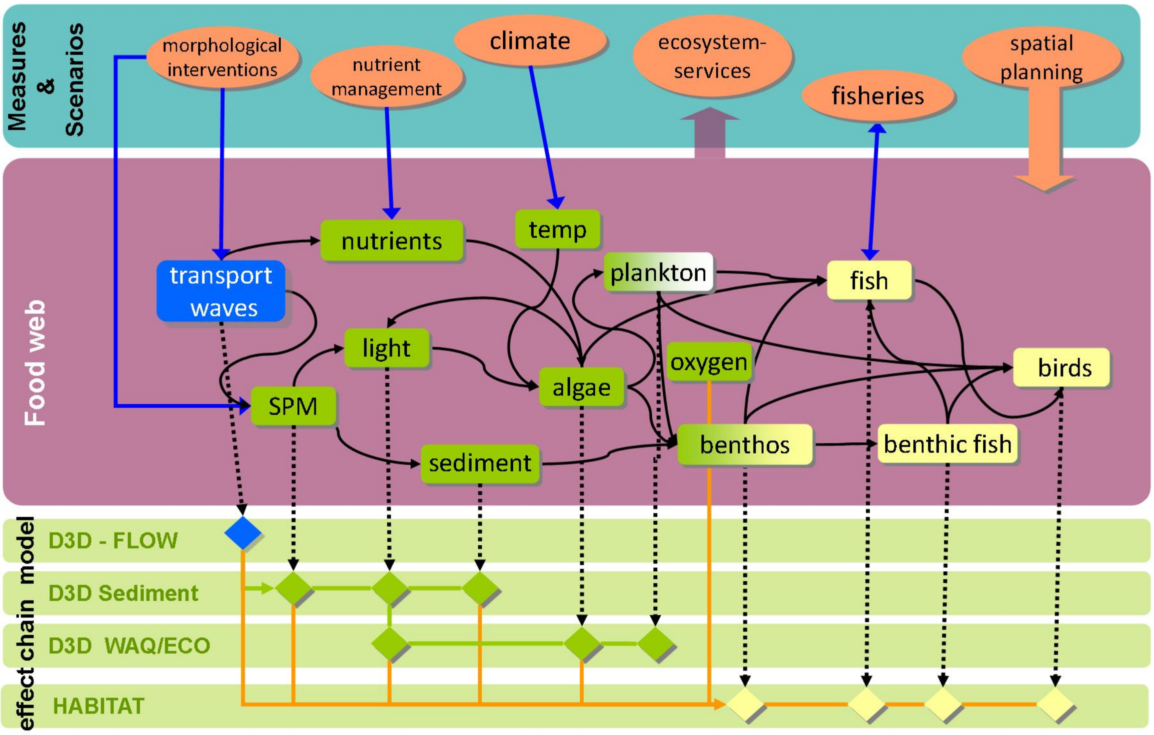

Figure 1.1: Schematic overview of effect chain and models

At the base of the effect chain model are three mass conserving deterministic models, integrated into one framework, which all allow for variations in time and space: First, a hydrodynamic model which simulates the driving forces of the natural system. This drives the second model, which simulates the transport of fine sediment. The third process-based model uses the water motion and sediment concentrations to calculate the transport of nutrients and the primary production.

This set of deterministic models provides the relevant abiotic and biotic conditions for the habitat model. The habitat model is a geographical information system (GIS) based tool that calculates the potential habitat suitability of species, using dose-effect curves.

The interaction between the two model types is one way interaction: there will be no reverse data streams from the habitat model to the deterministic models. This is a principal choice: since the deterministic models are defined on the level of functional groups and the habitat model aims at individual species the two approaches are fundamentally different.

All activities and results of the project have been documented in a series of yearly reports, which are listed in the References section at the end of this report. These yearly reports contain the details of the effect chain model of the Ems-Dollard estuary and its application, whereas the present report is meant for a quick access and overview.

In the next chapter, the main features of the Ems-Dollard estuary are described to provide the reader insight into the functioning of the system and its main features and trends. Subsequently, the set-up op the effect chain model is discussed, starting with hydrodynamics (Chapter 3), continuing with mud dynamics (Chapter 4) and nutrient transport and primary production (Chapter 5) and ending with habitat suitability evaluation (Chapter 6). The possible as well as actual application of the effect chain model is discussed in Chapter 7. The last chapter of this report discusses lessons learned (Chapter 8) and gives an outlook on further (modelling) actions in the Ems-Dollard.

2 System description

2.1 Present-day situation

The Ems-Dollard estuary is a partially mixed mesotidal estuary (tidal range 3.5 m) stretching from the island of Borkum on the seaward side to the weir in Herbrum at the landward side(Figure 2.1). The lower reaches are part of the Wadden Sea and mainly consist of deep tidal channels and sandy tidal flats (Figure 2.2). Sediment is redistributed by a combination of waves and strong tidal currents. The middle reaches of the Ems-Dollard consist of two tidal channel system around the Hond-Paap tidal flat, and the Dollard basin. The shallow and narrow channel West of the Hond-Paap is ebb dominated, while the flood channel East of Hond-Paap is deeper (30 m) and wide. The Dollard basin, created around 1209 by a series of storm surges flooding the low-lying hinterland, used to be substantially larger than it is today because of subsequent land reclamation activities since 1500 (Talke and De Swart, 2006).

The mud content of the soil increases in the upstream direction (Figure 2.2), especially on the tidal flats. The upper reaches of the estuary is the Emder Fahrwasser, continuing as Ems River upstream of Emden. The water depth varies from 4 to 8 m, and the salinity varies from 0 to 24 ppt. The freshwater discharge typically is 100 m^3/s. The Estuarine Turbidity Maximum (ETM) forms upstream of Leer, resulting in 2 m thick fluid mud (Figure 2.3). Of particular interest is that this high turbidity zone extends well into the freshwater zone, in contrast with most other estuaries. This may be caused by the asymmetry between flood and ebb currents, but also by turbidity currents and high loads of suspended matter (Talke and De Swart, 2006).

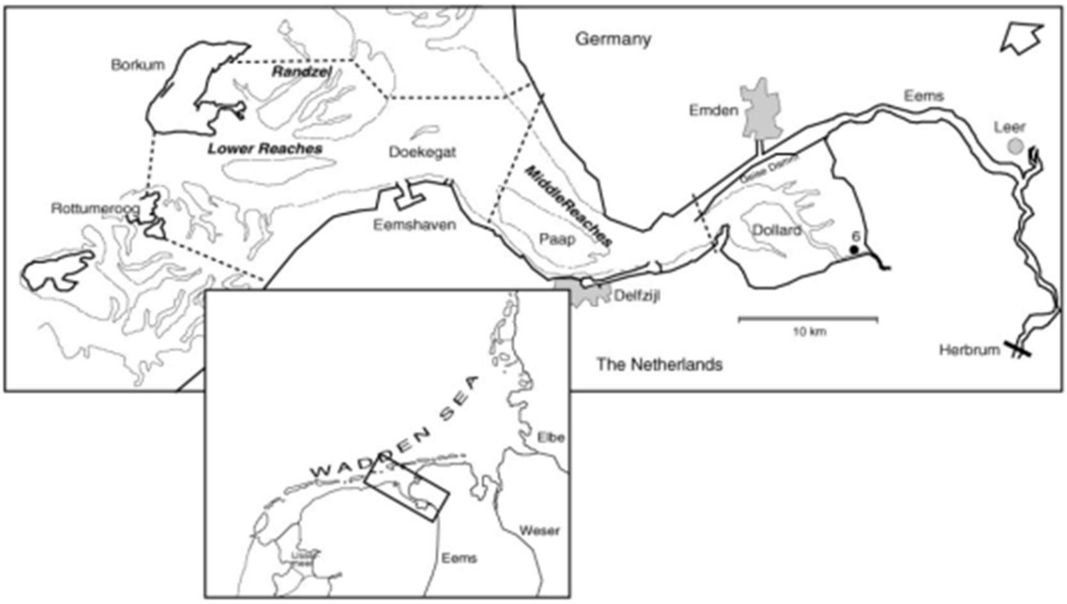

Figure 2.1 Map of the Ems estuary (from de Jonge, 2000).

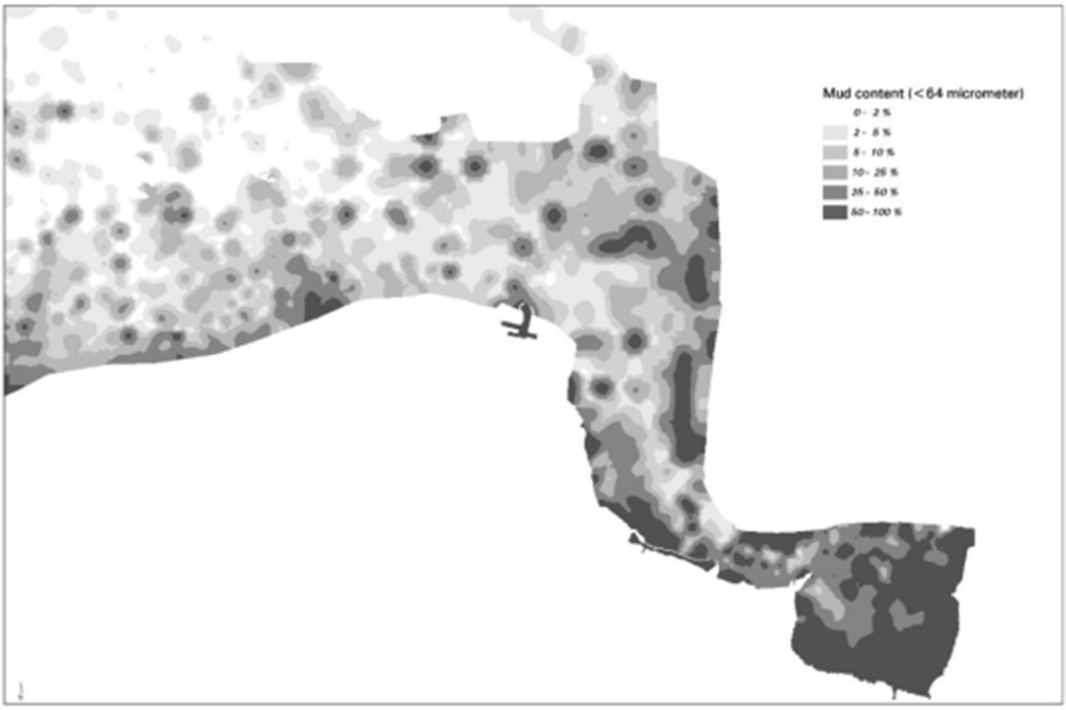

Figure 2.2 Mud content of the Ems-Dollard (from de Jonge, 2000).

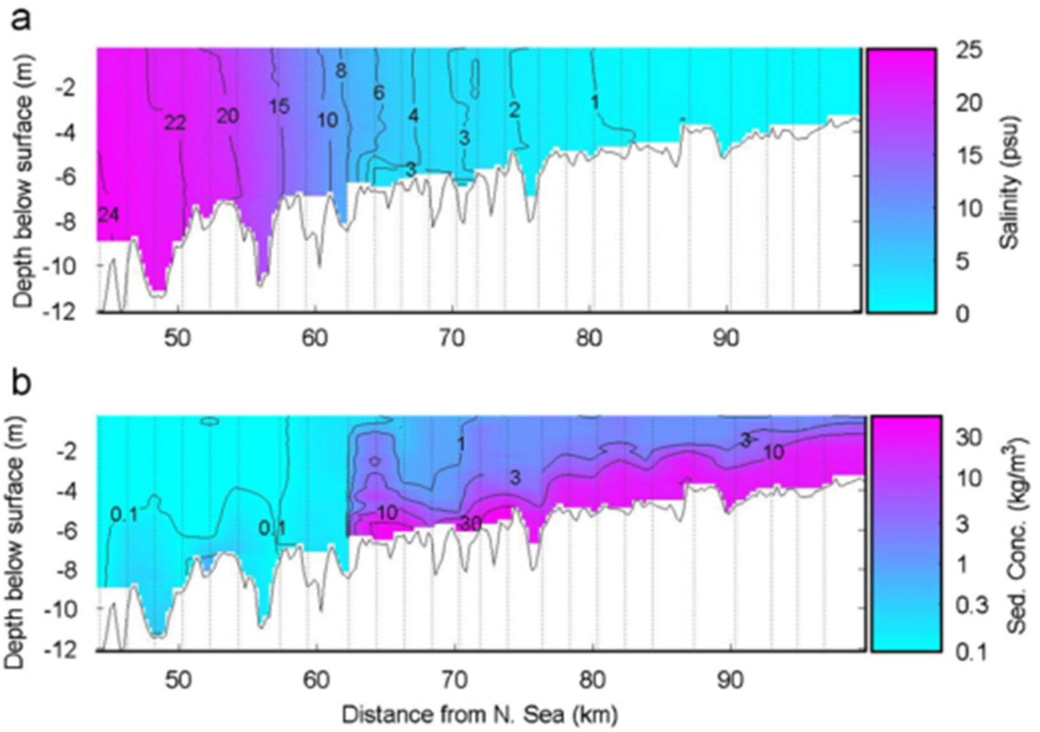

Figure 2.3 Longitudinal distribution of salinity (a) and suspended sediment concentration (b) along the Ems estuary during ebb tide on August 2, 2006. The 25 OBS/CTD casts are represented by vertical dotted lines. The cruise began just downstream of Emden (45km) approximately 4h before low-water (LW) slack, and ended in Herbrum (100km) at LW slack. From Talke et al., 2009.

2.2 Historic changes

In the past century, the hydrology and morphology of the Ems-Dollard region has been altered by human interventions, mainly dredging and land reclamation. Autonomous trends, such as sea level rise, have contributed to these changes. As a result, the tidal range has increased, while internal friction was reduced due to deeper and straighter channels and fluid mud formation. Compared to early 1900's, the tidal range at Herbrum has increased from 0 to 2.6 m, while the tidal range at Papenburg increased by 1.3 m (Talke and De Swart, 2006) due to decreased friction. In combination with a changed tidal asymmetry due to dredging (Talke and De Swart, 2006) and changing wind and wave climate, turbidity in the estuary has increased by 45 % over the last 30 years at Delfzijl (Mulder, 2004). Upstream, changes have been even more dramatic, and maximum concentrations of suspended matter increased from 100 mg/l (1954) to 5-25 g/l at present. Changes in tidal asymmetry and the large amounts of displaced dredging material (>10 $x10^6$ m^3 per annum) have resulted in changes in sediment transport and sedimentation/erosion patterns.

Anthropogenic water quality changes over the same period are large and have profound effects on ecological processes. Salinity fluctuations are unnatural due to regulated discharge patterns from polder sluices and pumps. Eutrophication with organic and inorganic nutrients has led to local hypoxia, while nutrient concentrations are too high in relation to the Water Framework Directive objectives. The estuary is also a nutrient source to the coastal North Sea, contributing to high biomass algal blooms in the area. Furthermore, despite measures, there are still problems with contaminant levels of TBT, PCB, metals, PAH, organic micropollutants. Sources are industrial waste water, diffuse input from agriculture and shipping. Moreover, water temperature is locally enhanced due to cooling water discharge from industry or power plants.

The changes in hydromorphological conditions and water quality have consequences for ecological processes. Primary production in the estuary is reduced due to increased turbidity. Eelgrass populations have deteriorated and salt marshes have decreased in quantity and quality, due to loss of suitable habitat. Macrozoobenthos communities have changed, due to dredging and dispersal of dredged material. The successful establishment of pacific oysters has furthermore changed benthic communities. Upstream bottlenecks in water quality and suitable (spawning) habitats have led to failing reproduction and recruitment of diadromous species; some diadromous species have disappeared already. Other fish species suffer from decreasing habitat due to turbidity or other water quality factors. Many of the causes to the loss in biodiversity can be tracked down to mainly two factors, anthropogenic eutrophication and increase of turbidity. As a result of high turbidity, eutrophication effects are at this moment limited to the outer regions of the estuary, because primary production in the inner part is severely light-limited due to this high turbidity. Thus, any measures directed towards habitat improvement by reducing turbidity, will have the unwanted effect to increase the risk for high biomass algal blooms in the estuary (Spiteri, 2010)

With respect to ecology several obvious changes have been reported. There seems to be considerable erosion of salt marshes. Loss of salt marshes is an international problem, as during the last decades salt-marsh areas all over the world are declining rapidly. Although many losses are caused by human pressures, causes are not always obvious. Similarly, methods to restore salt marshes are not always effective. In the Ems Dollard there seems to be a paradox. Although sediment availability is assumed to be sufficient, given the high concentrations of suspended matter, salt marshes are eroding. Apparently, marshes are unable to trap suspended sediment. This can be due to several potential causes, e.g. hydrodynamic conditions can be too dynamic for sediments to settle and consolidate.

Most of the ecological questions concerning the Ems-Dollard are linked to turbidity and the effects of fluid mud. One of the main effects of high turbidity levels is the decrease in primary production in the water column (De Jonge and Brauer, 2006). Influence of turbidity on benthic primary production in intertidal areas is considered to be modest (reference). Possibly, benthic primary production could benefit from low productivity in the water column because of a higher nutrient availability. However, the relation between benthic and pelagic primary production is a rather unexplored avenue.

2.3 Future changes and measures

Quality objectives for improvement of water quality have been formulated in the Water Framework Directive. Although there are differences in the way Germany and The Netherlands have defined these, there are very clear ambitions with regard to reduction of turbidity. How these objectives are going to be met, is not clear at this moment. The current study, and a follow-up project aiming at exploring different scenarios using the model set-up, gives more insight in the sediment behaviour and mechanisms that affect turbidity. If the turbidity will be reduced, it can be expected that phytoplankton and phytobenthos will reach higher production rates, and higher biomasses. For the Dutch part of the estuary, quality objectives with respect to the average chlorophyll-a concentration and the frequency of *Phaeocystis* blooms have been formulated in a river basin management plan (Spiteri, 2010). Therefore, measures to reduce turbidity will have to be accompanied by reduction of nutrient loads to the estuary. So, although nutrients loads to the estuary have already been reduced compared to levels in the 1970’s, further reduction will be necessary in order to comply with the quality objectives of the Water Framework directive.

The future changes in hydrology and morphology that are expected are mainly resulting from (see Jager *et al.*, 2009 for details):

- Extension of power plants, resulting in increasing thermal discharge and impingement of estuarine organisms
- Deepening of the navigation channel to Eemshaven
- Deepening of the navigation channel to Emden

The predicted changes in water quality are (see Jager *et al.*, 2009 for details):

- An increase in turbidity due to dredging
- A further extension of the oxygen depletion
- A reduction of nitrogen influx (and other nutrients?)

The ecology is expected to adapt to anthropogenic (by human demands and by restoration projects following legislation) and natural changes (climate change, regime shifts). Measures to mitigate the negative impact of these changes may consist of:

- Restoration of habitats e.g.
    - Restoration/preservation of sea grass
    - Reducing salt marsh losses in the Dollard
- Creating a salt water–fresh water transition near Nieuw Statenzijl.
- Creating fish passages and/or fish-friendly sluice policy near Delfzijl and Spijk
- Reducing turbidity caused by dredging
- Reducing the input of nitrogen
- Improving oxygen concentrations upstream of Emden

3 Hydrodynamic model

3.1 Grid layout

The grid layout of the hydrodynamic model is based on Alkyon's coarse model (Alkyon, 2008; see Figure 3.1). The depth is based on Alkyon's model as well, although the channel in the upstream parts of the Ems River is deepened and widened because the coarse grid resolution inhibited channel through flow. The bed level throughout the modal domain is depicted in Figure 3.2 and Figure 3.3.

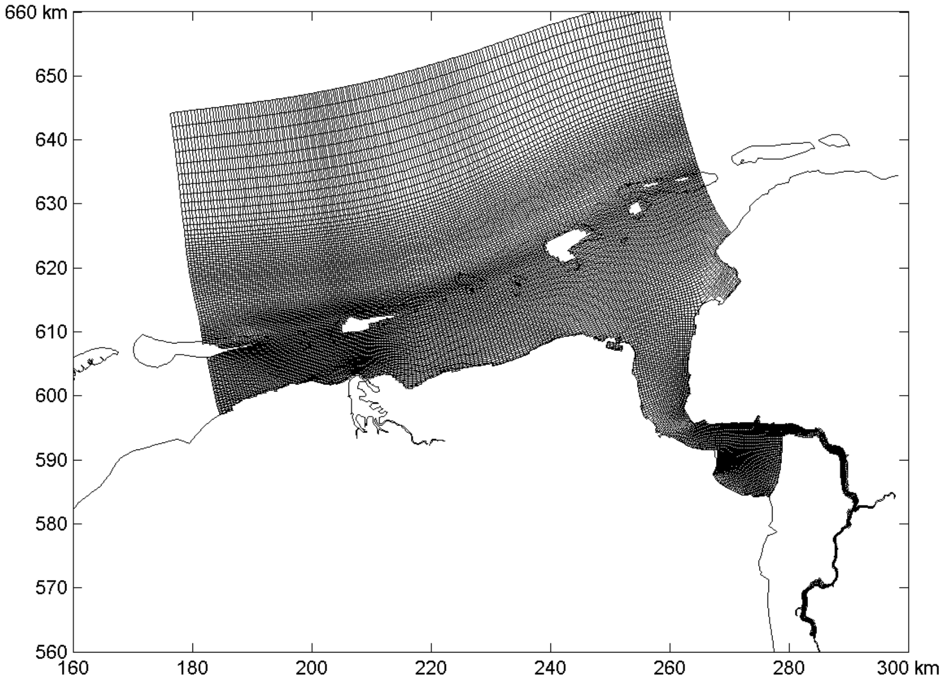

Figure 3.1 Model grid

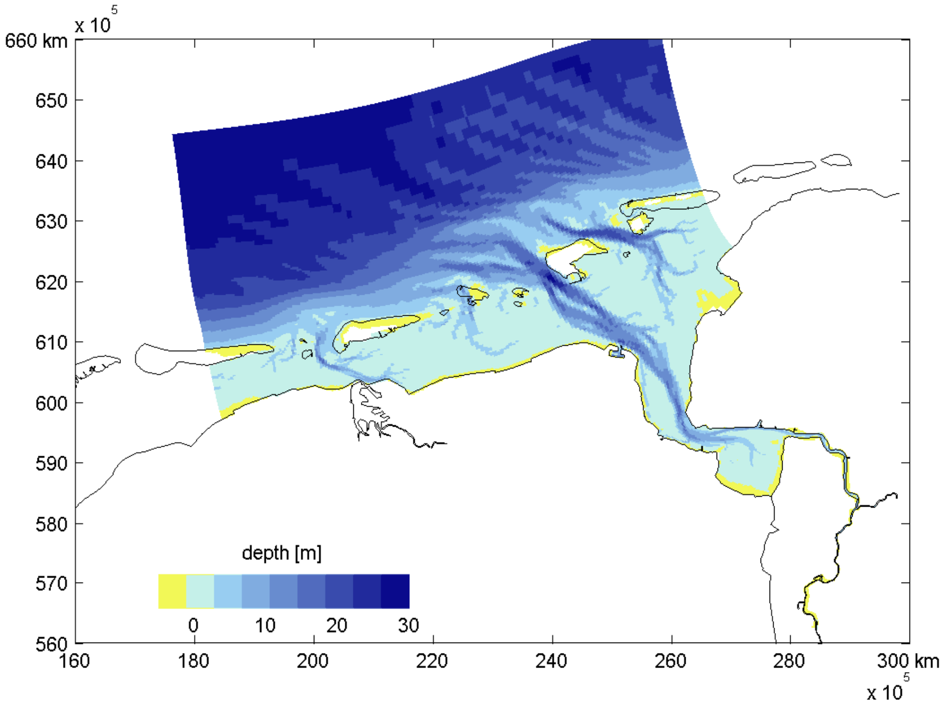

Figure 3.2 Water depth (m below NAP).

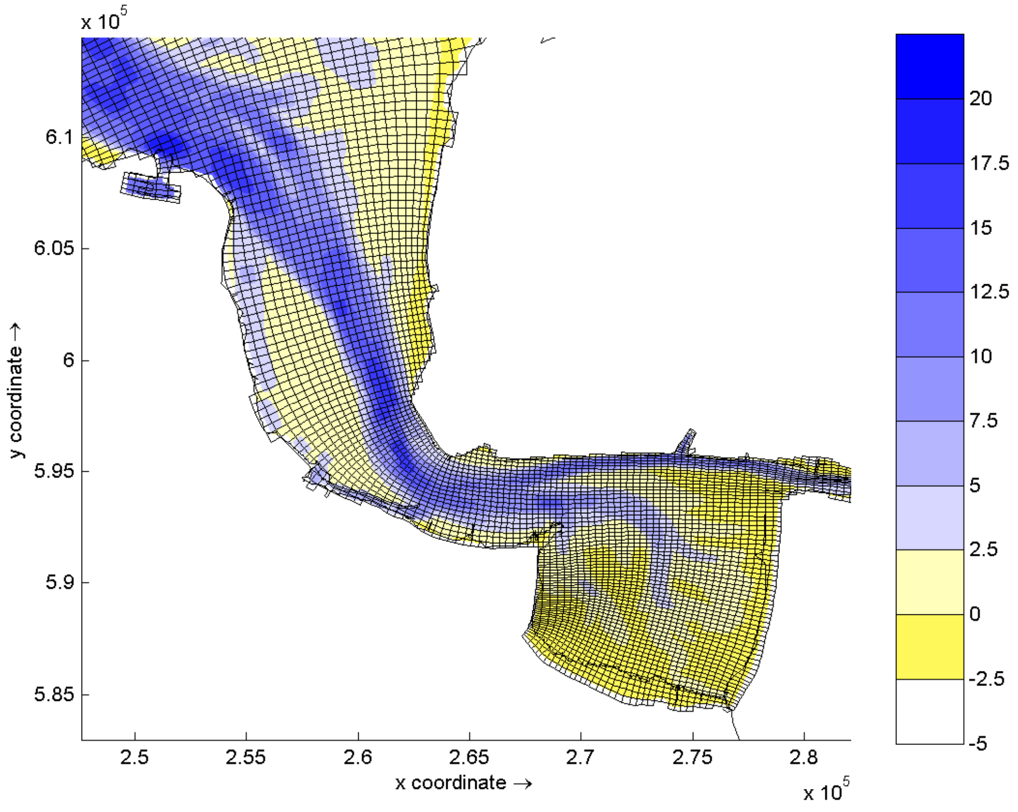

Figure 3.3 Detail of model grid and bathymetry.

3.2 Validation of hydrodynamics and salinity

The hydrodynamic model is adapted from the coarse 3D model (model grid with 189x321 cells horizontally and 8 sigma layers vertically) developed by Alkyon (2008). They developed several models of which a high resolution model (535 × 877) was calibrated most extensively. We briefly describe Alkyon's calibration of the coarse model, followed by an additional model validation performed with the adapted model.

The numerical settings for the hydrodynamics have been taken from the Alkyon (2008) model The layer thickness increases from near-bed to the water surface as 2, 3, 5, 8, 13, 19, 25 and 25% of the water depth. The Manning's hydraulic roughness decreases from 0.22 at sea to 0.12 in the upper Ems River. The horizontal eddy viscosity and diffusivity is 1 m^2/s and the background vertical eddy viscosity and diffusivity is 0.001 m^2/s. This relatively low Manning's roughness is needed to reproduce the upstream propagation of the tides, probably representing the low roughness due to sediment-induced damping of vertical mixing.

The calibration and validation of the hydrodynamics is described in the Alkyon (2008) report. Because of the importance of the upstream distortion of the tidal wave in the lower Ems River, we do an additional comparison with Van Leussen's (1994) data. This comparison is done qualitatively because we do not have boundary conditions for the measurement period, and an exact comparison also requires the exact bathymetry of that period. His nearly simultaneously collected through-tide measurements provide a data set covering the estuary from the seaward part to the lower Ems River. His data shows a rapid increase in flood velocities followed by a slow transition to maximum ebb currents (slack tide asymmetry) throughout the model, but especially in the upstream reaches of the lower Ems River. Simultaneously, the peak of the flood currents exceeds the peak of the ebb currents (again, more pronounced in the lower Ems River than in the estuary), compensated by a longer duration of ebb than flood (maximum flow asymmetry). Modelled water levels and flow velocities qualitatively agree with this pattern. Possibly the computed asymmetry in maximum flow velocities in the lower Ems River is slightly underestimated; although this difference may also result from the difference in location and hydrodynamic conditions (details of the tide, discharge). Most importantly, however, the typical asymmetry in the velocity field and in the water levels is reproduced by the model.

3.3 Adaptations made in the present study

Boundary conditions from the Alkyon model were only provided for the period May 2001. For other periods new boundary conditions have been constructed from an operational water level prediction model. For this purpose the Ems model was nested in the Kuststrook model, a SIMONA model maintained by RWS. The existing Ems-model was extended with temperature and was re-run with the 2001 boundary conditions. Figure 3.4 and Figure 3.5 show the results with regard to water level and salinity. Figure 3.6 shows the variation of the freshwater discharge over the year. Although the performance of the hydrodynamic model could still be further improved, results are judged suitable for further application in the mud transport and water quality models for the purpose of system understanding and sensitivity studies. Note that the largest deviations between modelled (black) and observed (red) water levels (see Figure 3.4) is caused by the boundary conditions (blue = Kuststrook model). For quantitative impact assessment of water levels, temperature and notably salinity further calibration is recommended. Apparently, the freshwater discharge into the Dollard (at Nieuw Statenzijl) is too low during periods of high discharge, explaining the too weak model response to freshwater discharge peaks in and overprediction of salinity at Groote Gat Noord.

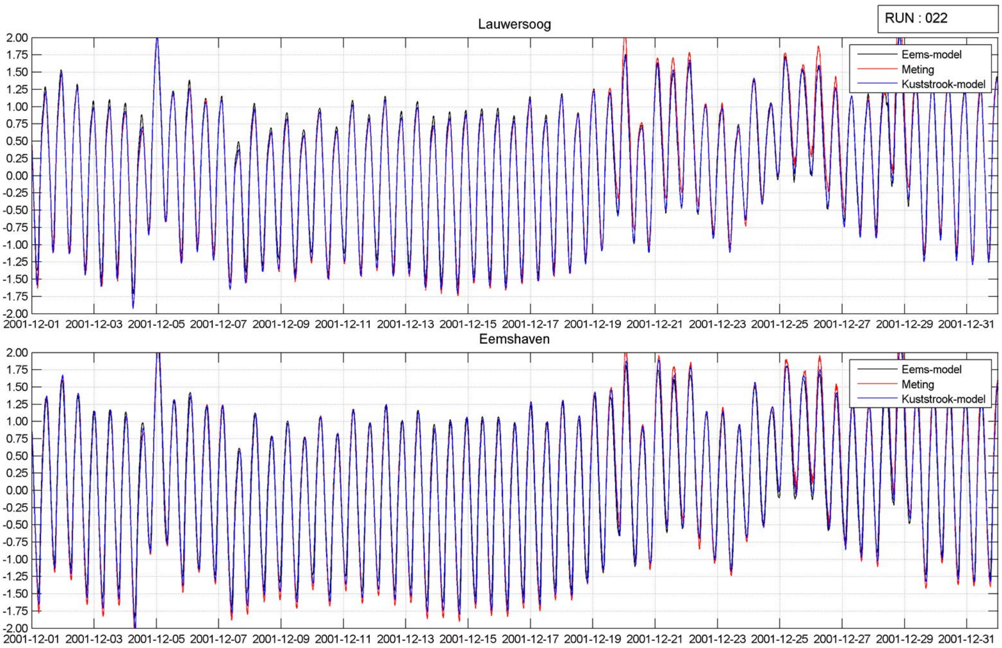

Figure 3.4 Measured and modelled water level at Lauwersoog and Eemshaven in December, 2001.

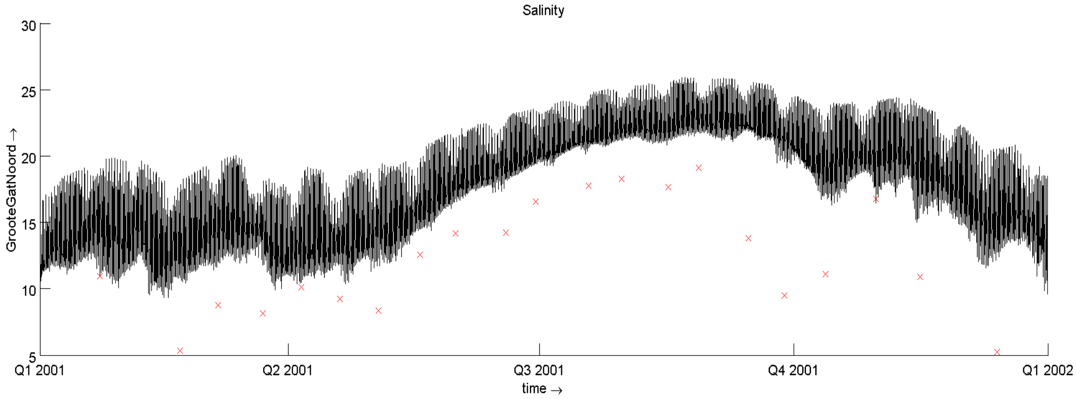

Figure 3.5 Measured (red marks) and modelled (black line) salinity (ppt) at Groote Gat Noord in 2001.

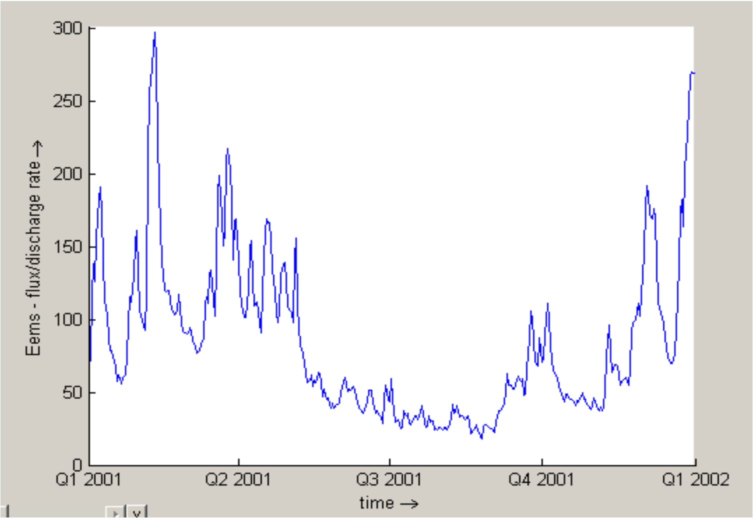

Figure 3.6 Applied Ems discharge (m^3/s) in 2001.

4 Fine sediment model

With regard to fine sediment transport, two types of models have been developed:

1. A model for the Ems and notably the Upper Ems (with density and without coupling), implemented in Delf3D-sedonline
2. A model for the Ems-Dollard (without density coupling), implemented in Delft3D-WAQ

The model with density coupling takes into account the effect of suspended sediment on fluid density. In this way a feedback between sediment dispersion and hydrodynamics is introduced. This coupling is only important for conditions where salinity- and temperature-induced density differences are secondary to sediment-induced density differences. This will occur in the Ems-river, where fluid mud layers are observed. Density coupling is less important for large-scale sediment transport in the Ems-Dollard, where the sediment concentration is lower.

4.1 Model with density coupling

The model with density coupling includes the basic formulations for fine sediment transport (advection – diffusion equation) and erosion /deposition (Partheniades – Krone). This modelling approach qualitatively reproduced the sediment dynamics in the Ems estuary and Ems River (as long as the effect of sediment on the density is accounted for), and a relatively large settling velocity of 1 to 2.5 mm/s was applied. The large settling velocity induces strong vertical concentration gradients, which in combination with the sediment-density coupling leads to suppression of turbulence in high-concentration areas (Figure 4.1). Since the flood flow velocity exceeds the ebb flow velocity in the Ems River, this enhances its trapping efficiency. The typical modelled sediment concentrations and the transport rates in the Ems Estuary agree well with measurements even though processes that are probably very important (flocculation, consolidation, re-entrainment) are not (yet) accounted for.

The sediment dynamics in the Dollard –both the sedimentation and the sediment concentration- are underestimated by the model. This may be caused by the relatively simple formulations used, but may also be caused by the model settings, model resolution, or time scales. Therefore an additional model was setup, in which more advanced erosion / sedimentation processes are implemented.

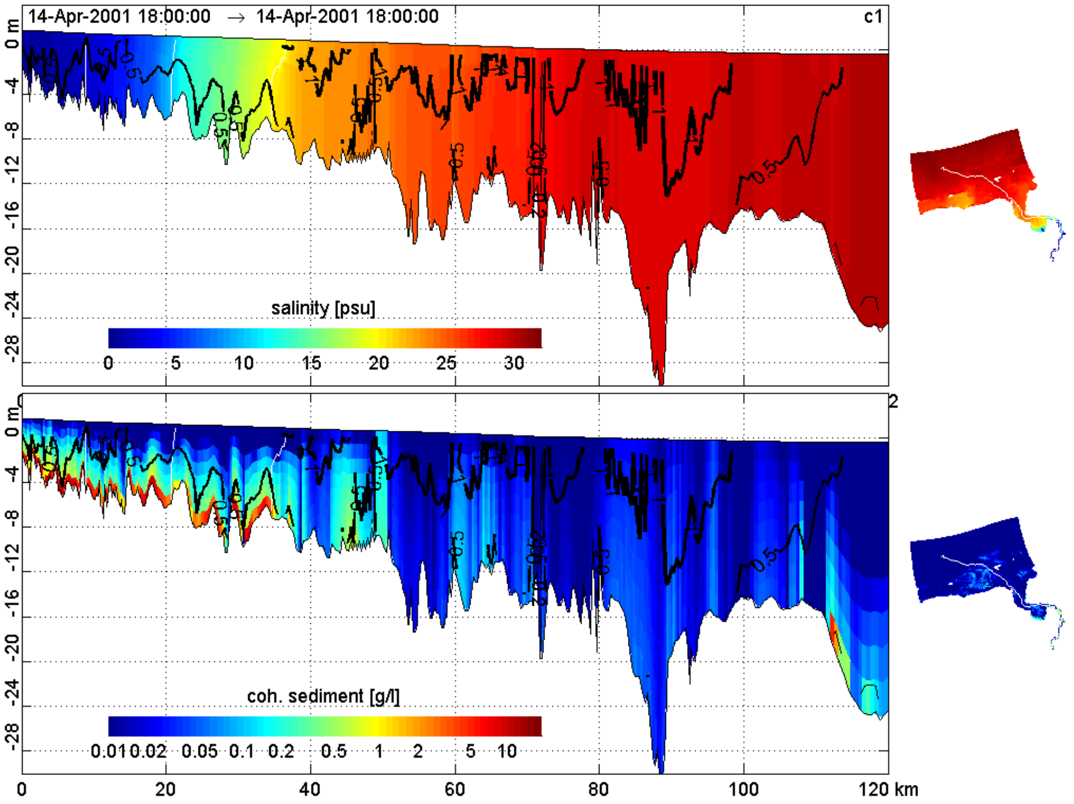

Figure 4.1 Modelled salinity (top) and sediment concentration (lower panel), with longitudinal flow velocity in black contour lines and salinity in white contour lines (lower panel only), for simulations with w_s = 2.5 mm/s, sediment-induced density effects, restart with Morfac = 1 (run 70), during ebb.

4.2 Model without density coupling

Delft3D WAQ offers more advanced formulations for sediment erosion and deposition, but does not allow the sediment-induced density coupling. Instead of a single bed layer, two bed layers are included, each with a different critical shear stress for erosion. Also, the erosion rate depends on the bed composition up to a certain limit: the higher the mud fraction, the higher the erosion rate. Beyond this limit, the erosion rate becomes independent from the mud availability. More details hereon are described in Dijkstra *et al.* (2011).

The model without density coupling, wave-induced resuspension is taken into account in either of two ways: 1. with a simple fetch-length approach or 2. with an assimilation method in which wave height and period observed with wave buoys is interpolated on the model grid using the year-average spatial distribution of wave height and period computed with SWAN, a well-known wave propagation model. These approaches are adopted to avoid excessive computation time that would be required to generate wave fields with SWAN on an hourly basis for a complete year. However, there approaches have a limited accuracy on a local scale which reduces their suitability for use for local habitat evaluation, see Section 8.3.

The more advanced formulations for erosion and deposition in the model without density coupling result in a better reproduction of observed sediment distribution on the bed in the Ems-Dollard (Figure 4.2). Also, the modelled suspended sediment concentration level at Groote Gat (in the Dollard) is in good agreement with observations (Figure 4.3). The pronounced seasonal dynamics at Huibertgat Oost is not reproduced by the model. It is noticed that this trend is exceptionally strong in 2001, in other years the observed trend is weaker. Figure 4.4 shows the computed spatial concentration distribution in the Ems. The computed gradual landward increase agrees with observed gradients from monitoring stations and remote-sensing data.

However, due to the absence of density coupling, the concentration at the Upper Ems becomes too low compared to observations. Also the amount of deposition in the Dollard area remains well below estimates based on field data (Figure 4.5). A higher critical shear stress for erosion would enhance deposition, but also would result in a lower suspended sediment concentration. As a realistic mud concentration in the water column is much more important higher up in the effect chain than a realistic deposition rate, the critical shear stress has not been increased to enhance deposition. These settings result in a mud balance with an import of 145 kton/y from the Ems estuary to sea, resulting from a fluvial import of 600 kton/y and a net deposition in the estuary of 745 kton/y. The net import of 145 kton/y is divided over an import of 300 kton/y for the coarse mud fraction (w_s = 1.25 mm/s) and an export of 155 kton/y for the fine mud fraction (w_s = 0.2 mm/s).

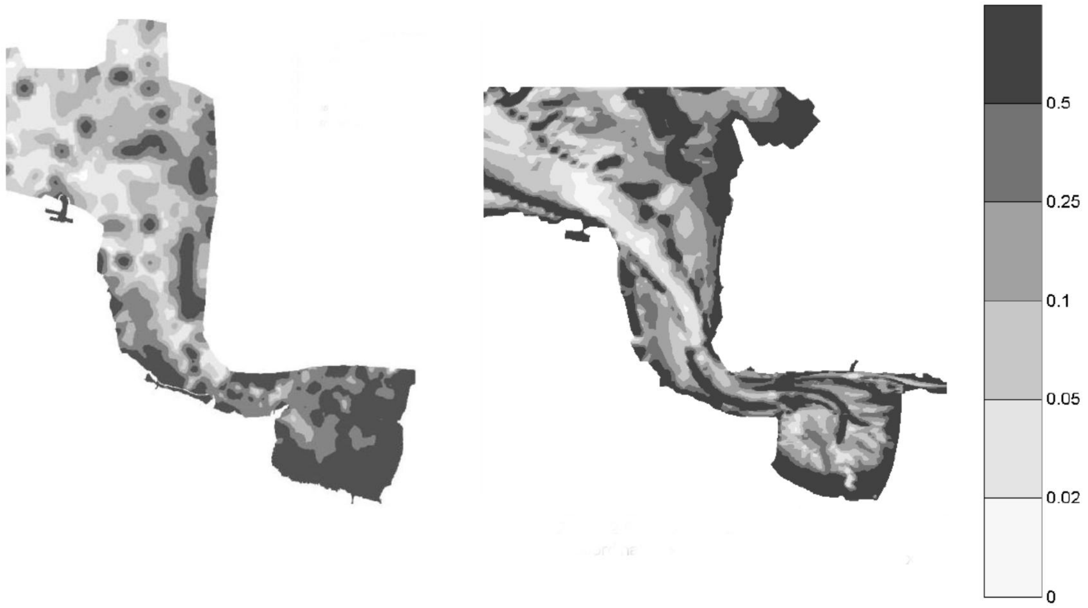

Figure 4.2 Observed (left, De Jonge, 2000) and modelled (right) mud fraction.

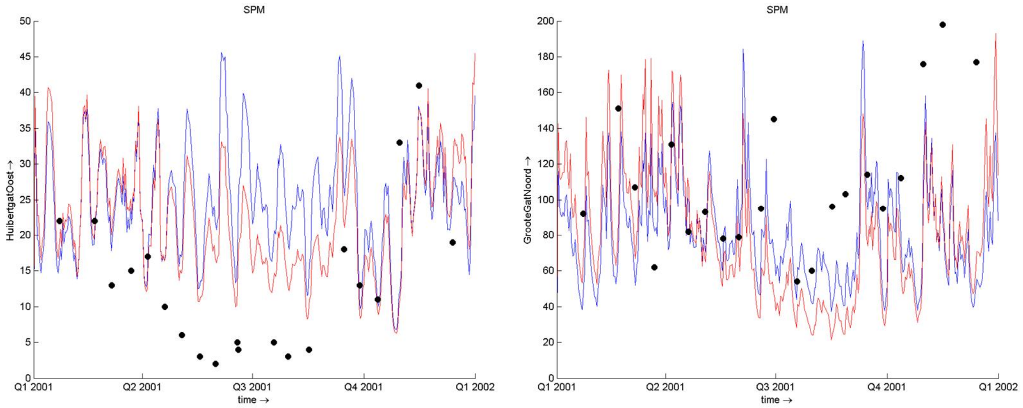

Figure 4.3: Modelled (lines) and observed (black dots) near-surface SPM concentration (mg/l) at Huibertgat Oost (left) and Groote Gat Noord (right). The blue lines represent a simulation with constant settling velocity; the red lines represent a simulation with temperature varying settling velocity. Year = 2001.

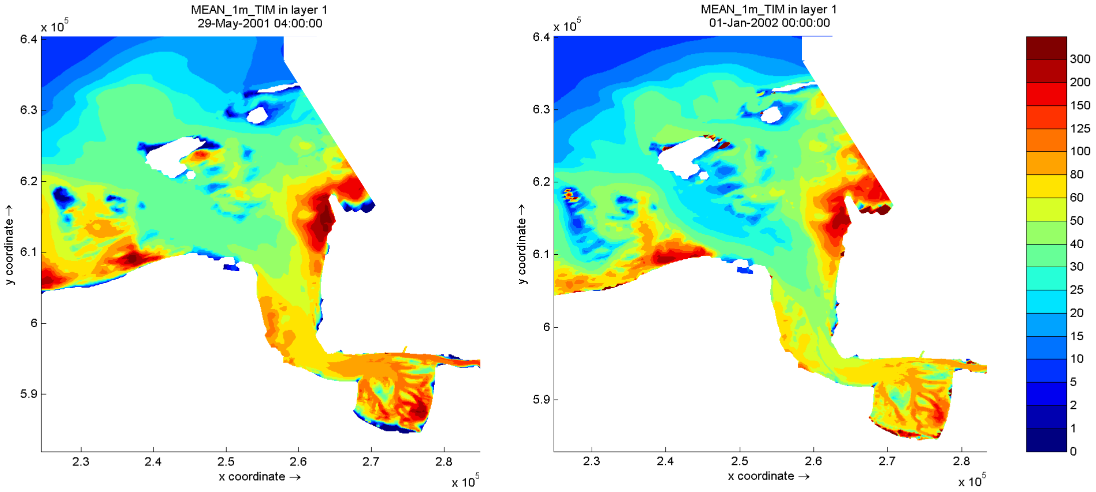

Figure 4.4: Modelled near-surface SPM concentration (mg/l). Left: averaged over May 2001. Right: averaged over the whole year 2001.

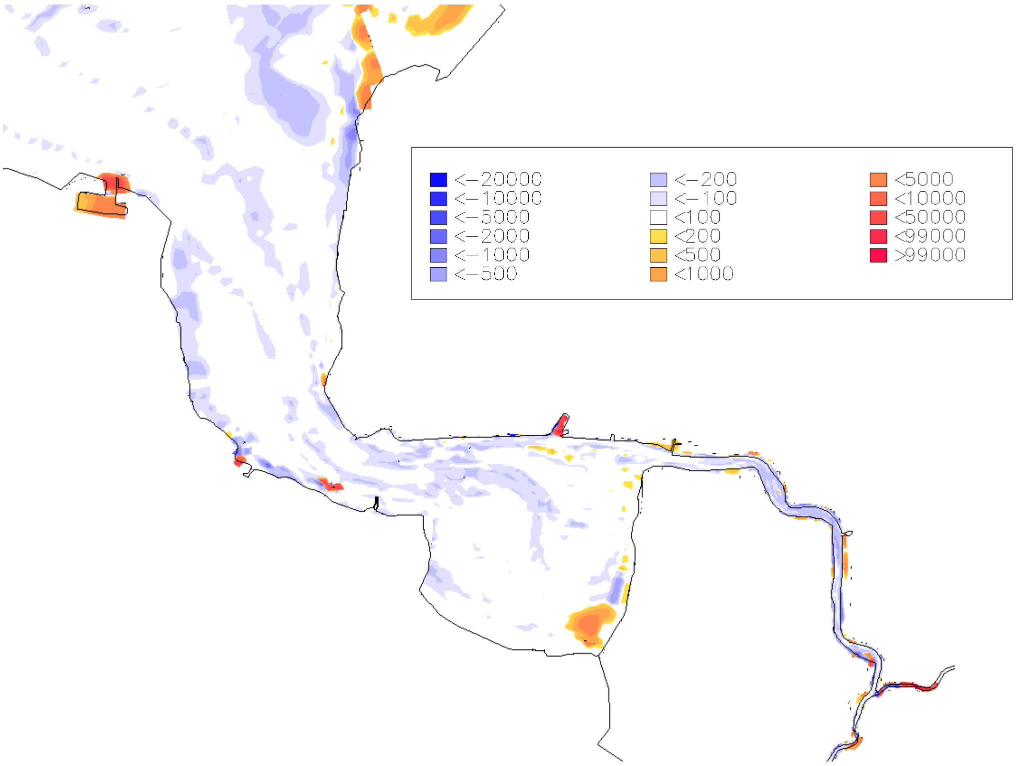

Figure 4.5 Computed net erosion and deposition (g/m2/y); net changes of 5000 g/m2 correspond to 1 cm.

Conclusively, there are two sediment transport models available for sediment transport in the Ems-Dollard estuary. The 2009 model better reproduces sediment import into the Ems River, but the 2010 WAQ model better reproduces sediment dynamics in the Ems and Dollard estuaries. As proper mud concentration levels in the water column are most important for the computation of primary productions, only the WAQ results are used higher up in the effect chain described in the next chapters.

5 Water quality and primary production model

5.1 Introduction

The average phytoplankton biomass is at acceptable levels as compared to the Water Framework Directive levels for good water quality (van Maren *et al.*, 2010), despite the high nutrient loads. This is mainly due to the high turbidity caused by man-made morphological changes. Measures that reduce turbidity in the estuary may therefore lead to unwanted high-biomass algal blooms in the estuary. The question arises what exactly is the interplay between turbidity and nutrient discharge from land in balancing the phytoplankton biomass during a season. Additionally, benthic primary production is of importance for the overall carrying capacity for higher trophic levels in the estuary. Therefore, decisions on measures to improve water quality should also consider the effects on benthic primary production.

The aim of this study is to develop a robust and quantitative assessment modeling tool to support management decision related to site-specific issues, such as the effect of nutrient inputs and dredging activities on water quality in terms of benthic and pelagic primary production and oxygen concentration.

5.2 Principles of the water quality and primary production model

The water quality module (Delft3D-WAQ/Eco) is part of an effect chain model. It uses transport and dispersion rates as well as temperature fields from the hydrodynamic model (Delft3D-Flow). Suspended sediment concentrations necessary to calculate light availability for primary production were obtained by a sediment model (Delft3D-Sediment) (see Chapter 4). The off-line coupling of these models ensures efficient recalculation of water quality and ecological parameters without running the hydrodynamic and sediment model. Results from all three models were used by the habitat suitability model which is discussed in Chapter 6. The water quality and primary production model was set up for a reference year (2001).

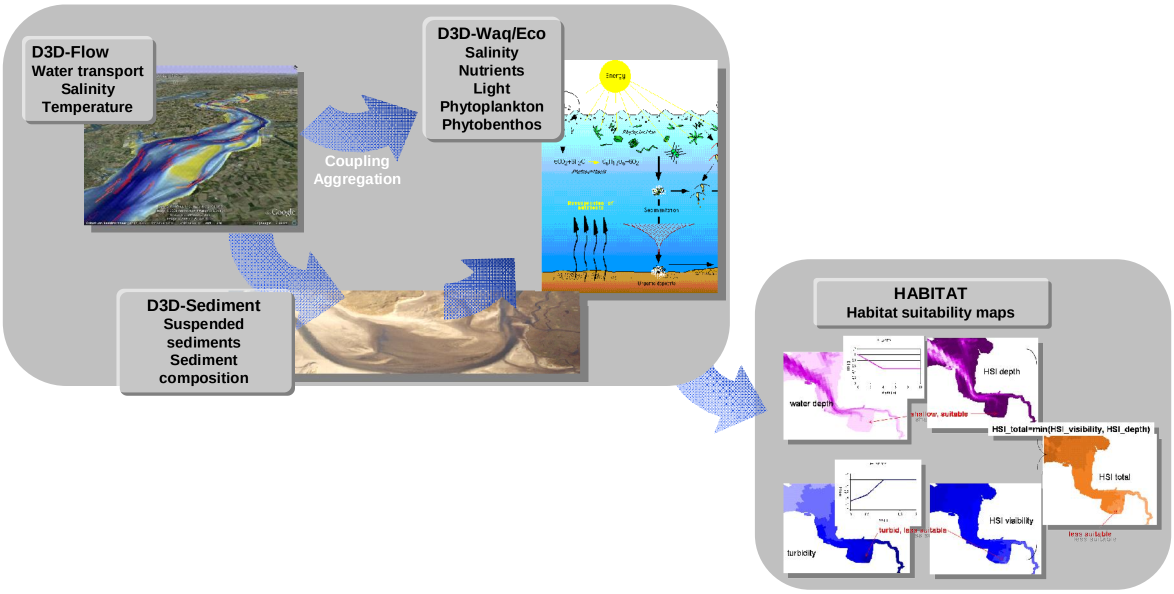

Figure 5.1 Schematic visualization of the model input into the water quality model D3D-Waq/Eco. Hydrodynamic flow fields, temperature are imported from the D3D-Flow model, suspended sediment concentrations are imported from the D3D-Sediment model.

The spatial grid on which water quality and primary production was calculated was based on the hydrodynamic grid. It was aggregated horizontally depending on the depth (Figure 5.2). Salinity profiles through the estuary calculated with the water quality model do not show a deterioration of the salinity gradient as compared to the results of the hydrodynamic model, indicating that the aggregation does not have a significant effect on the transport of substances in the estuary (Van Kessel et al., 2012).

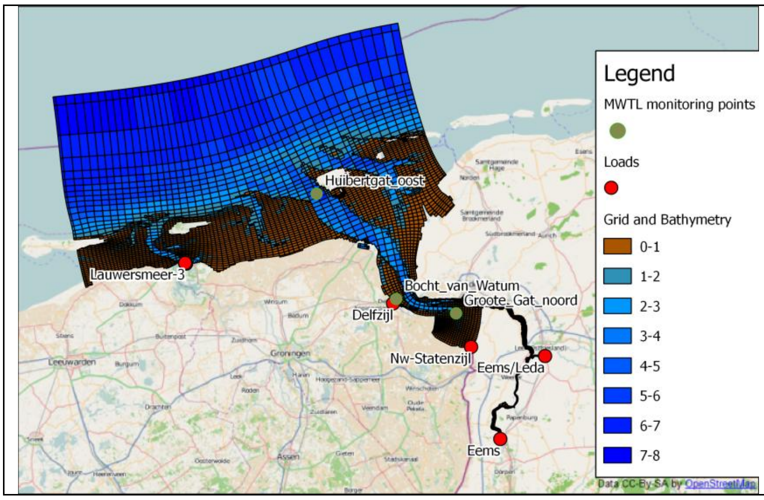

Figure 5.2 Model schematization for Ems-Dollard water quality model (D3D-WAQ). The grid is based on the hydrodynamic grid. For this purpose, the water quality grid is 2x2 cells aggregated for parts shallower than 5 meters, and 4x4 in deeper (>5 meters) parts of the estuary. MWTL monitoring points for validation and discharge points (Loads) are indicated.

5.2.1 Water quality and primary production processes

The growth of phytoplankton and phythobenthos is modelled as a function of light and nutrients (Los et al. 2008, Blauw et al. 2008). Four groups of phytoplankton are distinguished by the model, diatoms, dinoflagellates, *Phaeocystis* sp. and other flagellates. These groups differ in their physiological characteristics with regard to light response, nutrient quota and mortality rates. The model also includes one group of microphytobenthos, a benthic marine diatom. Three different types exist of each group representing light-, nitrogen or phosphorus limited phenotypes. Mortality of algae has a density-dependent and a salinity-dependent component, and dead algal material enters the detritus fraction, which can be remineralized in the water or after settling in the sediment. Nitrification and denitrification are included, both in the water column and in the sediment.

5.2.2 Validation

The water quality and primary production model was checked for consistency and validated for three MWTL monitoring stations in the estuary. Average levels of total nitrogen compared well to the observed values. Phosphorus concentrations have not been described satisfactorily at this stage, probably because the complex interactions with the sediments have not been incorporated yet. Despite an incomplete model description of the phosphorus cycle, modelled chlorophyll-a and oxygen concentrations still approximate the observed values (Figure 5.3). This is explained by the stringent light limitation during most of the year in large parts of the estuary. The highly dynamic fluctuations in the modelled chlorophyll-a at Groote Gat Noord station could not be validated, since no measurements with sufficient time resolution are available.

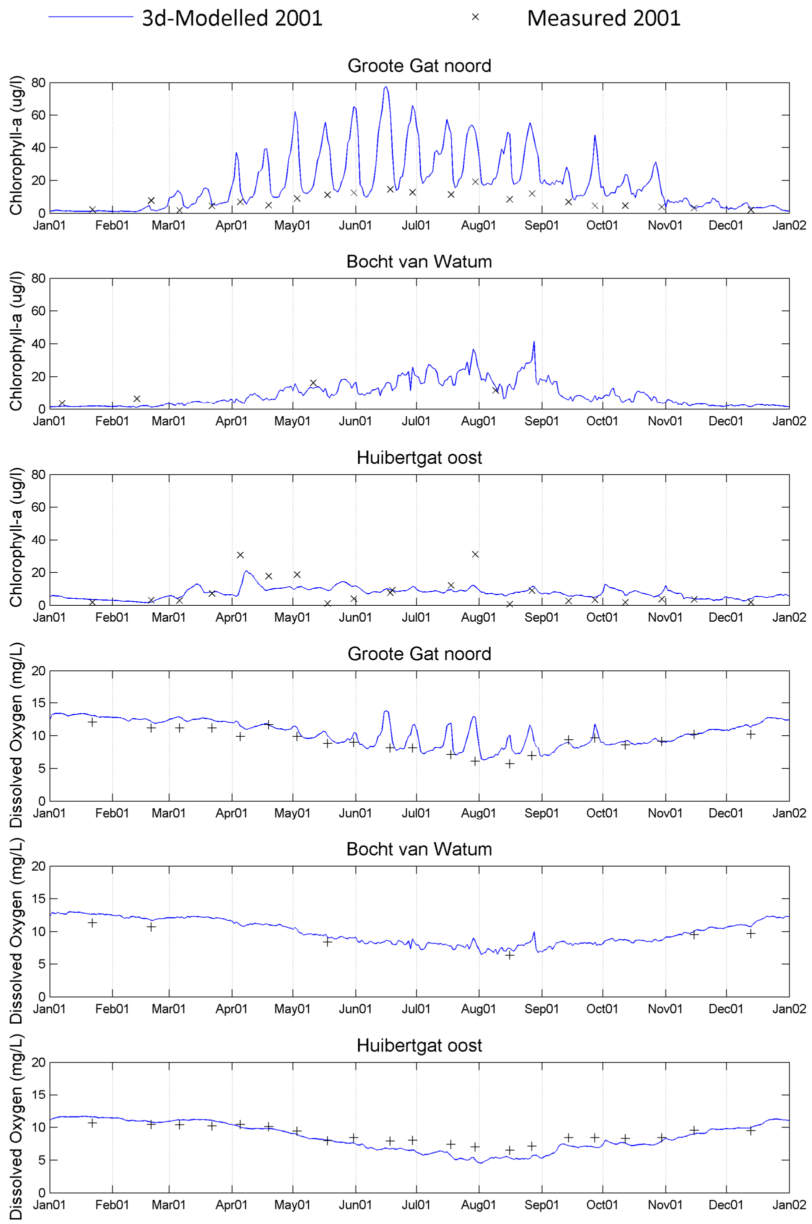

Figure 5.3. *3D modelled and observed concentrations of chlorophyll-a (top three panels) and oxygen (lower three panels) at three different monitoring stations in the Ems-Dollard estuary.*

5.3 Example results

5.3.1 Distribution of pelagic and benthic algae and substances

Spatial patterns of ecologically relevant substances and processes can be used to asses the ecological status of the estuary beyond the temporal and spatial limitations of monitoring programs.

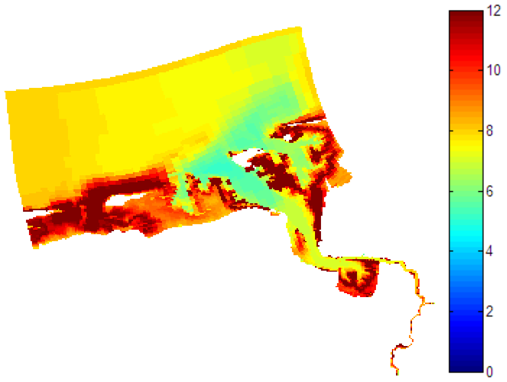

Figure 5.4. Modelled spatial distribution of dissolved oxygen concentration at 23 July 2001.

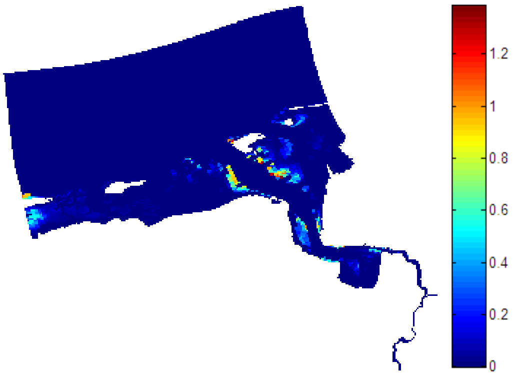

Figure 5.5 Snapshot of benthic diatoms biomass (in mgC/m^2) in the Dollard area modeled with Delwaq BLOOM. Growth is restricted to shallow areas due to light limitation.

For example, dissolved oxygen concentrations in the lowest water layer (Figure 5.4) can be used to assess the suitability for benthic habitats, which is further described in section 6. Another example is the assessment of benthic primary producers (Figure 5.5), information that can be used to better estimate the carrying capacity for benthic life. When better measurements come available within the planned monitoring program of benthic primary production during 2013, the benthic algae module will be recalibrated and validated to better fit the observed patterns (van Maren *et al.*, 2011).

5.3.2 Nitrogen budgets

Nitrogen budgets of the different parts of the estuary show the net sinks and sources of nitrogen compounds, and the net transport through the estuary. For example, it can be used for quantifying the role of the estuary as a net source of nitrogen to the coastal North Sea, where it contributes to coastal eutrophication effects. During the reference year 2001, most of the nitrogen coming into the estuary is transported to the Wadden Sea and North Sea (roughly 25 000 tonnes yr^{-1}). Only a small portion (2 000 tonnes yr^{-1}) is retained in the estuary by sedimentation or removed to the atmosphere by denitrification (red figures in Figure 5.6). These figures compare well with estimated budgets during 1975-1976 (van Beusekom & de Jonge, 1998). They found a seaward transport of 25 000 tonnes nitrogen yr^{-1}, and a retention of less than 1 000 tonnes nitrogen yr^{-1}.

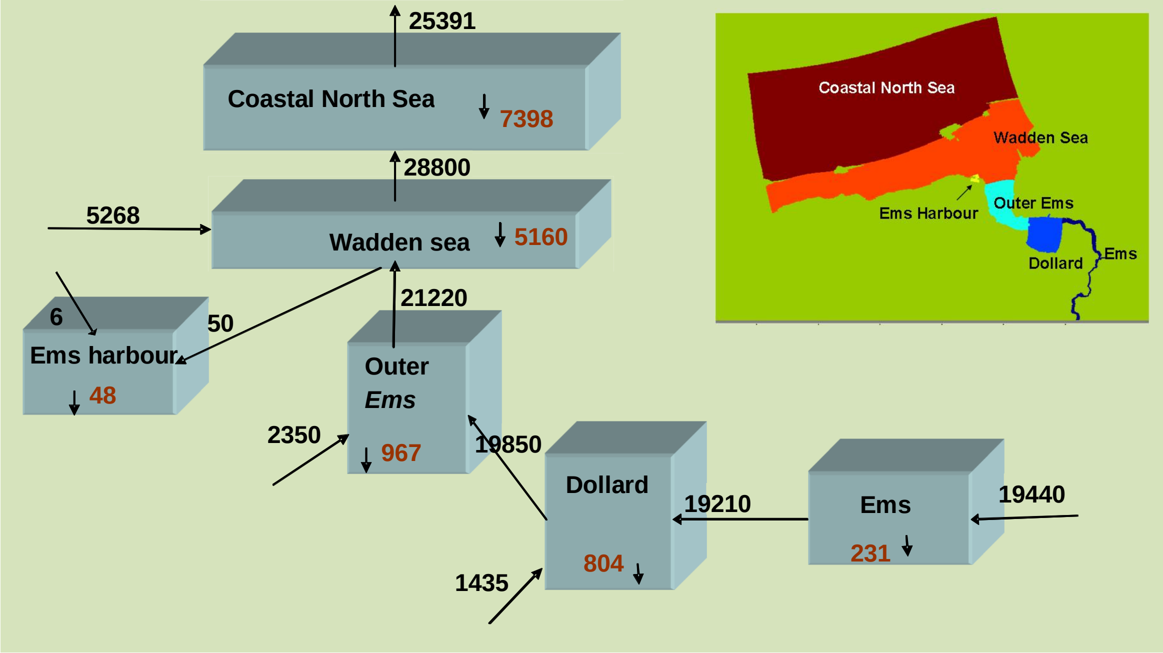

Figure 5.6 Nitrogen (tonnes/yr) budgets through the different parts of the estuary for the reference year 2001. Numbers in red are nitrogen fluxes to the sediment due to sedimentation or atmosphere due to denitrification.

6 Habitat evaluation model

6.1 Introduction

The objective of this Ems-Dollard effect chain modelling study was to identify and describe the biotic and abiotic factors that determine the structure and functioning of this particular estuarine system, and to facilitate the assessment of impacts that may result from natural or anthropogenic changes. An overview hereof is shown in Figure 6.1.

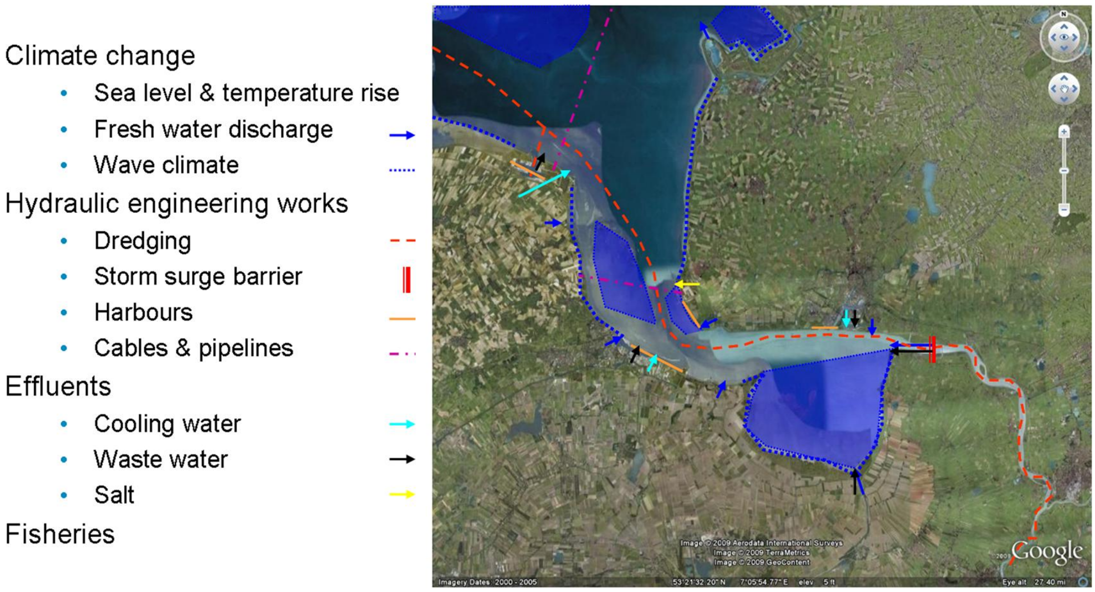

Figure 6.1 Type and location of main activities in the Ems-Dollard basin.

6.2 Species of the Ems-Dollard ecosystem

The report by Talke and de Swart (2006) gives a good overview of existing models and literature as well as changes to the system. The Ems-Dollard ecosystem has considerable spatial gradients in e.g. salinity, turbidity, depth, and therefore accommodates many different organisms, which are inexhaustively mentioned here.

Phytoplankton and microphytobenthos are the most important primary producers in the estuary and are dealt with in chapter 5. Macroalgae or seaweeds-, like e.g. sea lettuce (*Ulva spp.*) and bladder wrack (*Fucus vesiculosus*), are mostly attached to hard substrates like rocks, stones or shells and provide a shelter and food source for other organisms. Although they can be locally important, they have not been included in the effect chain model.
Two groups of higher plants occur: the seagrasses *Zostera marina* (eelgrass) and *Zostera noltii* that occur on the intertidal flats, and a number of species (e.g. *Spartina anglica*; Cordgrass, *Salicornia europaea;* marsh samphire, *Phragmites australis*: common reed) that occur on or just in front of the salt marshes at the margins of the basin.
The benthic macrofauna group, i.e. the group of invertebrates that live in or on top of the bed, contains many different kinds of animals: molluscs, polychaetes and crustaceans. An extensive overview of all species of macrofauna in the Ems-Dollard area can be found in Ysebaert et al. (1998). Lugworms (*Arenicola marina*), ragworms (*Nereis diversicolor*),

paddleworms (*Eteone longa*) and *Marenzelleria* are the most abundant worms in terms of biomass. Two species of large crabs are common in the area: the flying crab *Liocarcinus holsatus* and the green shore crab *Carcinus maenas*. Shrimps are also abundant, with the most prominent species the brown shrimp *Crangon crangon,* the mud shrimp *Corophium volutator* that feeds on benthic algae and sand dagger shrimps *Bathyporea spp.* Most molluscs in the Ems-Dollard are suspension feeders: blue mussel *Mytilus edulis*, sand gaper *Mya arenaria*, *Spisula truncate* and cockle *Cerastoderma edule*. Mussel and oyster banks occur on the Hond-Paap and in the Wadden Sea, banks of cockles occur at Voolhok (between Eemshaven and Delfzijl).

According to Elliot and Dewailly (1995), the number of fish species in the Ems-Dollard is comparable to other European estuaries. It accommodates typical estuarine species, juveniles of marine species such as Herring and seasonal marine fish such as flounder. Due to the transition from fresh to salt water, the Ems-Dollard is an important area for diadromous fish.

Like in the western part of the Wadden Sea, the abundance and diversity (ca. 40 species) of birds in the Ems-Dollard area is high: The shallow water, intertidal areas and bordering salt marshes provide plenty of food, as well as nesting opportunities. In numbers, waders are the biggest group. Apart from some exceptions, most ducks and geese are herbivores, whereas most waders and gulls eat fish or invertebrates. The species most typical to the Dollard are the barnacle goose (*Branta leucopsis*), graylag goose (*Anser anser*), common teal (*Anas crecca*), avocet (*Recurvirostra avosetta*), spotted redshank (*Tringa erythropus*) and twite (*Carduelis flaviostris*). The harbour of Delfzijl is home to a large colony of common terns (*Sterna hirundo*).

Only three species of mammals are more or less at home in the estuary: the common seal, the grey seal and porpoises. Generally, these animals hunt for fish in deeper, more open waters with less shipping traffic. The presence of inter- and supratidal areas is favourable for seals, which use these areas as a resting and nursing place.

The Ems-Dollard houses many kinds of organisms that interact with each other and their physical and chemical environment. To identify and visualise the key factors in the system, a word cloud has been made (Figure 6.2). The size of the words is a rough estimate of whether a factor has a strong influence on others, and whether this occurs in a considerable part of the estuary.

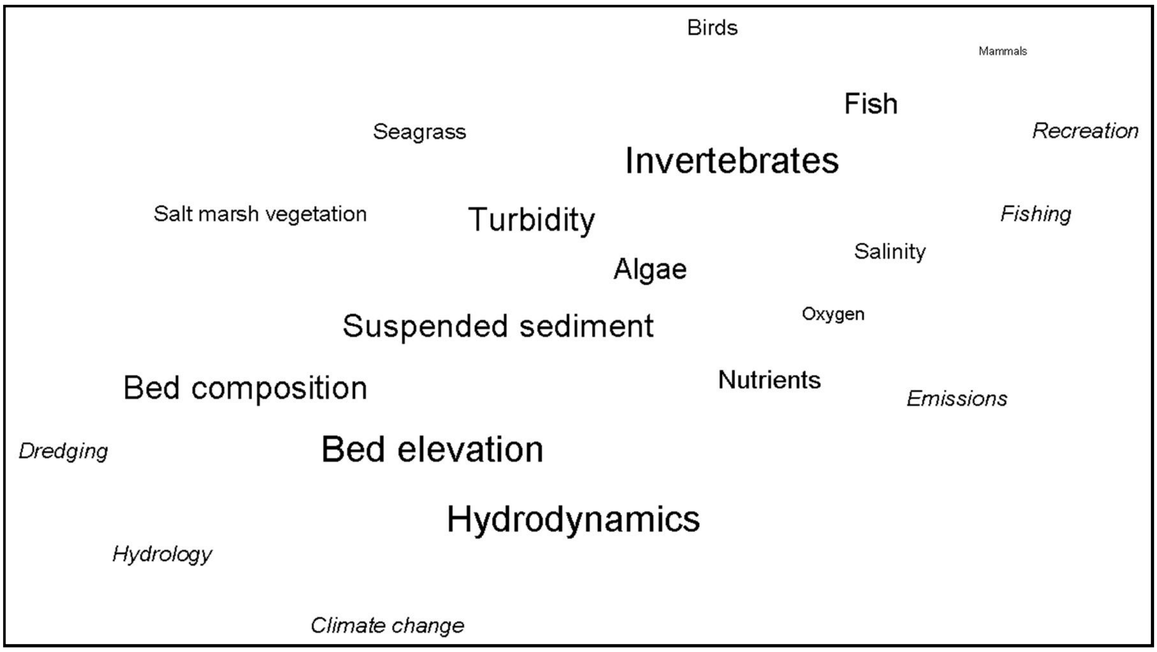

Figure 6.2 The most important human influences, physical and chemical entities and organisms in the Ems-Dollard estuary. Italics indicate external influences. The larger the word, the more it is considered to be a key factor. This figure is an update from a similar one in the first report (Dijkstra, 2010), now also incorporating which parameters were the most important for habitat suitability.

6.3 Habitat modelling

Regarding ecology, several modelling approaches were available: e.g., one can create an ecotope map, determine habitat suitability, make a dynamic population model for individual species or follow a statistical approach. For this study, the assessment of habitat suitability seemed the most promising method (Dijkstra, 2010). A habitat, a type of environment in which an organism or population occurs, is species-specific and changes in the environment will be reflected in the habitat suitability index (HSI). This index does not tell how many organisms will be present at a certain time, but it does tell how suitable the environment will be for a specific species, at any location within the study area.

This suitability not necessarily depends on abiotic factors only but can also be due to the presence of organisms lower in the food chain. By including factors step-by-step, it is possible to indicate the driving and limiting factors per species, which makes this approach transparent and matches with the effect-chain approach. What is more, habitat loss or gain is easy to quantify and visualise spatially by means of the applied GIS-based model ‘Habitat’. Factors that can be important for the actual occurrence of a species, but that cannot be studied by this type of model are competition between (possibly invasive) species, events such as diseases and accidents, and impacts on migratory species occurring elsewhere.

The input of Habitat consists of response curves for each relevant parameter (e.g. temperature, flow velocity, water depth, salinity) combined with maps of each of these parameters. Parameter maps were obtained from the different components in the effect chain model (see also Table 6.1). The total habitat suitability is calculated as the minimum suitability for all parameters combined. Figure 6.3 illustrates this with an example of an animal that requires shallow and clear water. The shallower the water the better, but the animal does not care if the water is deeper than 4 m (upper curve). Better visibility also means higher suitability until 1m, which is more than sufficient.

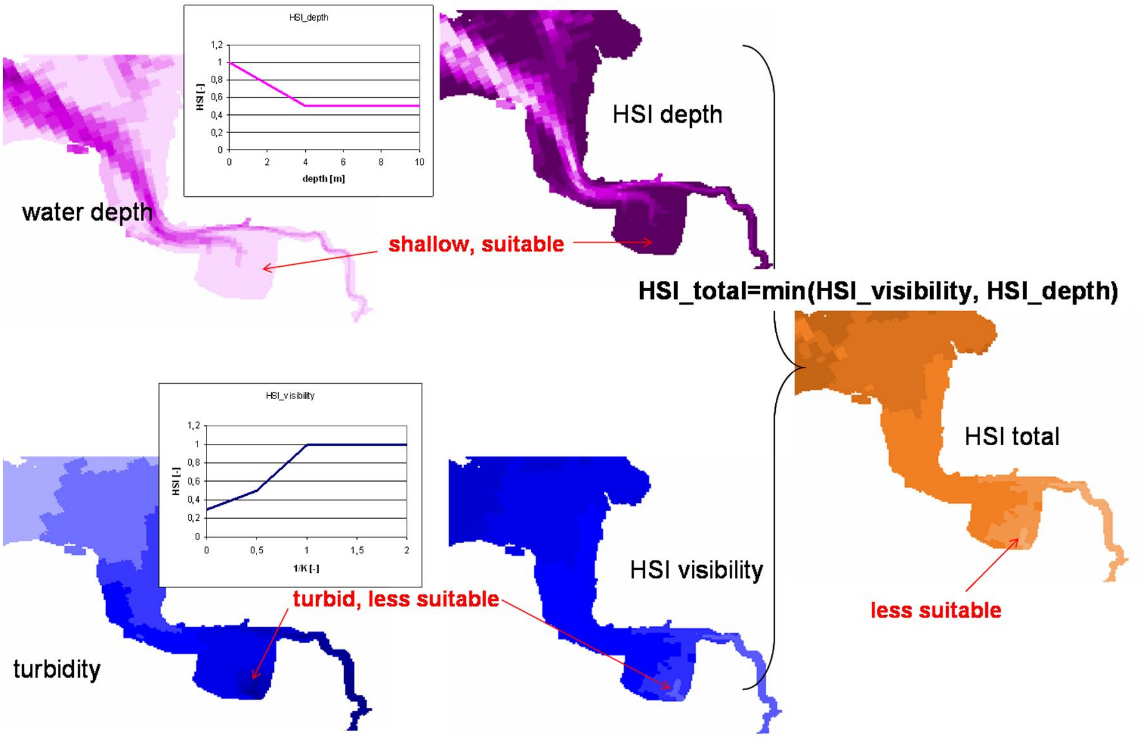

Figure 6.3 A fictitious example of habitat suitability based on two parameters and their response curves.

Given the nature of the system and the goal of this study, it was necessary to model developments over a longer period rather than instantaneously. The daily and spring-neap cycles are important abiotic forcing of the system, as are the seasons that force biotic development to a large extent. As a compromise between calculation time and temporal resolution, while maintaining the essential dynamics of the system over the year, four ‘seasons’ were used. Each season comprised a set of representative conditions for the duration of a month, i.e. two spring-neap cycles.

A selection of several key species that should be representative for the majority of the organisms in the Ems-Dollard was made because the total number of plant- and animal species in the area is too large to study all. Moreover, the available information on actual occurrence and habitat preference is only available for a limited number of species. This selection comprised Eelgrass, salty pioneers and salt marshes (habitat types H1310-H1330) as indicators for the suitability for various types of plant communities, the blue mussel and the cockle as epibenthic and endobenthic molluscs, juvenile herring as a fish with considerable oxygen and transparency demands, and the common Tern as a diving, fish eating bird. Other species that were considered to be representative, but were excluded from this report due to limited information were the lugworm and mudshrimp (macrofauna), sparling (fish), avocet, eurasian widgeon and red-breasted merganser (birds) and the three species of mammals.

This summary cannot discuss the response curves of all species. Instead, the main abiotic factors per species are listed: The plants need light to photosynthesize, which in turbid water implies that they require sufficient emersion time (i.e. elevation) to be able to grow, and they cannot cope with high dynamics, i.e. high orbital velocities. For molluscs, oxygen, saline water, sufficient inundation time and currents for feeding, a low sediment concentration in order not to clog their feeding apparatus and a stable bed are critical factors. Juvenile herring requires oxygen, quite deep saline to brackish water and low turbidity to find their food visually. The suitability of foraging area for the Common Tern is determined by water depth and flow velocity.

6.4 Validation and results

The table below summarizes the variability of the physical and chemical conditions throughout the year 2001 that were used to determine the habitat suitability in the Ems-Dollard. Note that spatial differences over the vertical are not taken into account because a two-dimensional model was applied. For the assessment of the majority of species and parameters these two instead of three dimensions are not crucial. Only in case of sessile, bottom-bound organisms (e.g. cockles, lugworms), extremely low oxygen conditions resulting from stratification can be important.

Table 6.1 Input parameters for the Habitat suitability model, with its source, and indication of the variability.

Parameter	source model	Spatial variability	Seasonal variability
Depth	Flow	Large	None
Indundation time	Flow	Large	Limited
Wave height	Sediment	Large	Only maximum; average is constant
Orbital velocity	Sediment	Large	Only maximum
Flow velocity	Flow	Large	Limited
Sediment concentration	Sediment	Large	Limited
Secchi depth	WAQ/Eco	Considerable / large	Moderately
Temperature	WAQ/Eco	None	Large
Salinity	WAQ/Eco	Considerable	Considerable
Oxygen	WAQ/Eco	Large	Considerable
Bed composition	Sediment	Large	None

For eelgrass, the habitat suitability in the outer area and the Dollard was overestimated by the model because the orbital velocities were not used as a criterion after calibration. The modeled orbital velocities were too high to enable any eelgrass growth, also on Hond-Paap where these plants actually grow. The modeled suitability for salty pioneers and salt marshes was more in agreement with observations: The highest suitability for these habitat types predominantly occurred at the landward margins; the largest areas were found just behind the barrier islands Borkum and Rottumeroog, just west of Eemshaven, near Rysumer Nacken and in the Dollard. The pioneers occupied a relatively narrow zone just seaward of the salt marshes.

After calibration, which involved a 20% reduction of the modeled orbital velocity, a stricter standard for the maximum occurrence depth, a more lenient criterion for inundation time and the incorporation of a criterion for the suspended sediment concentration, no part of the Ems-Dollard was considered to be more than moderately suitable for the Blue mussel. The most suitable areas were the lower intertidal to subtidal flats in the outer area, near and on Hond-Paap and in the Dollard. Because actual mussel presence in the Dollard was not reported, and because this prediction seemed to roughly match the locations of mussel banks in the outer area, further calibration, e.g. by using stricter condition for sediment concentration or by including a criterion for bed composition, seems necessary.

Contrary to the limited actual occurrence of cockles in Ems-Dollard, the modeled habitat suitability was very good in the shallow parts of the system. The suitability based on oxygen concentration, salinity, depth, and emersion time compared well to the known occurrence. However, sediment dynamics, possible frost and impeded feeding conditions are known regulating parameters, but have not been incorporated yet. For example, in the Dollard, where frost can be a limiting factor for cockle distribution, the model can not be used in its current state.

Although one measurement point is not enough to establish the spatial distribution of juvenile Herring, the area that was modeled as reasonably suitable (the channels in the outer area) did actually accommodate this fish. The presence of terns, which feed on juvenile herring, near Delfzijl however, indicates the presence of this fish in areas that were found to be moderately suitable as well.

For the common tern, suitable feeding areas were identified in close proximity of their reported colonies, which can be regarded as a clue for the model working correctly. The suitability for their breeding colonies was not modeled, as this would involve detailed terrestrial information that is not part of this effect-chain model.

7 Application

So far, the effect chain model has been applied to two scenarios, one to study the effect of the release of dredged material from harbour maintenance and another to study the effect of the increase in suspended sediment concentration over the past 50 years.

7.1 Possible applications and propagation of errors

7.1.1 Possibilities and limitations for application of the current model set-up

Currently, the model is validated with respect to salinity, nitrogen, oxygen concentrations and phytoplankton concentrations and groups. Phosphorus concentrations are not yet described very well due to the importance of sediment processes in the estuary, which currently are not represented in the model with sufficient detail. It can therefore be used to describe effects of changes nitrogen loads too the estuary. Because the water quality/primary production model is coupled to the hydrodynamic and sediment models, effects of dredging and dumping or morphological changes on water quality and primary production can be explored. The outcome of the model can be presented as (changes of) primary production in the water column and at the sediment and thereby contributing to the discussion whether and how much certain scenarios will increase or decrease the carrying capacity of the estuary for higher trophic levels. Also, outputs can be generated for further studies related to habitat suitability of certain species of plants or animals. Such outputs could be statistically aggregated maps (mean, minimum, maximum) of any state variable in the model or derived parameters, for example light availability at the sediment surface or turbidity. The 3D version of the model can also be used to study effects on deep water oxygen concentrations. The 2D version can not be used for this purpose, but is useful when large numbers of scenarios need to be calculated, for example when uncertainty analysis is needed.

7.1.2 Propagation of errors

In the effect chain model, the various components run independently and communicate with each other by means of data files. This information transfer is fully standardised for some components (e.g., from hydrodynamics to fine sediment), but only partly for others. E.g., the time-intervals and the grid size that are used to pass information to Habitat were chosen specifically for this study. Applying a so-called continuity-calculation showed that the coupling between the flow model and the water quality model was mass-conserving and that the transport patterns were pretty well reproduced. Minor variations arose due to the use of 1) different time steps and 2) different numerical schemes. We suppose that these consistency issues do not hamper the interpretation of results from different scenarios, because all scenarios are affected equally.

The application of a series of coupled models might lead to the presumption that the uncertainties at the base of the effect chain will be amplified throughout the chain. E.g., uncertainties in the hydrodynamics would lead to larger uncertainties in the primary production simulations, and even larger uncertainties in the Habitat model. Yet, this presumption is overly simplistic because errors can also diminish as a result of feedback mechanisms or differences in spatial and temporal scales. E.g., an error in the calculation of nutrient levels does not necessarily affect algal growth if light is the limiting factor. Amplification of errors, i.e. small changes in the forcing lead to crucial differences in results, can be expected in models with strong feedbacks, such as predator-prey relations, which are not incorporated in this effect-chain model.

A more elaborate discussion of issues and error propagation related to the application of effect chain models can be found in (Harezlak *et al.*, 2012).

7.2 Scenario 1: Release of dredged material

With the calibrated SPM model, the release of 120 kton of fines is simulated within a five day period (Jan 15-20, 2001) from location P5 about 5 km northwest of Eemshaven (see Figure 7.1). As an alternative, the same amount of material was released at location P6, just in front of Eemshaven. Figure 7.1 shows the relative daily average near-surface concentration increase during and just after sediment release. The sediment spreads rather quickly over a large area within the estuary. Because of dilution, the concentration increase diminishes gradually.

Figure 7.2 shows the natural background daily-average suspended sediment concentration over 2001 at location 'geul km70' indicated in Figure 7.1. The concentration ranges between about 20 mg/L in summer and 60 mg/L in winter. Figure 7.2 also shows the computed concentration increase due to the release of dredged material at locations P5 or P6. Initially the concentration increase amounts to tens of mg/L, but after three months the excess concentration is reduced to a few mg/L or less.

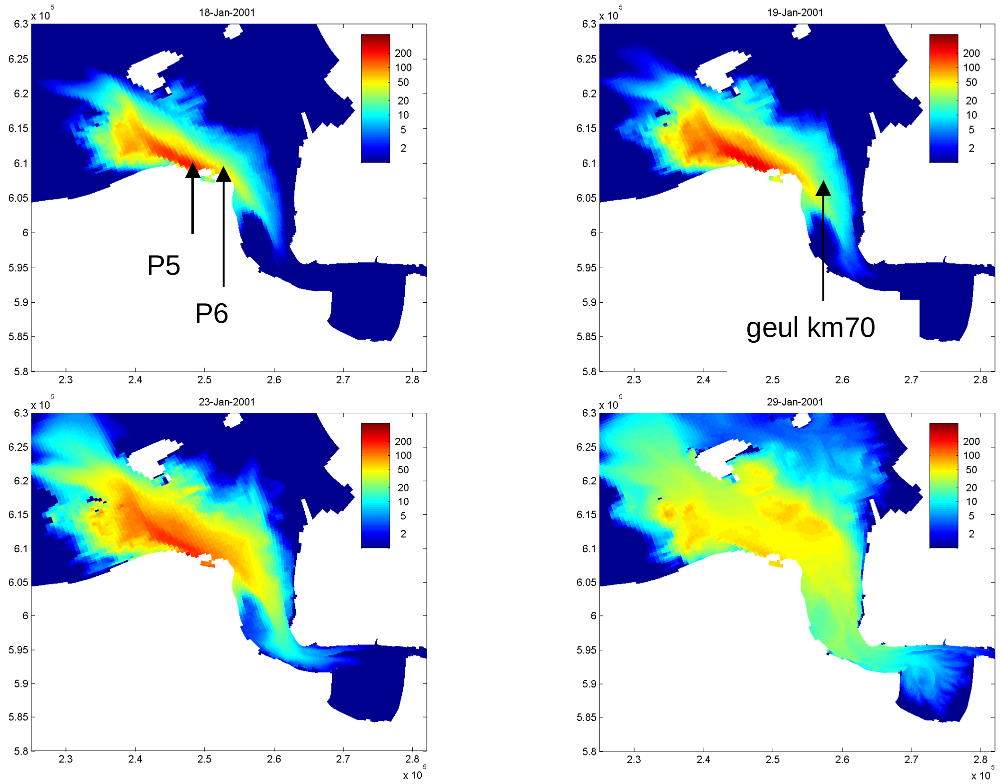

Figure 7.1 Daily-average SPM concentration increase (%) in the surface layer on 18, 19, 23 and 29 January 2001 due to sediment dispersion of 120 kton at location P5 in the period of 15 to 20 January, 2001.

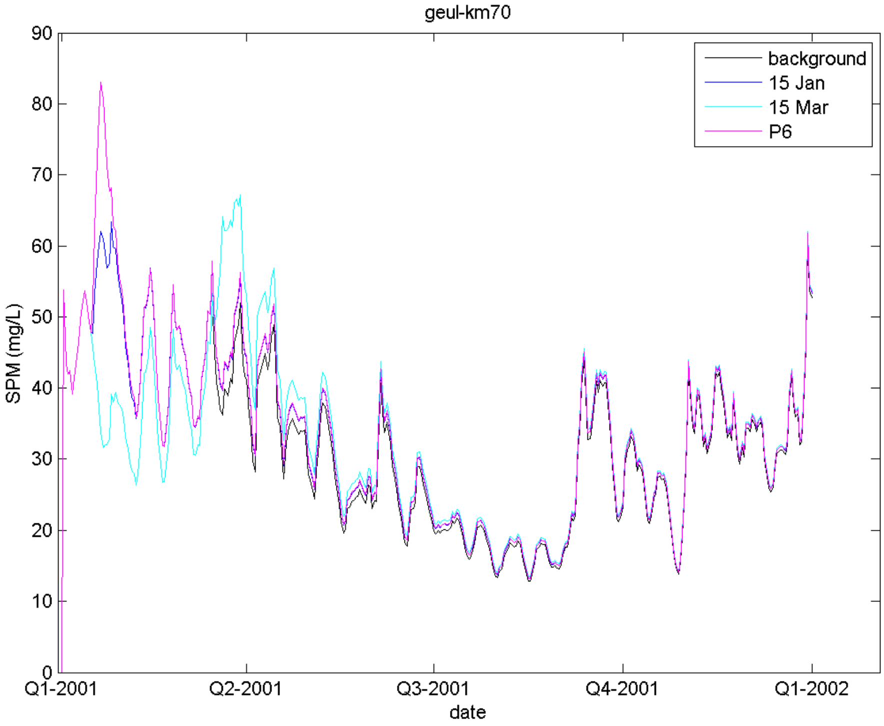

Figure 7.2 Daily-average near-surface suspended sediment concentration at location 70 km in year 2001 for scenarios 0 (background without release), 1 (release at P5 from 15 Jan), 2 (release at P6) and 3 (release at P5 from 15 Mar). The black curve overlaps with the light blue curve prior to 15 March.

The effects of both dumping scenarios on primary production were computed with the effect chain model. Suspended sediment concentrations calculated with the sediment model were used as an input for the water quality and ecology model. For the three reference stations, SPM concentrations were influenced most at Huibertgat Oost, with a higher effect at the P5 scenario than the P6 scenario. Chlorophyll concentrations were reduced in May and the beginning of June (Figure 2.1), and were slightly enhanced later on in the season, probably due to a higher availability of unused nutrients. Chlorophyll-*a* and Total Net Primary Production were influenced over a large area but the effect was often relatively small as compared to the total production.

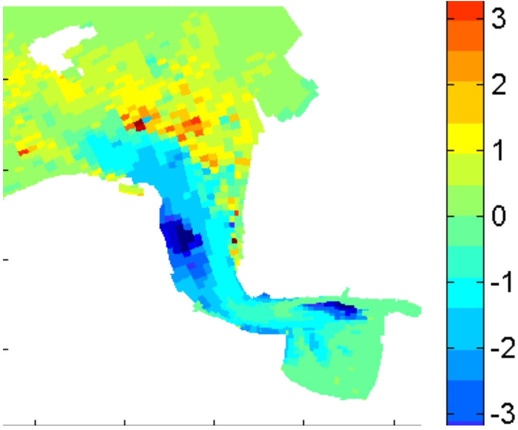

Figure 7.3 Difference maps of the Chlorophyll concentration in µg/L in the surface layer (Scenarios P5 – Reference) on 21 May, a period with relatively high chlorophyll-a concentrations.

7.3 Scenario 2: Turbidity reduced to historical levels

In recent decades, the turbidity has strongly increased in the Ems River, gradually decreasing in the seaward direction. The exact mechanisms behind this change in turbidity are still insufficiently known, and therefore this change cannot be reproduced with the sediment transport model. As an alternative, we modify the present-day turbidity by applying a space-varying concentration multiplication factor. This map with multiplication factors was constructed from historical measurements by De Jonge (Raad voor de Wadden, 2010), see Figure 7.4. The multiplication factor equals 1 at the North Sea (i.e. no reduction), but decreases to 0.8 in the Wadden Sea, 0.4 in the Dollard and 0.2 in the Ems River.

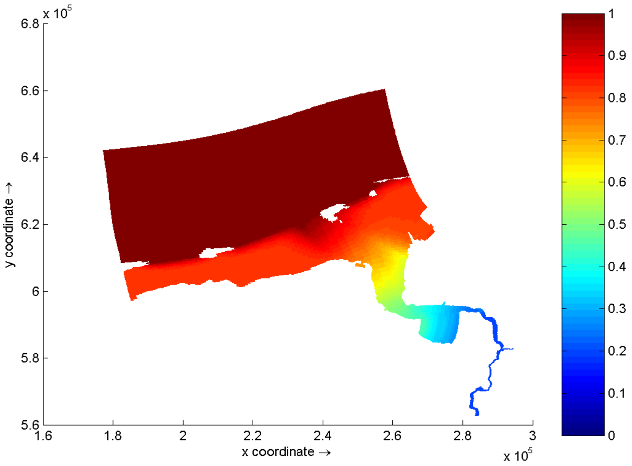

Figure 7.4 Multiplication factor for suspended matter concentration for the historical scenario.

7.3.1 Effect on primary production

Suspended sediment concentrations have increased more than 5-fold in the inner parts of the estuary and the Ems river since the 1950's (Raad voor de Wadden, 2010). The effect of a reconstructed historical (lower) suspended sediment concentration on light extinction (Figure 7.5) and the effects on primary production in the estuary were calculated using the effect chain model.

In the Dollard and outer Ems, the computed total net primary production of benthic algae was almost as high as the total pelagic production. Both the computed pelagic and benthic production were considerably larger when using the historical suspended sediment concentrations. This effect was strongest at the inner part of the estuary, where the increase of suspended sediment has been most pronounced (Figure 7.6). This is a strong indication that primary production in the estuary is presently light-limited. This indication for light limitation matches with the fact that the types of phytoplankton that thrive well in light-limited conditions were dominant in the mode in space and time (Stolte *et al.*, 2012); different types of model output support the same hypothesis.

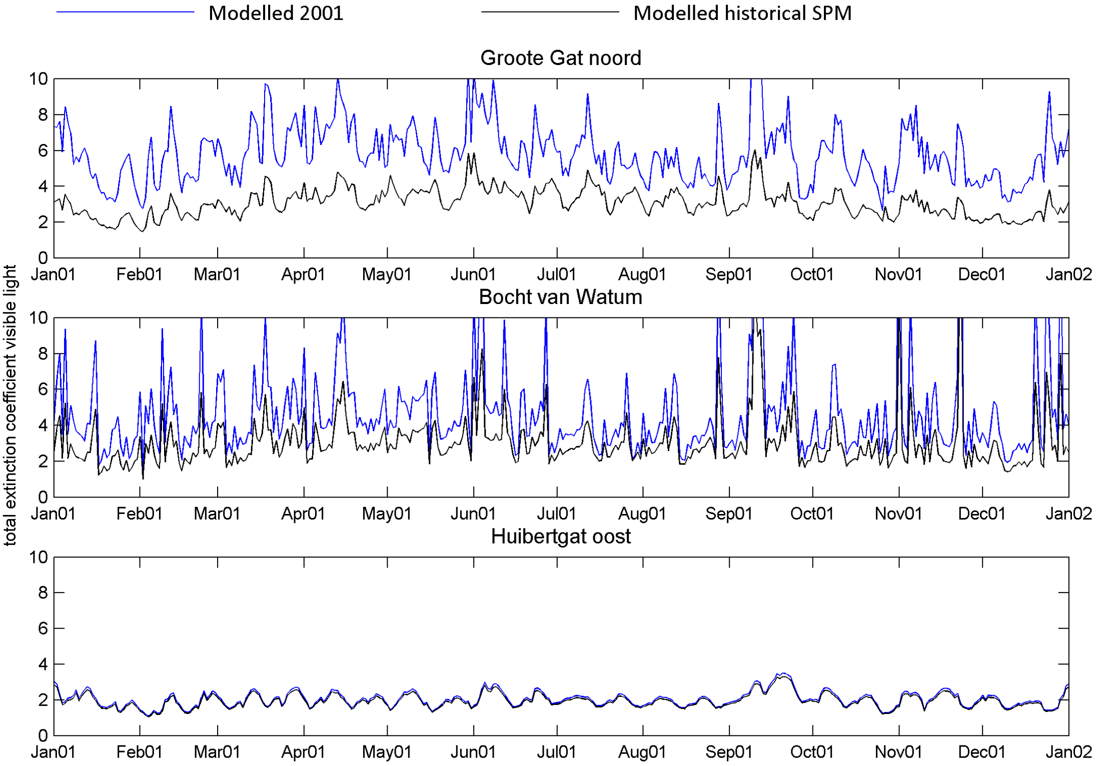

Figure 7.5 Modelled total extinction of visible light at the most inland station, Groote Gat Noord, using present day suspended sediment concentration (blue) and a modified concentration simulating a historical scenario (black).

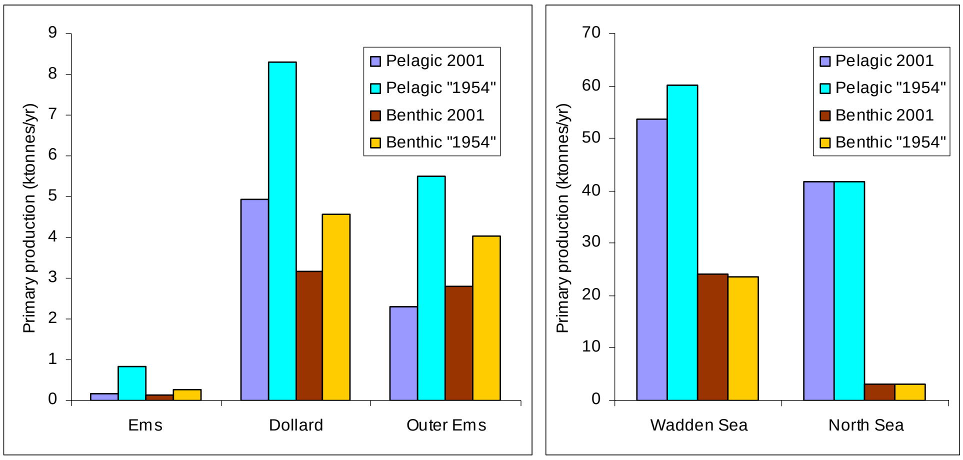

Figure 7.6 Total primary production in ktonnes nitrogen/yr. Note different scales.

7.3.2 Effect on habitat suitability

The effect of the modeled historical lower sediment concentration and consequently increased visibility was calculated for the habitat suitability of juvenile herring. Most other species are either unlikely to be directly affected by these conditions (e.g. emergent plants, most macrofauna, wading or herbivorous birds, mammals) or their sensitivity for the calculated range of changes in sediment concentration is uncertain, as is the case for bivalves. For the visually hunting juvenile herring, the increased visibility in the historical scenario gave considerably larger habitat suitability than the present conditions (Figure 7.7). Additionally, the higher primary production in the simulated historical conditions, and the longer duration of this high primary production, will also contribute to the suitability for herring, but this effect cannot be quantified with the present effect chain model.

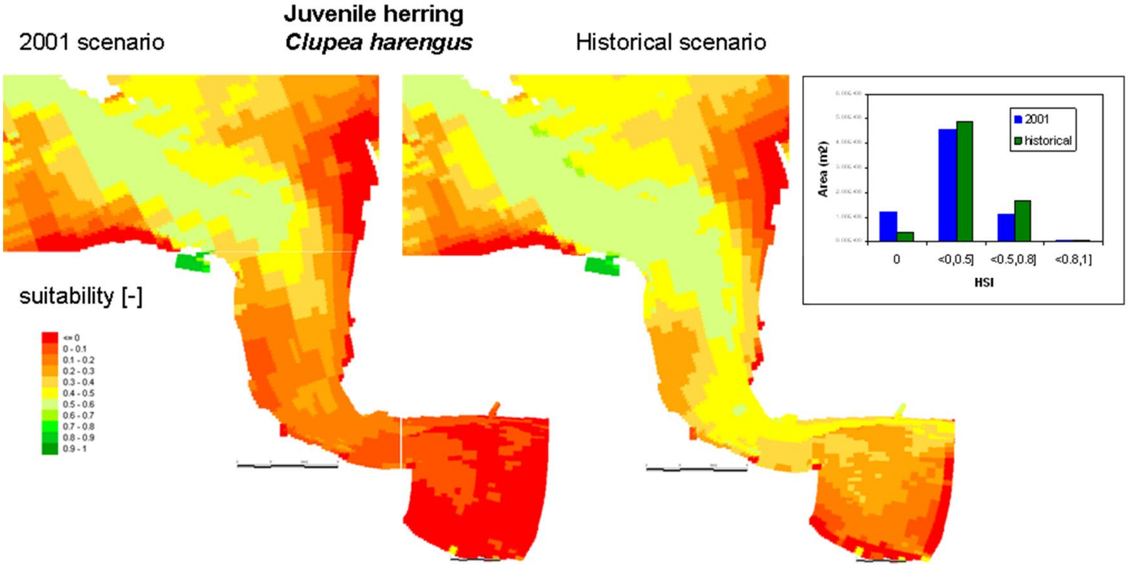

Figure 7.7 The example of how historical –lower- turbidity levels created a larger area of suitable habitat for juvenile herring (Clupea harengus) than in 2001.

8 Lessons learned

The following main lessons have been learnt during the set-up and application of an effect chain model for the Ems-Dollard estuary, which was the main objective of this study. These lessons are useful for follow-up activities after the completion of the present study, such as the on-going study for the Water Framework Directive Ems-Dollard (Van Maren *et al.*, 2011). Knowledge exchange with German parties took place several times, for example trough meetings of the “Arbeitsgruppe Baggergutunterbringung Aussenems” in Emden.

8.1 On hydrodynamics and SPM modelling

The hydrodynamic and suspended sediment models are able to explain and reproduce the main observed physical processes in the estuary. Although the hydrodynamic and SPM model has not been identified as a weak link in the effect chain, further improvement is still recommended. Whereas the hydrodynamic model reproduces time-average salinity gradients along the estuary satisfactory, it does not always reproduce short-term variations caused by freshwater discharge peaks well. This may be caused by inaccurate discharge data, but also by model limitations on dispersion.

Two different SPM model applications have been developed in this study, one including the sediment-density coupling and another model with more sophisticated erosion-sedimentation formulations. The former computes most realistic figures for the net import of marine sediment into the upper Ems river and the SPM concentration of the upper Ems river, the latter reproduces observed SPM concentrations in the Ems-Dollard estuary much better. As primary production computations are highly sensitive to SPM levels and insensitive to net sediment fluxes, the model excluding density coupling is the preferred one to include in an effect chain model. However, it would be an important step forward to combine the strengths of both models.

The SPM model has been applied to compute the effect of the release of dredged material on the suspended sediment concentration in the Ems-Dollard. The results show that fine fractions spread rather quickly (within days) over a significant part of the estuary (well beyond 10 km from the release location). The local concentration increase is most sensitive to settling velocity (apart from the load, obviously), but at greater distance also the likelihood of resuspension and deposition of the sediments determines further spreading.

8.2 On primary production modelling

The water quality and primary production model can be used to explore and evaluate different measures and scenarios aiming at improving the ecological status of the Ems-Dollard estuary. The current version of the model is validated for the year 2001, which will be used as a reference year. Currently, new monitoring results for the year 2012 come availabe for pelagic primary production, concentrations of substances and phytoplankton, while during 2013, new results come availble on benthic primary producers and production. These results will be used to evaluate the model for the current situation and will be used as a base for future projections.

The reduction of turbity is needed in order to improve the ecological status of the Ems-Dollard. This will undoubtedly lead to higher primary production by algae, thus a higher carrying capacity for higher trophic levels. However, more algae may lead to unwanted effects, such as high biomass algal blooms, or low oxygen concentrations in the bottom layers, which will adversely affect fish and benthic populations. Model outcomes from different scenarios assist in a priori evaluation of different scenarios.

The effect of different dredging and dumping scenarios on primary production can be investigated. Short term effects, through reduction of the light climate, mainly exist in a temporal and local decrease in primary production and chlorophyll-a concentrations. However, left-over nutrients from the decreased production will be used elsewhere by other algae. Therefore more likely than an overall decrease in primary production, part of this production will be delayed and will occur elsewhere as a result of sediment dumping. More detailed studies may reveal the effect on yearly production and nutrient retention in the estuary.

The scenario with historical suspended matter concentrations shows an increase in transparancy, which also results in substantial higher annual primary production both in pelagic and benthic production. The increase is most pronounced in the inner parts of the estuary, where suspended matter concentration was most reduced. In relative terms, the increase was lower in the Wadden Sea part, but in absolute terms, the increase in the Wadden Sea was in the same order of magnitude as in the more inner parts, due to the larger area. Remarkably, benthic primary production was not enhanced as a result of lower SPM concentrations in the Wadden Sea area. This can be explained, because in the model, phosphorus rather than light was limiting benthic production in the Wadden Sea area. Phosphorus redelivery by the sediment, a process that is currently not described with the model, might play a role in the change of benthic primary production, especially in this part of the model domain.

The current model set-up has limitations, most importantly the incomplete description of sediment biogeogemistry and phosphorus exchange between water and sediment. However, especially in the inner and middle parts of the estuary, phosphorus is never likely to become a limiting nutrient.

8.3 On habitat suitability

The present study shows that effect-chain modelling in Ems-Dollard is possible, but is limited to a few of the many plant and animal species occurring in the estuary (Stolte *et al*., 2012), which are mentioned below. Nevertheless, the effects on even this limited amount of species can help to quantify the impacts of measures and to aid management decisions.

For eelgrass, salt marshes and the associated pioneer vegetation the modelled habitat suitability matches the actual occurrence, except for locations where the wave dynamics are the decisive factor. The applied simple fetch-length approach overestimated wave dynamics on intertidal areas, thus rendering these unsuitable. Ignoring the criterion for wave dynamics, the area identified as suitable plant habitat is much greater than the actual habitats. Therefore, future studies would benefit from a full wave model that can calculate the wave dynamics in sheltered and shallow areas.

The model correctly identified the shallow areas where the blue mussel occurs as (reasonably) suitable, but also, incorrectly, classified some deeper, bare areas similarly. This is likely due to the absence of a relation between sediment dynamics (accretion/erosion rates) and habitat suitability. Similarly, the suitability for cockles was modelled too optimistically, which was even boosted by the absence of a cockle-specific relation for sediment concentration, which might hamper feeding, and habitat suitability.

The area modelled as suitable for juvenile herring matched the opinion of experts and the observed presence of predators, as well as the single monitoring point. As far as the limited validation data allow, the location of suitable feeding areas for the common tern was modelled correctly: these areas were near existing colonies, which would not be there if there was no food nearby. Other species were considered to be part of this effect-chain model, but dropped because of a lack of good dose-response curves and/or validation data.

The improvement of suitability curves requires a considerable effort. For some species this involves further literature study, but for most it involves further calibration with actual field data. Such improvement likely benefits from a focus on a couple of well-known and representative species as in the final report (Stolte *et al.*, 2012), rather than the initial broad approach (Dijkstra, 2010) of the present study.

Most physical and chemical parameters are modelled realistically (i.e., they cannot always be validated exactly, but seem reasonable) by the preceding components in the effect-chain, with the exception of the wave dynamics (discussed above) and the minimum oxygen concentrations in shallow areas. These concentrations incorrectly dropped to zero occasionally, while they are critical to the habitat suitability for most species of macrofauna. The importance of stratification for habitat suitability was not studied, but for most species and locations the applied two-dimensional water quality model seems to work well. A three-dimensional model is required if issues related to oxygen and salinity, which can be relevant to sessile benthic organisms and migratory fish, are of particular interest. The applied grid of 50 by 50 metres has a high resolution compared to that of the models earlier in the chain, but this resolution is necessary: Otherwise, steep gradients, which are important for the delineation of habitats, will be smoothened out.

8.4 Continuing research and modelling activities in the Ems-Dollard

The current state of the effect chain model will be further developed and used in the on-going project of the Water Framework Directive (WFD) that is commissioned by Rijkswaterstaat Directorate Noord-Nederland. This research (Van Maren et al., 2012) has created the opportunity to collect recent data in the Ems-Dollard on e.g. water quality, sediment composition, macro-invertebrates, and many more parameters in the coming years. This will help to give a better description of the present state and functioning of the water system of the Ems-Dollard and will help to identify measures to improve the situation in future.

The results of the present KPP study contributed to a flying start of the WFD-related project. The KPP project provided a good basis of the modelling framework and helped overcome several obstacles in applying different modules.

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