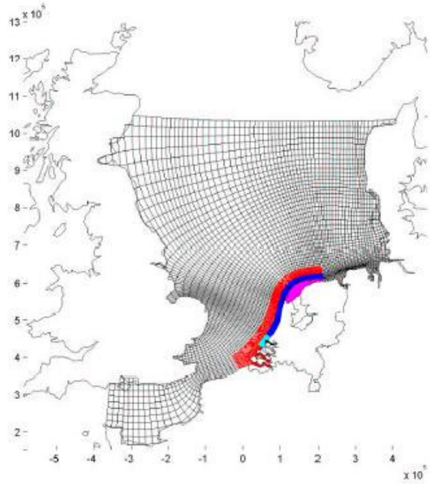

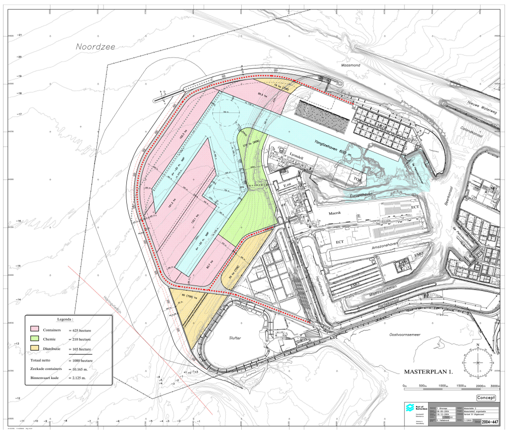

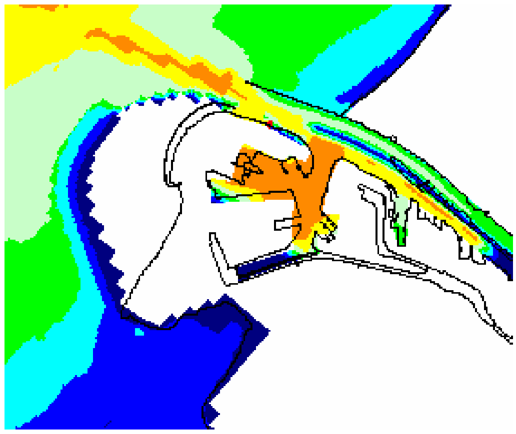

Effects of Maasvlakte 2 on the Wadden Sea and the North Sea coastal zone

Track 1 Detailed modelling research

Port of Rotterdam & National Institute for Coastal and Marine Management RIKZ

18 November 2005

Final report

9R2847.A0

WL | delft hydraulics

ANIMAL SCIENCES GROUP
WAGENINGEN UR

Netherlands Institute for Fisheries Research (RIVO)

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CONTENTS

1 INTRODUCTION

1.1 Background

1.2 This report gives an overview of the effects of Maasvlakte 2 on the transport of mud, nutrients and fish larvae within the framework of the Appropriate Assessment for the Wadden Sea. This research was initiated following the verdict of the Raad van State that stated "…it cannot be repudiated that land reclamation has an effect upon the transport of fish larvae and mud along the coast in the northern direction and that this can have significant effects on the protected zone in and around the Wadden Sea based on the European Bird and Habitat Directive". Moreover, the Raad van State concluded that it is "not plausible to suggest that new research cannot contribute to a better insight into the magnitude and effects of a decreasing mud and fish larvae transport upon the protected features of the Wadden Sea with respect to the preservation objectives".

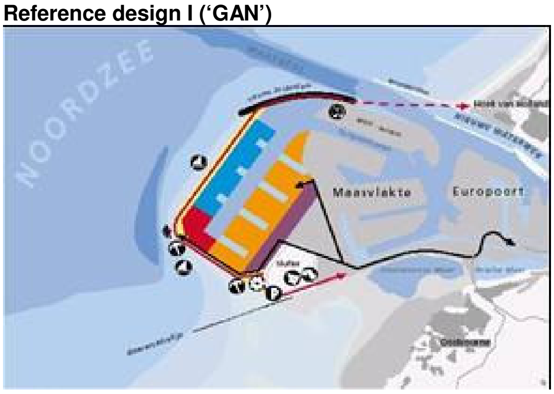
The land reclamation near the harbour of Rotterdam, Maasvlakte 2, is situated at the seaward side of the present Maasvlakte. Various alternatives of the land reclamation layout have played various roles in recent years. These alternatives are summarised in Figure 1. In the PKB, the Reference Designs I and II were studied. These have been referred to as GAN and GAB respectively. The major difference between the two is that Reference Design II (GAB) has its own harbour entrance, including an extension of the harbour breakwaters, whereas the entrance in Reference Design I (GAN) has been realised by extending and widening the harbour in the existing Maasvlakte. The current design is called the *Doorsteekvariant*. The geometry of this design is quite similar to Reference Design I (GAN), but it is slightly smaller at the southwest side.

In the framework of Project Mainport Rotterdam (PMR), several studies have been carried out to assess the effects of Maasvlakte 2. In order to substantiate the conclusions of these studies using state-of-the-art knowledge, new research has been initiated within the framework of the Appropriate Assessment for the Wadden Sea. The Appropriate Assessment focuses on the Wadden Sea and the coastal zone of North Holland, north of Petten and including the coastal zone of the Wadden Islands, which areas are protected in the European Bird and Habitat directive. In this technical note, these areas are referred to as the Wadden Sea and the Dutch coastal zone respectively.

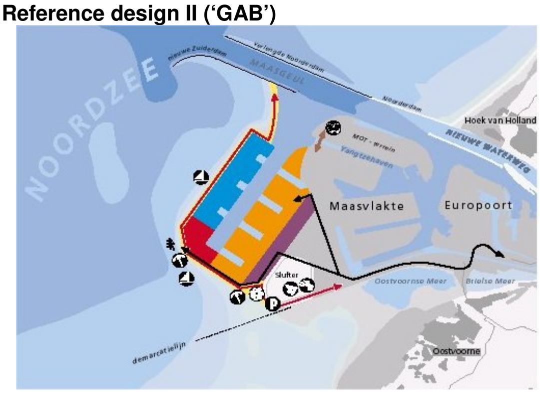
1.3 Objective of research

The objective of this research is to quantify and explain the effects of Maasvlakte 2 on mud transport, nutrients and fish larvae for the Wadden Sea and the Dutch coastal zone, utilising all available knowledge and state-of-the-art tools. For this purpose, the entire Southern North Sea from the English Channel to the German Bight has been chosen as the study area. The specific area of interest is the Dutch coastal zone and the Western Wadden Sea ending at the tidal boundary to the south of Ameland. From previous studies, it can be concluded that the effects of Maasvlakte 2 are negligible in the vicinity of the tidal boundary south of Ameland and in the eastern part of the Wadden Sea.

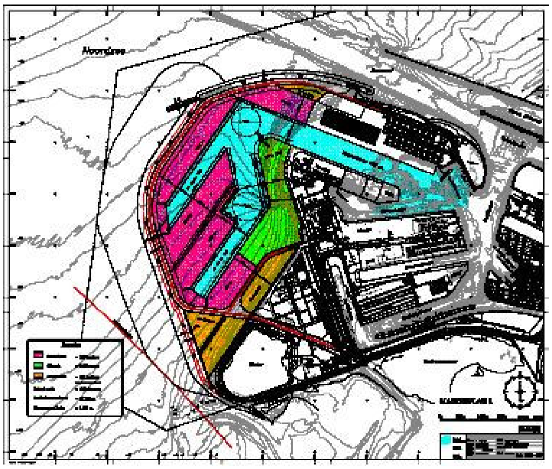
Reference design I ('GAN')



Reference design II ('GAB')



Doorsteekvariant



Doorsteekvariant with Reference design I

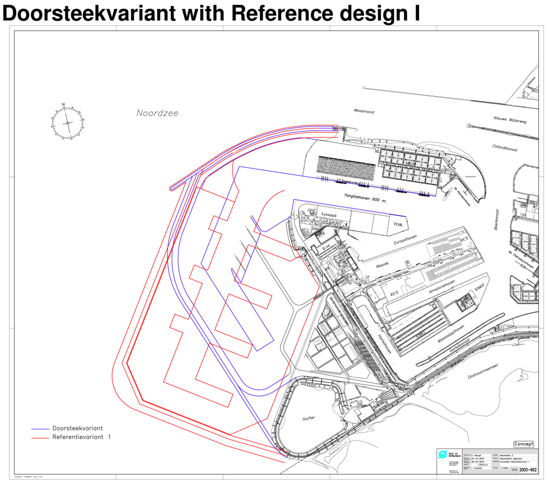


Figure 1: Land reclamation alternatives of Maasvlakte 2.

1.4 Contents

The contents of this technical note are as follows:

- In section 2, a problem analysis is presented in which the central question is posed regarding the impact of Maasvlakte 2 on the transport processes of mud, nutrients and fish larvae in the Dutch coastal zone, and how these effects may have an impact on the Wadden Sea. In addition, an overview is given of the magnitude of these effects based on the results of previous studies of PMR.
- In section 3, a description is given of the present modelling approach. Attention is paid to the models used and the assumptions that have been made in this research. The results of the model study are presented in this section along with a discussion of the significance of these results in the light of the results from earlier studies.
- This is followed by a review of the approach chosen for the modelling and the results of this study in Section 4. This includes an analysis of the strengths and weaknesses of the study that was carried out. There is also a discussion on the influence of the uncertainties in the approach and the results on the Maasvlakte 2 impact assessment.
- Finally, conclusions are presented in section 5.

2 POSSIBLE IMPACT OF MAASVLAKTE 2 ON THE WADDEN SEA

2.1 Introduction

The construction of Maasvlakte 2 consists of two main activities: sand mining in the North Sea and land reclamation near the harbour entrance of Rotterdam. Along with several autonomous developments (e.g. sea level rise, nutrient reduction), these activities will have an impact on the surrounding water system (Figure 2). The land reclamation affects the water motion (currents and water levels) in the Rhine-Meuse estuary.

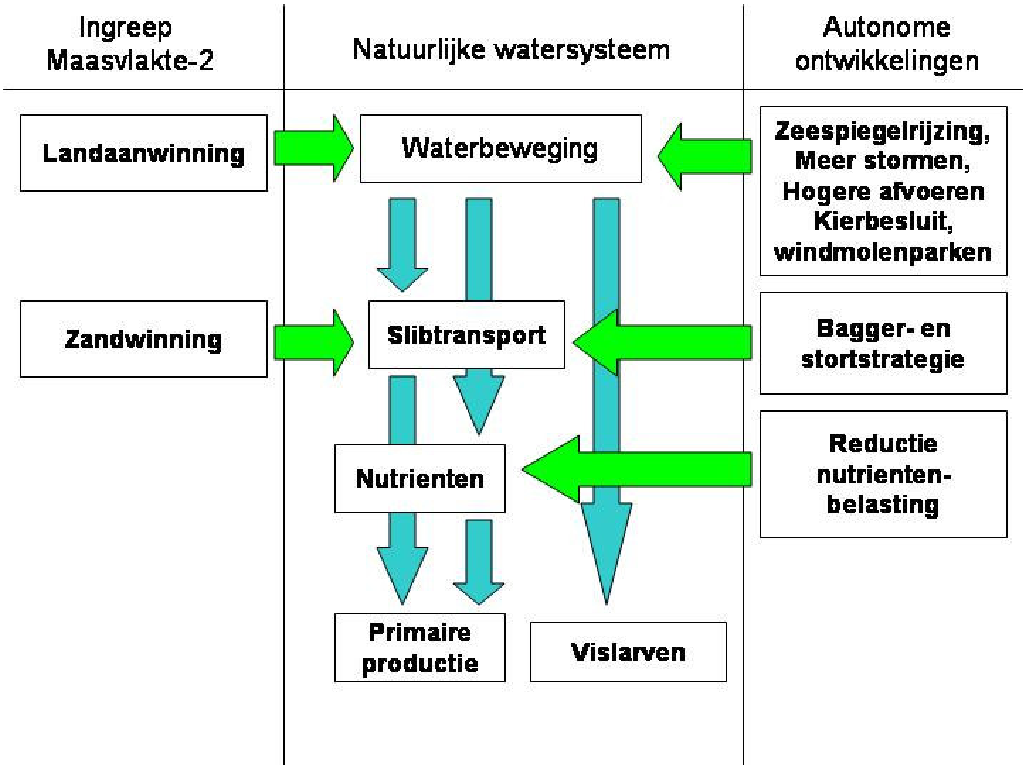


Figure 2: Relationships between the activities of Maasvlakte 2 and the processes in the surrounding water system. The autonomous developments are also visualized which have an impact on the system as well.

This chapter describes the impact of Maasvlakte 2 on the Wadden Sea. First, the aspects are discussed that have no effect and which aspects should be considered further (2.2). Next, the present situation for the aspect to be investigated (i.e. hydrodynamics, mud transport, nutrients and fish larvae) is described based on the present knowledge. Moreover, the possible impact of Maasvlakte 2 is discussed based on the results of previous studies. Only essential references are discussed that are of specific importance for the situation around Maasvlakte 2 in relation to the Wadden Sea (2.3 – 2.5). This section closes with an overview of the possible effects of Maasvlakte 2 based on previous studies (2.6).

2.2 Scope of aspects

The primary effect of Maasvlakte 2 is the effect on the hydrodynamics (currents and water levels) in the vicinity of the outflow of the Rhine and Meuse. The effects on water levels as a result of land reclamation and sand mining is expected to be less than a centimetre and thus of no further consequence in this study. The Maasvlakte 2 activities will not affect the tidal amplitudes along the Dutch coastal zone. With respect to large-scale sand transport, it can be concluded that the effects will be negligible. The mean long shore transport in the Dutch coastal zone is approximately 0.2 – 0.5x10^6 m^3 per year. This transport is mainly wave-driven and is only affected locally by the Maasvlakte 2 extension. The Maasvlakte 2 does not affect the wave climate along the rest of the Dutch coast. Currently, about 12x10^6 m^3 of sand is supplemented along the Dutch coast each year. This human activity has a much more significant effect on the sand budgets along the Dutch coast.

However, the effect of the land reclamation on the currents is important. The land reclamation affects the local current pattern. In particular, changes in the local residual currents will affect the distribution of fresh water that flows from the Nieuwe Waterweg and Haringvliet into the North Sea. In turn, these changes influence the *coastal river* in the northern direction along the Dutch coast towards the Wadden Sea. As a result, effects may occur on a much larger scale than just the area around Maasvlakte 2.

The coastal river transports fresh Rhine water, mud, nutrients (dissolved and particulate matter), algae, polluted substances, and organisms, of which a certain fraction ends up in the Wadden Sea. The possible effects of Maasvlakte 2 will manifest themselves mainly in the Western Wadden Sea. The Eastern Wadden Sea will be less affected because this area is dominated by exchanges with the North Sea only. Pollutants will be affected in the same way as (dissolved) nutrients and mud. Maasvlakte 2 will not change the loads with pollutants in the coastal zone, but could change the spreading of pollutants. The magnitude of these effects will be comparable to mud and/or nutrients are not investigated separately. The only living organisms that can be expected to be affected by changes in the coastal river are those that are passively transported by the currents. This is only applicable to fish larvae.

It should be noted that water from the River Rhine and mud in the coastal zone have different spreading patterns. Hence, the effects of Maasvlakte 2 on these patterns are also different. The same holds for dissolved substances and substances that adhere to mud. Dissolved nutrients can be adsorped to mud or consumed by algae. In this way, the spreading is more or less similar to dissolved substances. On the other hand decay of nutrients by desorption can transform the nutrients into a dissolved phase. As a result, nutrients have their own spreading pattern that differs from fresh water from the river Rhine and mud particles in the coastal zone.

Sand mining results in a temporary increase of the mud concentration in the water column as a result of the sand mining process. The local change of the sea bed due to sand mining will affect the current pattern around the sand pit, but this is not important for the Wadden Sea.

2.3 Water motion

2.3.1 Present situation

The presence of the coastal river between the Rhine-Meuse estuary (Nieuwe Waterweg / Haringvliet) and Den Helder is the key factor in the possible influence of Maasvlakte 2 on the Wadden Sea. This is a small stretch of 20 – 30 kilometres wide along the Dutch coast with transport in a northerly direction of fresh Rhine water rich in mud, nutrients, and fish larvae. Due to this transport phenomenon, the coastal river functions as the primary source of these elements for the Wadden Sea.

The behaviour of the coastal river along the Dutch coast is referred to in the literature as the Region Of Fresh water Influence, i.e. ROFI (Van Alphen et al., 1988; McClimans, 1988; Simpson en Souza, 1995). It is governed by the interaction between density differences of fresh and salt water, and earth's rotation, and has a strong three-dimensional character. A distinction is generally made between the "near-field" and "far-field" zone in a ROFI in which different processes and time scales are of importance.

The near-field zone is limited to a zone with a radius of 10 kilometres around the outflow of the River Rhine and is characterized by a semi-permant salt stratification. The far-field zone is between Schouwen and Den Helder and is characterized by the presence of salinity gradient in cross-shore direction. This salinity pattern causes in combination with earth rotation the typical net current pattern near the coast (see e.g. De Kok, 1994). The length of the far field zone is approximately 120 kilometres. Its width is 20 – 30 kilometres, depending on the river discharge, the wind and the tides. This zone sometimes is found near the Westerschelde and in front of the Flemish coast, depending on the hydrodynamic conditions.

An important aspect of the coastal river is the difference in residual currents over the water column. Near the water surface, the residual currents are directed more or less parallel to the shoreline with a small component offshore. However, near the bed the residual current is directed towards the coast. This difference has important consequences for mud transport, of which the highest concentrations occur near the bed. The result of this is that mud is trapped in a narrow strip along the coast containing relatively high concentrations (see also section 2.3). Some of the nutrients are also transported by the mud fraction and fish larvae also use the residual current in onshore direction to reach the nursery areas.

Waves also affect the behaviour of dissolved and particulate matter towards the Wadden Sea. The effect of waves is predominant near the coastline due to the limited water depth. On the one hand, waves increase the bed shear stress. On the other hand, there is a wave-driven component in the water transport in the coastal zone and subsequently also in the transport of dissolved and particulate substances.

2.3.2 Impact of Maasvlakte 2

Briefly, the effect of the land reclamation on the water movement is shown in Figure 3. The extension of Maasvlakte 2 widens the "near field zone" of the fresh water from the River Rhine that mixes with the salt water from the North Sea. Hence, the mixing of fresh and salt water increases. As a result, the cross-shore salinity gradients decrease in the cross-shore direction in the "near field zone" and in the "far field zone". Increased mixing implies that the salinity differences decrease with a subsequent decrease of the

residual current near the bed in the direction towards the coast.
Moreover, the widening in the coastal river also implies a less intense residual current in the long shore direction in the coastal zone. These effects have been confirmed in the previous impact assessments of Maasvlakte 2.

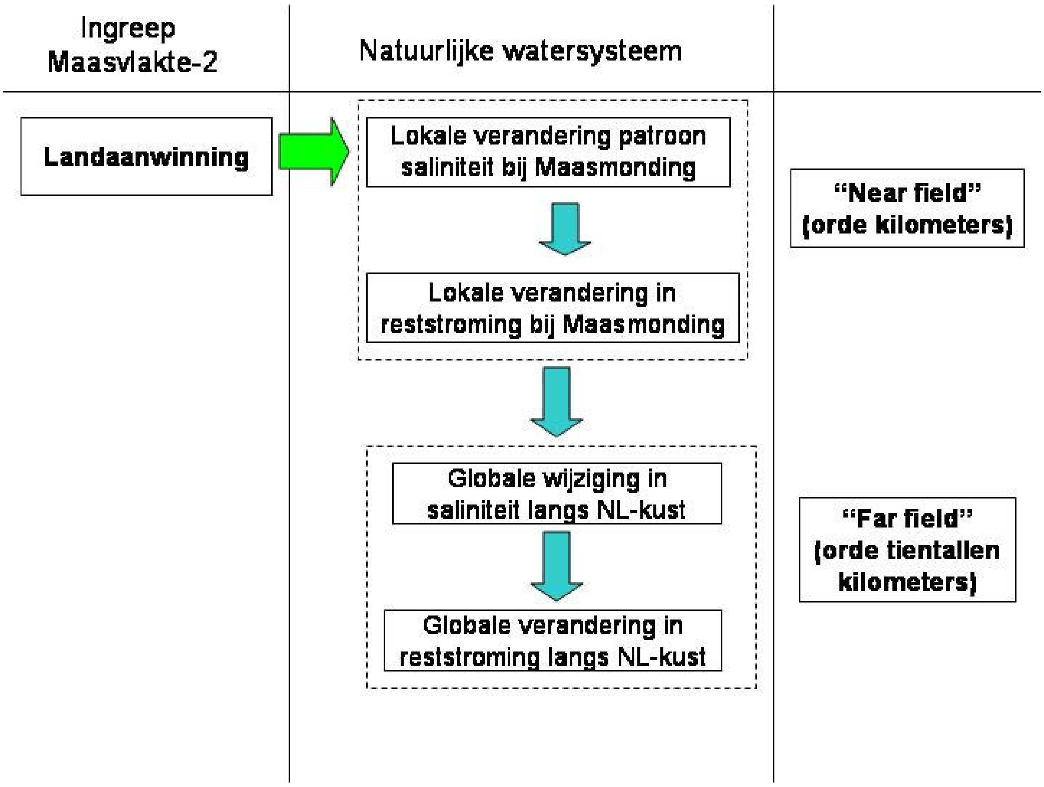


Figure 3: Effect relationships for the water motion as a result of Maasvlakte 2.

A commonly raised question is why a small geometrical change near the Maasvlakte could have any effect near the Wadden Sea. It should be noted that the situation in the "far field zone" is partly governed by the situation in the "near field zone". For example, Garvine (2001) has shown that effects in the "far-field" zone occur with only small localised geometric changes in the "near-field" zone in the vicinity of the fresh water outflow, whilst all other parameters were kept constant (e.g. supply of fresh water, mud). As discussed earlier, the "far field zone" of the coastal river extends beyond Den Helder. It is therefore not possible to disregard possible effects in and near the Wadden Sea beforehand.

A widening in the coastal river implies that the amount of dissolved and particulate matter is spread over a larger width in the coastal zone. As a result the amounts that enter the Wadden Sea may decrease. It is important to note that the total amount of dissolved and particulate matter will not change, but that these are only distributed over a larger area.

2.4 Mud transport

2.4.1 Present situation

At a large scale, the supply of mud in the Dutch coastal zone is governed by the net discharge through the English Channel in a northerly direction (yearly averaged 50.000 – 150.000 m^3/s), together with the mud erosion in the Channel zone and the Flemish Banks (De Kok, 2004). Mud is largely transported in suspension in the water column of the North Sea, and net sedimentation in the Southern part of the North Sea is limited due to the relatively high current velocities. Net sedimentation only occurs in the harbours along the North Sea coast (e.g. Zeebrugge, Rotterdam) and in the former ebb-tidal deltas of the tidal basins of Zeeland (Haringvliet, Grevelingen) and in the Wadden Sea. The accumulated mud in harbours is dredged and released in the open sea to a large extent so that the total amount of mud in the system does not change.

It follows from direct measurements and satellite images that the mud concentration near the coast is high (50 – 100 mg/l). However, the mud concentration is much lower offshore (Suijlen&Duin, 2002). The high concentration in the coastal zone is due to the residual current pattern in the coastal river. Near the water surface, the residual current vector is directed slightly offshore. Near the bed, the residual current is directed towards the coast. The mud concentration is high near the bed and therefore the net mud transport occurs towards the coast and a narrow strip with relatively high concentrations develops. In the long shore direction the residual current and the net transport of mud is directed in a northerly direction. The yearly averaged net mud transport along the Dutch coast is estimated to be 10 - 25 Mton/year (De Kok, 2004).

Satellite images give an impression of the spatial distribution of suspended matter in the coastal zone (Figure 4). Moreover, these images also show a strong annual variation with high concentrations in the winter period with relatively rough weather and low concentrations in the summer period with relatively calm weather. The measured variations are large and vary from several mg/l in calm conditions to several hundreds of mg/l in rough conditions.

Computations show that wave-driven transport of mud along the Dutch coast is approximately two to three times higher than current-driven transport in the surf zone (Torenga, 2002). This implies that the contribution of the wave-driven mud flux to the total mud flux along the Dutch coast is at least 10%. This contribution is possibly much higher because the knowledge about mud concentrations and fluxes during storm conditions is quite limited. The contribution of wave-driven transport is especially high in these periods.

Figure 4: Satellite image of the Southern North Sea. The brown patterns show areas with relatively high mud concentrations in the water column. The coastal river along the Dutch coastal zone with high concentrations is clearly visible.

2.4.2 Impact of Maasvlakte 2

In various studies, the effect of Maasvlakte 2 (i.e. Reference design I and II) on the transport of mud along the Dutch coastal zone and towards the Wadden Sea has been assessed. The studies show the following picture with respect to the effect of Maasvlakte 2 (De Kok, 1999; Thoolen et al., 2001; Boon et al., 2001):

- The impact of Maasvlakte 2 is visible over a relatively large distance along the Dutch coastal zone north of Callantsoog,
- The coastal river widens due to Maasvlakte 2. This results in a lower mud concentration and lower mud transport flux near the coast at Callantsoog and higher concentrations further offshore.

The persistence of these conclusions is remarkable because these studies have all made use of different model schematisations, computational grids, forcings, and mud transport formulations.

The aforementioned effects on mud are explained by taking into account the effects on the water motion (see section 2.2). The decreasing residual current towards the coast causes a decreasing net mud transport in this direction. As a result, the mud concentration decreases near the coast and increases further offshore. The changes in the cross-shore direction have an effect on the transport in the long shore direction. In the zone near the coast, the mud flux decreases, whereas the mud flux increases further offshore.

Quantitatively, the results from the previous studies show a large bandwidth with respect to the decreasing mud flux due to Maasvlakte 2. The computed decrease of the net mud flux at Callantsoog varies between 5 – 25% in these studies. It should be noted that this is the result of various choices with respect to computational grids, layouts of Maasvlakte 2, and forcings. Moreover, the net mud flux is very sensitive to the chosen forcing and the selected time frame. The net mud flux is the difference between the gross mud fluxes in the northern and southern directions and is generally less than 10% of the gross fluxes. The relative effect of Maasvlakte 2 on the gross flux in both directions is less than the effect on the net flux.

2.5 Nutrients and primary production

2.5.1 Present situation

In the study of the new airport in the North Sea (*Flyland* project), Los (2000) has given an overview of the current situation with respect to suspended matter, nutrients, primary production and the possible influence of autonomous developments. Additionally, he has summarised the results of research on nutrients and primary production in the North Sea that has been carried out at WL | Delft Hydraulics in the preceding decades. This study contains many references to related research. In recent years, results of the Flyland project have become available (Mare, 2001a, 2001b) and additional model research has been carried out to estimate the possible effects of an increasing discharge capacity in the Afsluitdijk (WL | Delft Hydraulics, 2003), and the response of primary production and phytoplankton in the North Sea due to the reduced nutrient supply from the rivers (WL | Delft Hydraulics, 2004).

Briefly, the following picture emerges from these studies. Unlike the sources of mud, the rivers are the most important sources of nutrients for the Dutch coastal zone, in particular the Haringvliet and the Nieuwe Waterweg. From the 1950s until the 1980s, the supply of nutrients from the rivers has increased, followed by a subsequent decrease due to the implementation of various measures. The N/P-ratio has been increasing since 1988 because the decrease of phosphate is larger than nitrogen. The supply of nutrients towards the Western Wadden Sea from Lake IJsselmeer is comparable to the supply coming from the North Sea (Laane, 2005). Additionally, atmospheric deposition plays a role for the North Sea and the Wadden Sea (Laane, 2005).

Similar to the transport of mud, the coastal river is an important transport route for nutrients from the River Rhine towards the Wadden Sea. The nutrient concentrations are higher in a narrow strip near the coast. The total nutrient concentrations are approximately inversely proportional to the salinity and are therefore very sensitive to the mixing of fresh water from the rivers and salt water from the North Sea.

The sea bed plays an important role in the nutrient dynamics because the bed may act as a temporary or permanent buffer for nutrients, especially in the Wadden Sea. The variation in time and space of the nutrient concentrations is highly related to the primary production, which varies in the North Sea between 45 and 572 $gC.m^{-2}y^{-1}$. Near the coast, primary production is mainly limited by light. Further offshore, nutrients (especially phosphate) limit the primary production. The limitation due to phosphate generally decreases in summer because phosphate is released from the sea bed in summer.

The presence of mud in the water column is also an important factor for the primary production. If the mud concentrations are high, primary production is limited due to a limited availability of light. Hence, primary production is lower near the coastline than further offshore due to the higher mud concentrations. A change in mud concentrations will directly result in a change in the spatial and temporal pattern of primary production. The average primary production over the entire North Sea will probably remain the same, but the primary production will increase or decrease locally depending on the location.

2.5.2 Impact of Maasvlakte 2

As a result of Maasvlakte 2, the current pattern and the transport of mud will possibly change along the Dutch coast. Both effects have an impact on the primary production through changing transport paths of nutrients, or through changing light availability. A changing N/P-ratio can result in a changing algae composition and the occurrence of nuisance algae. In the framework of Project Mainportontwikkeling Rotterdam (PMR), a study has been carried out to quantify the above effects (WL | Delft Hydraulics, 1999). A summary of this study is given in Los (2000) as follows:

Summary "Large-scale effects of Maasvlakte 2 on nutrient and chlorophyll concentrations in the coastal zone" (WL | Delft Hydraulics, 1999)
The Generic Estuarine model (GEM) has been applied to estimate the effect of Maasvlakte 2 on the primary production. One GEM-computation has been carried out for the situation without Maasvlakte 2 and one computation with a land reclamation near the Maasvlakte that protrudes approximately 5.5 kilometres into the sea. In both computations, a changed sluice management of the Haringvliet sluices called "Tamed Tide" was included as well. The hydrodynamics and the mud patterns were computed with a constant south-western wind of 7 m/s (Bf 4). Each computation lasts a full year in which temperature, light extinction, supply of nutrients and the magnitude of the mud concentration were varied. During the year, the hydrodynamics of each tidal period are repeated so that the horizontal mud patterns remain constant.

The model results show that the horizontal mud and nutrient concentrations decrease over a 15 kilometre wide strip near the coastline as a result of the changing current pattern. The change equals -40% for mud as well as nutrients near the South Holland coast, and -30% for mud and -5% for nutrients near Callantsoog on the North Holland coast. A slight increase in concentrations occurs outside the 15 kilometre strip, in particular for nutrients, arising from the fact that the total supply of suspended matter from the Nieuwe Waterweg and the Haringvliet remain constant.

More recent computations using the Flyland modelling framework show a decrease of 0 – 15% in the nutrients in the direction of the Wadden Sea due to the Maasvlakte extension. This result is for Reference Design II (see Figure 1), which has a much larger effect than the Doorsteekvariant as shown in Section 3. The effect on nutrients is mainly governed by the change in mud concentrations. This result shows that Maasvlakte 2 could have a significant effect on the phytoplankton biomass and its composition in the nearshore coastal zone.

2.6 Fish larvae

2.6.1 Present situation

The coastal zone in the North Sea and the Wadden Sea are well-known for their role as nurseries for fish species such as sole, plaice and herring (Zijlstra, 1972; Van Beek et al., 1989; Asjes et al., 2004). The shallow areas are rich in food and the conditions are relatively calm. The spawning areas of these species are in the deeper parts of the North Sea and the Channel. The transport of eggs and larvae from the spawning areas towards the nurseries is largely governed by the currents, and is partly influenced by the biological behaviour of the larvae. A crucial aspect is the residual circulations in the North Sea as a result of the tidal motion and the exchanges with river water. Similar to mud and nutrients, the coastal river plays an important role for the transport of fish larvae along the Dutch coast towards the Wadden Sea. The larvae species are an important source of food for the ecosystem and successful recruitment of adult fish populations is of importance for the commercial fisheries.

2.6.2 Impact of Maasvlakte 2

It is argued that the Maasvlakte 2 will have an effect on fish larvae due to the expected changes in the current pattern (magnitude and direction) and the salinity gradients in the North Sea in general and in the coastal river in particular. A distinction should be made between two different effects. On the one hand, the current direction and the onshore component of the velocity can change. This effect could influence the number of fish larvae that reach the Wadden Sea. On the other hand, the magnitude of the residual current could change. This affects the transport time towards the Wadden Sea and the moment at which the fish larvae reach the Wadden Sea. Changes in the salinity gradients could have an effect on the magnitude as well as the transport time towards the Wadden Sea.

A change in the magnitude and time of the larvae transport could possibly influence the final success rate of larvae reaching the nursery areas. A decreasing supply of larvae could influence the recruitment of adult populations. It has been shown that the egg and larvae stadia determine the strength of each class year (Brander & Houghton, 1982; Zijlstra et al., 1982; Van der Veer et al., 2000) and that the transport towards the nursery areas can play a role (Van der Veer, 1998).

In the framework of the PKB it was argued that the influence of Maasvlakte 2 on the transport of fish larvae will be limited (Goderie et al., 1999). However the effects of Maasvlakte 2 have not been quantified. Within the framework of the Appropriate Assessment for the Wadden Sea, these effects are being estimated by using a hydrodynamic model and a behaviour model for fish larvae (see section 4).

2.7 Overview

In the preceding sections the state-of-the-art knowledge with respect to mud, nutrients and fish larvae in the Dutch coastal zone has been summarised. Moreover, the effects of Maasvlakte 2 are discussed based on the present knowledge and foregoing model studies. Based on this, the following can be concluded regarding the effects of the Maasvlakte 2 land reclamation on the Wadden Sea:

- **Mud:** All studies show a decrease in the mud flux towards the Wadden Sea. The decrease varies between 5- 25% depending on the geometry of the Maasvlakte 2 and the forcing, and the bandwidth in the results is large.
- **Nutrients:** A previous study shows that the total nutrient concentrations decreases in the first kilometres near the coastline at Callantsoog between 0 - 15%. As the total nutrient load from the river Rhine does not change, there is a slight increase in flux further away from the coast.
- **Fish larvae:** The effect of Maasvlakte 2 on the transport of fish larvae has not been quantified yet. Based on previous research it seems reasonable that the effects are limited because the effects of Maasvlakte 2 on the large-scale flow patterns in the Southern North Sea are negligible.

The aforementioned effects include many uncertainties. Various assumptions have been made in the model studies regarding the forcing, and the processes to be modelled. Only a qualitative judgement has been made for fish larvae. The actual effect on the transport of fish larvae towards the Wadden Sea will depend on the significance of the changes in hydrodynamics due to Maasvlakte 2. This holds in particular for sole and plaice, because these species make use of the shoreward directed component of the currents in order to reach the nurseries.

Within the framework of the Appropriate Assessment for the Wadden Sea, new model research has been carried out to quantify the effects of Maasvlakte 2 on mud transport, nutrients and fish larvae using state-of-the-art knowledge and models. The approach and results will be discussed in the next chapter.

3 MODEL APPROPACH AND RESULTS

3.1 Approach

This research combines a number of models to quantify the effects of mud, nutrients, primary production and fish larvae. In the figure below, the information flow and relationships between these models are summarised. The foundation of this entire model chain is formed by a good representation of the hydrodynamics. The results of the hydrodynamics are used as an input for the fish larvae model and the mud transport model. The results from the hydrodynamic modelling and the mud transport model form the input for the modelling of nutrients and primary production.

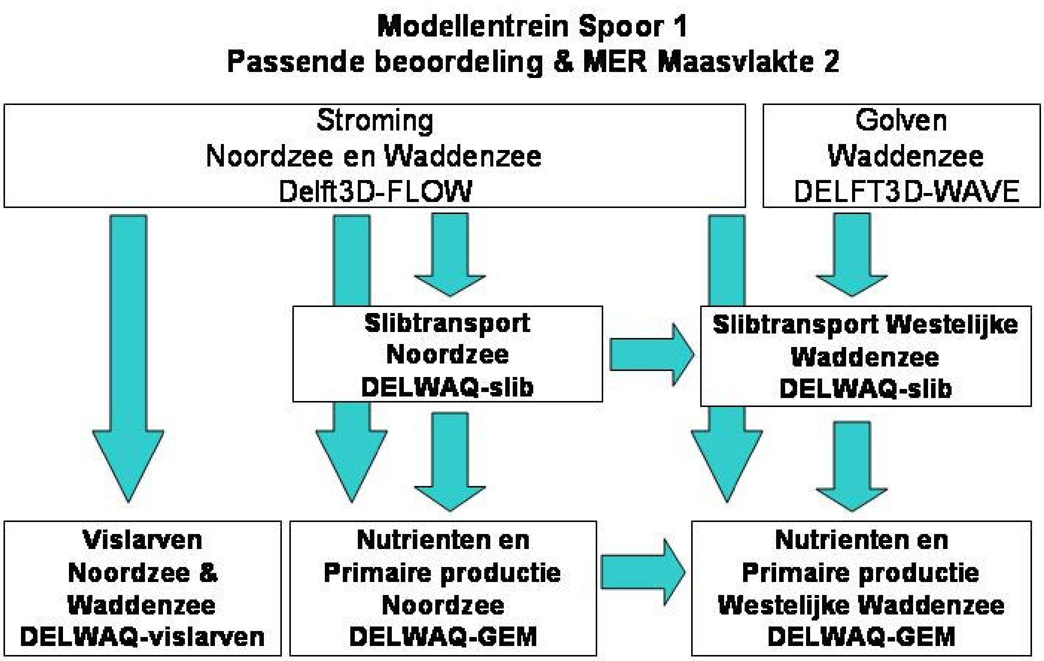


Figure 5: Overview and relationships of the models used.

An important assumption in this research is that only the long-term effect of short waves in the North Sea is accounted for in the choice of the parameter settings (critical erosion and deposition shear stress). The short term effect of buffering and release of mud by wave action (intermitting) is neglected. The reason for this choice is that the inclusion of waves in the computations would require too much computational effort, which was impractical given the time frame of this project. It is known that the role of waves is less than tidal motion, wind and river discharge in the transport and distribution of dissolved and suspended matter. Nevertheless, the effect of waves in the North Sea is not negligible and attention will be paid to this assumption in the discussion of the results. In particular, the effect of waves is crucial for the behaviour of mud and hence for nutrients and primary production in the shallow western part of the Wadden Sea. Therefore, the effect of waves has been included for this area (see also Figure 5).

In this research two different model schematisations with different resolutions have been used for the southern North Sea and the Wadden Sea:

- **ZUNO-coarse:** This model schematisation was already available, and has been applied in various studies (e.g. Maasvlakte 2 and Flyland). A comparison with measurements has shown that this model is able to adequately reproduce the large-scale water level fluctuations, current velocities, and salinity patterns in the North Sea as a result of tides, wind, and river discharge.
- **ZUNO-DD:** A new model schematisation has been set up in this study, because the mesh resolution of ZUNO-coarse is not sufficient to include the local change in the geometry of the coastline near Maasvlakte 2. For this purpose, the ZUNO-coarse model has been divided into several domains with varying mesh resolution. A very fine resolution has been applied around Maasvlakte 2, in the Dutch coastal zone and in the western part of the Wadden Sea.

The ZUNO-coarse model has been applied only for fish larvae. The ZUNO-DD model has been used for the transport of mud, nutrients, primary production and fish larvae.

Along with different model schematisations, two different simulation periods have been applied in this study: year computations and 14-days computations. This is because it is not practically feasible to compute all alternatives using year computations due to the computational effort required. The computations have been defined as follows:

- **Year computations:** The actual forcings of the river discharge, the wind velocity and direction and the atmospheric pressure have been applied in the year computations. Due to the actual forcing, the results of these computations can be compared with measurements. A one year computation with ZUNO-DD has been made for the period November 1988 to November 1989, whereas 9 years have been computed with ZUNO-coarse. In combination with the available measurements, these computations help provide an estimate of the natural variability of the system.
- **14-days computations:** The mean river discharge and a representative wind climate have been applied in these computations. This computation represents a “long-term average” situation.

Table 1 provides an overview of which computations have been applied to which aspect of the study, including the objective of the computation in each case.

Model schematisation	ZUNO-coarse	ZUNO-DD	
	Year computation (9 years)	Year computation (1988-1989)	14-days computations (representative period)
Hydrodynamics	Variability	Check of effects	Effects Maasvlakte 2
Mud transport	-	Variability and effects	Effects Maasvlakte 2
Nutrients	-	Variability and effects	Effects Maasvlakte 2
Fish larvae	Variability and sensitivity analysis	Effects Maasvlakte 2 and comparison with ZUNO-coarse	-

Table 1: Overview of the model schematisations and model simulations in this study

The following sections describe the approach and the assumptions in the modelling of hydrodynamics (section 3.2), mud transport (section 3.3), nutrients and primary production (section 3.4), and fish larvae (section 3.5). Additionally, an overview is given of the available results to-date.

3.2 Hydrodynamics

This study makes use of the state-of-the-art modelling system Delft3D-FLOW (WL | Delft Hydraulics, 2001). This model describes the three-dimensional hydrodynamic behaviour of free-surface water movement based on the shallow water equations in combination with a k-ε model for turbulence. The equations are solved on a curvilinear grid that can be adapted to follow the complex geometry. A large number of modelling studies for a variety of different areas has demonstrated that this model is able to describe complex three-dimensional patterns of currents and salinity distributions under the influence of tides, river discharges and wind conditions. Moreover, it is possible to apply domain decomposition to obtain a higher resolution in specific areas. In Figure 6, the curvilinear grid of the ZUNO-DD model of the Southern North Sea is shown, including the domains along the Dutch coast with a high resolution.

In the Western Wadden Sea, the effect of waves is included by using Delft3D-WAVE (i.e. SWAN) (WL | Delft Hydraulics, 2000). This model includes the present state-of-the-art knowledge regarding growth, propagation, and dissipation of waves in shallow water. The model computes the change in wave characteristics (e.g. wave height, wave period) based on an energy balance approach in which processes such as wind growth, refraction, breaking, white-capping, and wave-wave interaction (e.g. triads, quadruplets) are included as source and sink terms.

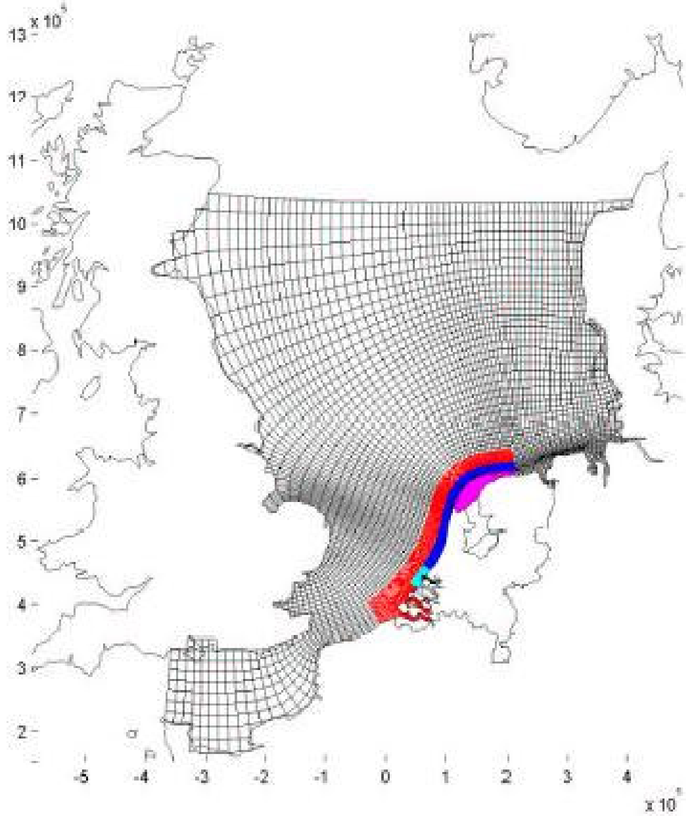


Figure 6: Curvilinear grid of the Southern North Sea model (ZUNO-DD).

The calibration and validation results based on the 14-days computations with the model schematisation ZUNO-DD give the following results:

- **Tidal propagation:** The model reproduces the tidal propagation along the Dutch coast and in the Western Wadden Sea very well. The error in the amplitude and phase of the most important components of the tide (i.e. M_2, S_2, N_2, O_1 en M_4) is small. The mean rms-value of the amplitude error is 2 cm (1%) in the North Sea coastal zone and 5 cm (3%) in the Wadden Sea area.
- **Salinity patterns:** The large scale salinity pattern agrees reasonable well with the long-term average situation along the Dutch coast compared to measurements (see Figure 7). The computed salinity along the Dutch coast is slightly low in the 14-days computations as well as in the year computations (approximately 1 ppt).
- **Residual discharges:** The computed annual residual discharge through the English Channel is 70.000 m^3/s in the year computation. The 14-days computation shows an annual residual discharge of 170.000 m^3/s. The latter is relatively high compared to measurements, whereas the result of the year computation is within the measured range (i.e. 50.000 – 150.000 m^3/s). The annual residual discharge through the Marsdiep for the year computation and for the 14-days computation both differ from the measurements. The long-term measurements show an annual export of water of approximately -2500 m^3/s. For the 14-days computation, the model computes a negligible annual residual discharge whilst for the year computation of 1988/1989 a net discharge of -500 m^3/s is computed.
- **Residual velocities:** The computed residual velocities have been compared in detail with measurements array at Noordwijk. The magnitudes and directions of the velocities agree well at the surface and near the bottom. Along the Dutch coast, the annual residual velocity is directed towards the north with a magnitude of 5 – 10 cm/s. Near the bottom the residual velocity is directed onshore and is about 0 – 5 cm/s.

In summary, the year computation and the 14-days computation reproduces the hydrodynamic characteristics along the Dutch coast. The computed annual residual discharge through the Marsdiep in the 14-days computation is a point of concern. This has no consequences for the computations of effects on the North Sea. The effect on the transport of mud and nutrients towards the Wadden Sea is also probably limited. The effect on the results in the Wadden Sea has been studied in more detail in a sensitivity analysis. The discrepancy in the annual residual discharge of the 14-days computations has no consequences for the fish larvae computations because only year computations are used in this part of the study.

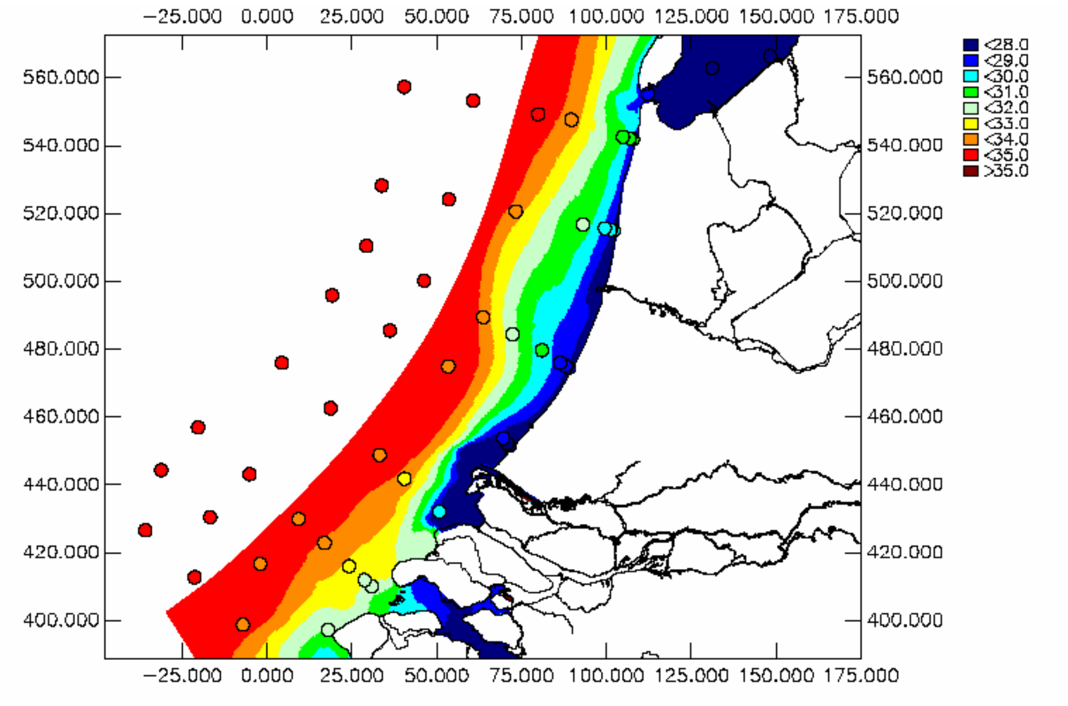


Figure 7: Comparison between salinity near the surface based on the computation (coloured area) and the measurements (dots). The model result is a mean value from a spring-neap cycle.

Based on the 14-days computation, the following can be concluded regarding the effects of Maasvlakte 2 on the hydrodynamics. The effects on the salinity along the North Sea are very small for the Reference Design II (GAB) and the Doorsteekvariant. The increases and/or decreases are at most 1 ppt compared to a background salinity of 25 - 35 ppt.

3.3 Mud transport

The DELFT3D-WAQ (SED) model has been applied for assessing the effects on the transport of cohesive sediment or mud. This model simulates the three-dimensional behaviour of mud in the water column and at the bed. Sediment transport processes such as vertical mixing in the water column, and exchange of sediment with the bed are accounted for. Typical processes such as flocculation and consolidation are not explicitly taken into account but are included empirically in the calibration parameters.

An important assumption in the modelling of mud transport is that the effect of water-bed exchanges due to seasonal variations has not been included. The knowledge about this temporal storage and release from the sea bed is limited and the existing models are not capable of describing these processes in an accurate way. In reality, various mud studies have shown that mud is temporarily stored in the North Sea and it is released again during storm conditions. The net sedimentation of mud in the North Sea bed is very small. This implies that neglecting the seasonal effects will not influence the magnitude of the effects but only the time-scale of these effects.

The calibration results show a good reproduction of mud concentration patterns in the North Sea. The mud concentration is high near the coast (50 - 100 mg/l), whereas the mud concentration is low further offshore (< 10 mg/l). The magnitude of the computed mud flux along the Dutch coast is approximately 8 Mton/year within the first 40 kilometres from the coastline. This is relatively low compared with estimates from the literature (i.e. 10 – 25 Mton/year), which are based on measurements and model results. These model results refer to the mud flux over a width of 70 km. The contribution of wave-induced transport was neglected in all studies. This part could be at least 10% of the total mud flux (Torenga, 2002).

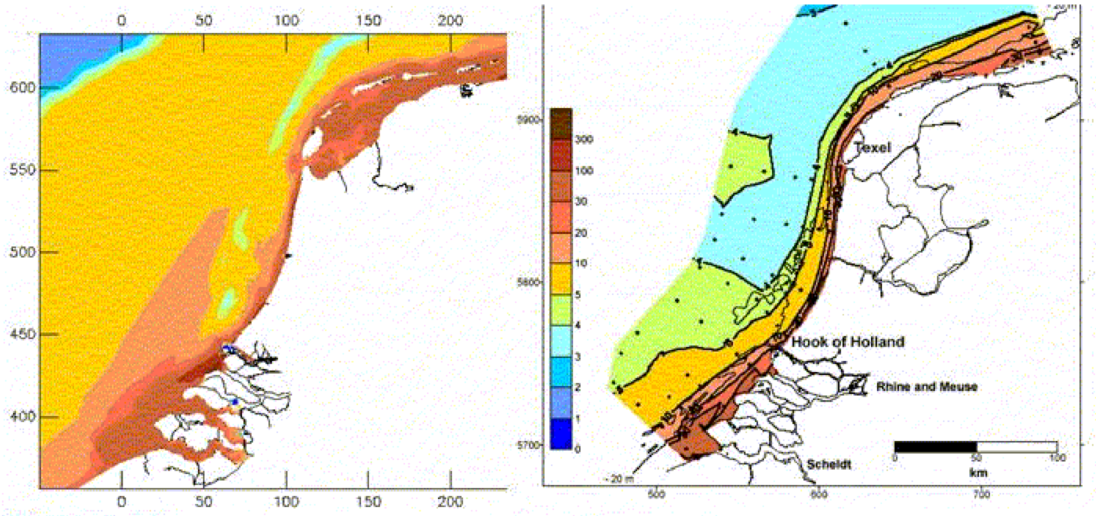


Figure 8: Long-term mean mud concentration base don measurements (right panel) and based on model results (left panel).

The computations of effects of the Maasvlakte 2 give the following results (see also Figure 9 for the Doorsteekvariant):

- The effects of the Reference Design II (GAB) are visible over a relatively large distance towards and even in the Western Wadden Sea. The mean mud concentration decreases in the Western Wadden Sea by 7 mg/l. Compared with the mean mud concentration in the autonomous situation (i.e. 40 mg/l) the mud concentration decreases by up to 17%. The decrease in the North Sea coastal zone is 13%. These effects are within the range described in the PKB of 5 – 25%.
- The effects of the Doorsteekvariant are much smaller than those of the Reference Design II (GAB). The computed mud concentration decrease is 3 mg/l. In a relative sense, this decrease is -8%. The effect in the North Sea coastal zone on the mud concentration is -10%.

Experts estimate the accuracy of the aforementioned effects at ± 50%.

These results agree with the conclusions of earlier studies. Due to the widening of the coastal river, the mud concentration near the coast decreases. The mud flux towards the north also decreases in the nearshore coastal zone (e.g. approximately 15 km). This is partly compensated by a higher mud flux further offshore. The decrease in the mud flux leads to a decrease in the mud concentration in the Western Wadden Sea.

The model results for the effects of sand mining show the opposite effect in the North Sea coastal zone and in the Western Wadden Sea compared to the effects of the land reclamation. Due to the release of mud during sand mining, the concentrations increase in the Dutch coastal zone. The sand mining will therefore not aggravate the effects of the land reclamation.

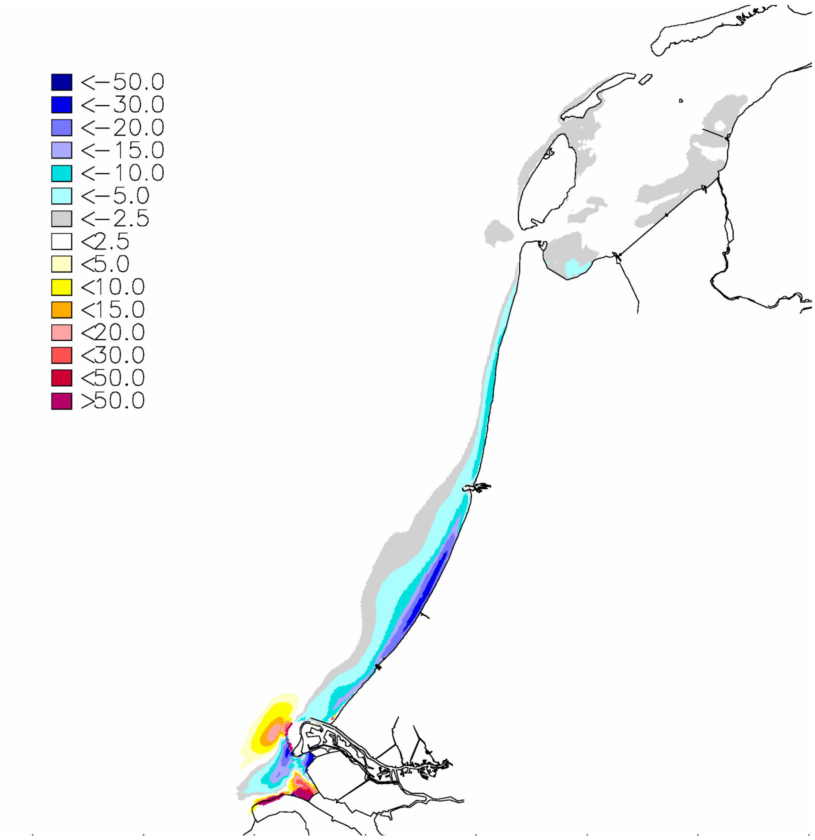


Figure 9: Effect of Doorsteekvariant on the mud concentration in mg/l base don the year computation 1988-1989.

3.4 Nutrients and primary production

This study used the DELFT3D-WAQ(GEM) model for modelling nutrients and primary production. This ecological model includes the cycles of carbon, nitrogen, phosphate, silicate, and oxygen, and includes primary production. Important processes are growth, decay, respiration, and sedimentation of phytoplankton, mineralisation, nitrification, denitrification, adsorption, and the burial of organic material. The computed phytoplankton biomass and composition consists of various species and is influenced by variations in the internal N/P-ratios. The results show that the model is able to reproduce the variations in the measurements reasonably well (see Figure 10). Moreover, the results are in line with the previous results in the Flyland project.

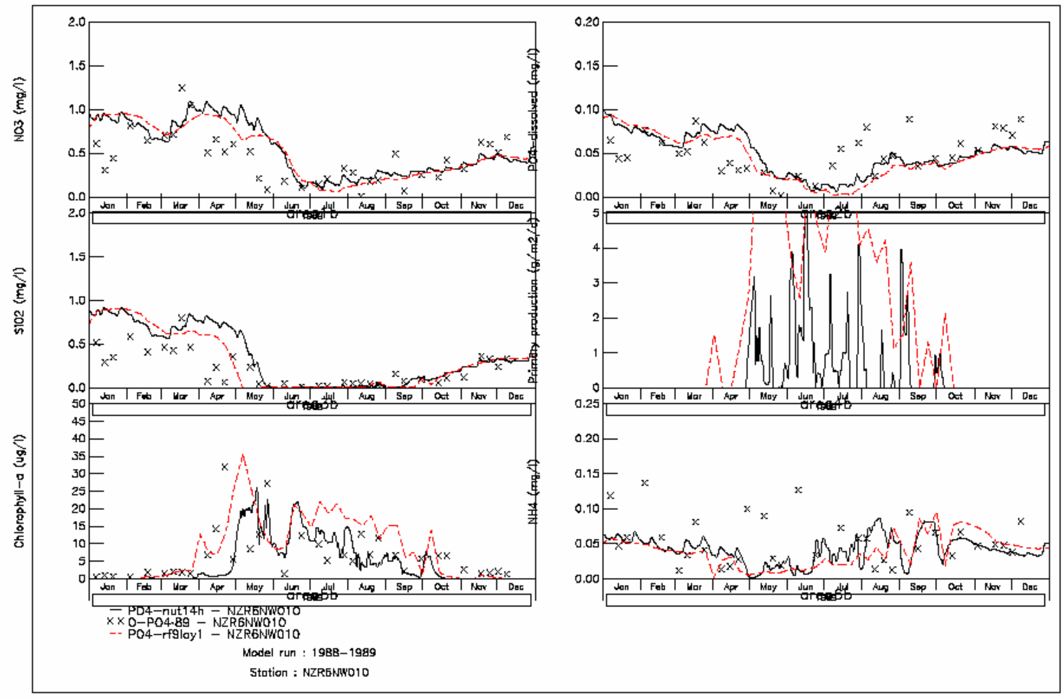


Figure 10: Comparison between measurements (x) and modelled results for ZUNO-DD (red line) and Flyland (black line) at Noordwijk 10. The figures show a comparison for dissolved nitrogen (upper left), silicate (centre left), chlorophyll-a (lower left), phosphate (upper right), primary production (centre right), and ammonium (lower right).

The computations of effects of Maasvlakte 2 show the following results:

- The effects on nutrients and primary production near Maasvlakte 2 due to the land reclamation are primarily caused by changes in the mud concentrations. The mud concentration decreases near the coast, and subsequently light limitation is less pronounced in this zone. In the spring, as the amount of light increases due to the increasing daylight hours, a small shift in the timing of the spring bloom is noticed. In areas of decreased mud concentration, the light required to initiate the spring bloom is available earlier in the year.
- The time shift in the spring bloom also results in a change in nutrient consumption. Due to the changes in the spatial variation of primary production, less nutrients are available in areas located further offshore. More nutrients are being consumed in the nearshore coastal zone leading to a decrease in the primary production further offshore.
- The effects of the Reference Design II (GAB) are much larger than the effects of the Doorsteekvariant. The effects of Reference Design II (GAB) are visible along the entire coast of South Holland and North Holland and sometimes also in the Voordelta. The effects occur in spring as well as in summer. Moreover, a shift becomes apparent between the supply of dissolved nutrients and the supply of particulate (organic) nutrients. The effects of the Doorsteekvariant only occur in spring (April) and are mainly visible along the coast of North Holland. The effects of the Doorsteekvariant are small in summer.
- The effects of the Reference Design II (GAB) and the Doorsteekvariant on nutrients show decreases with an order of magnitude of several percent (see Table 2). The effects on chlorophyll-a, primary production, and organic carbon show increases of a similar magnitude. This is due to the decreasing mud concentration in the coastal zone. Organic carbon is considered to be one of the most important parameters for

determining the subsequent effects on higher trophic levels in the ecosystem. Experts estimate the accuracy of these results at ± 50%.

Land reclamation MV2	Parameter	North Sea coastal zone	Western Wadden Sea
Reference Design II	Total phosphorus	-1%	-3%
	Total nitrogen	-3%	-2%
	chlorophyll-a	+8%	+2%
	Primary production	+5%	+5%
	Organic carbon	+4%	+4%
Doorsteekvariant	Total phosphorus	-1%	-2%
	Total nitrogen	-2%	-1%
	chlorophyll-a	+2%	0%
	Primary production	+5%	+1%
	Organic carbon	+2%	+1%

Table 2: Yearly averaged relative change in the North Sea coastal zone and in the Western Wadden Sea for total phosphate, total nitrogen, chlorophyll-a, primary production and organic carbon as a result of land reclamation Maasvlakte 2.

The quantification of the effects of sand mining on the nutrients and primary production is currently being undertaken. Initial model results show that sand mining has the opposite effect compared to the effect of the land reclamation in the North Sea coastal zone and the Wadden Sea. The sand mining will therefore not aggravate the effects of the land reclamation.

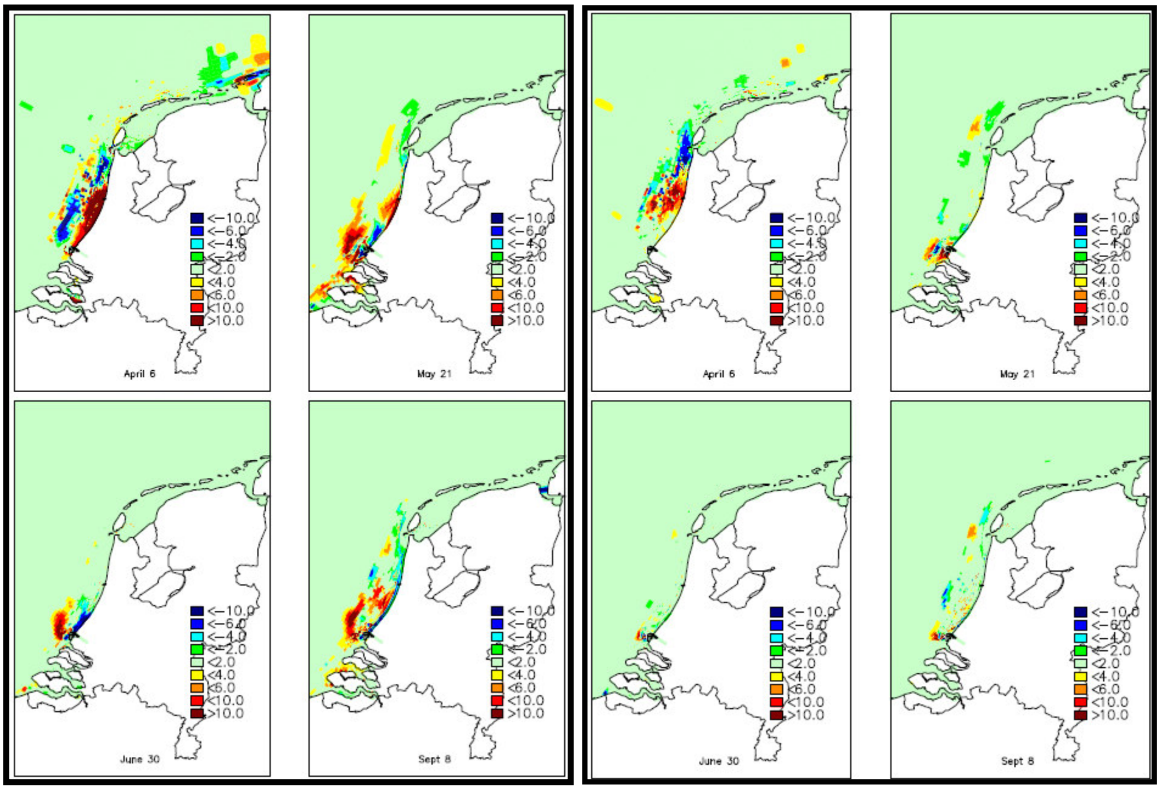


Figure 11: Effect of land reclamation due to Reference design II (left, blue frame) and Doorsteekvariant (right, black frame) on chlorophyll-a. In each figure the instantaneous difference in chlorophyll-a concentration (in µg/l) is shown at four moments during the year. A negative value indicates that chlorophyll-a decreases as a result of the land reclamation and vice versa.

3.5 Fish larvae

The model instrument Delft3D-WAQ has been applied to estimate the effects on the transport of fish larvae. A special model application has been developed in which the larvae transport of herring, plaice and sole is computed based on the physical (e.g. tidal currents, salinity) and biological (e.g. specific behaviour for a certain species) mechanisms. The version used in this study is an extension of an earlier application used in previous studies. State-of-the-art knowledge from literature and from experts, field data (e.g. RIVO-surveys, Balgzand-NIOZ-data), and new modelling techniques with realistic wind forcing in the hydrodynamic model have been used.

In the framework of this model research a literature survey has been carried out for herring to substantiate the formulations of behaviour in the fish larvae model (Dicky-Collas, 2005). The text below is a summary of this survey. After a short demersal phase (yolk-sac), the transport of herring larvae is primarily passive pelagic, although the larvae migrate vertically up and down in a day-night rhythm. Field data have shown that this vertical migration is related to the distribution of zooplankton. The amplitude of the vertical migration increases when the larvae grow and the growth rate is determined by temperature. The model includes the vertical migration and the variation as a result of growth. The spawning grounds in the Southern North Sea are modelled as realistically as possible.

Summary "Desk study on the transport of larval herring in the Southern North Sea (Downs herring)"
Current understanding about the drift and behaviour of larval herring is reviewed with particular emphasis on the Downs herring and the development of a model for larval transport. Downs herring are the component of North Sea herring that spawn in the southern North Sea and English Channel. Generally the larvae of the Downs herring drift east towards the German Bight and Skagerrak, but this is dependent on the sea currents. Whilst it has been possible to model the broad trajectory of the larvae, modelling the yearly variability in drift patterns has proved difficult. The drift of the larvae and post-larvae does take them close to the Dutch coast in some years (as shown by survey results). It is during this phase of their life cycle (from larvae to metamorphosis) that the strength of the recruiting class year is determined. The larvae show vertical migration as they grow and also begin to aggregate after metamorphosis. There is no evidence in the primary literature for triggers for directional movement (such as salinity or depth of water column). There is no work published to date, on the impact of anthropogenic disruption of larval drift on the productivity of Downs herring or on the fishery.

The eggs and larval phases of plaice and sole are dominated by passive pelagic transport. The late larval and juvenile phases show vertical migration probably related to the tidal phase. This so-called STST-behaviour (Selective Tidal Stream Transport) is possibly triggered by salinity differences and depth. The mechanism and the trigger parameters are implemented in the model. Some experts are of the opinion that flat-fish larvae have a passive demersal transport phase instead of STST behaviour. Hence, both options have been modelled separately to be able to compare these options. The length of the various phases depends on the temperature, which is also included in the model. The growth parameters have been calibrated with otolith data from Balgzand.

Various sensitivity computations have been made with the model schematisation ZUNO-coarse. These computations show that the year-to-year variations in the hydrodynamic behaviour of the North Sea have an enormous impact on the transport of fish larvae towards the Wadden Sea. In some years the amount of fish larvae reaching the Wadden

Sea is large, whereas other years show the transport success towards the Wadden Sea is almost zero. Furthermore, the computations show that the percentage of herring and sole larvae that reach the Dutch coast and the Wadden Sea is very small in comparison with the total population (e.g. about 0.5-7%). However, a large part of the spawning population of plaice in the Southern Bight of the North Sea reaches the Wadden Sea (e.g. 22-30%).

The analysis of the computations of effects focuses on two parameters:
- *Delivery rate*: this percentage shows the total number of larvae that reach the nurseries after transport. In this analysis, a distinction is made between several sub-areas (e.g. North Sea coastal zone, Western Wadden Sea etc.).
- *Timing*: the timing shows at which moment the larvae reach a certain area. Just like the previous parameters, this parameter can be computed for various sub-areas.

With the help of these parameters, the effect of the land reclamation on the transport of fish larvae can be estimated quite well.

Fish larvae	natural year-to-year variability	T0	"Kier"	MV2	effect MV2 compared to 'Kier'	annual variation
Herring	0.5 - 7%	1.2%	1.2%	1.2%	-0.8%	170%
Plaice (STST-behaviour)	3 - 15%	11.7%	11.8%	11.9%	0.2%	126%
Plaice (Demersal behaviour)	2 - 11%	8.9%	8.9%	8.9%	1.0%	138%
Sole (STST behaviour)	1.2 - 2.3%	1.4%	1.4%	1.3%	-5.8%	58%
Sole (Demersal behaviour)	0.7 - 2.0%	1.4%	1.4%	1.3%	-6.3%	93%

Table 3: Delivery rates of fish larvae to protected Wadden Sea area in present situation (T0), in autonomous development ("Kier") and with Maasvlakte 2 (MV2). A distinction is made between passive demersal ("dem") and selective tidal stream transport ("stst") for plaice and sole. All computations are based on the spawning populations in the southern area of the North Sea (English Channel and Southern Bight).

Table 3 shows that the amount of fish larvae that reaches the protected zone for a situation with and without Maasvlakte 2 (Doorsteekvariant). For plaice and sole, a distinction is made between a passive demersal transport and selective tidal stream transport because no choice could be made based on the available literature. Figure 12 shows these variations with respect to the natural variability. The results show the following:

- **Herring & Plaice:** The results show that the impact of Maasvlakte 2 is very limited on the number of fish larvae reaching the protected area (< 1%). This effect is negligible with respect to the natural variability.
- **Sole:** The effect of Maasvlakte 2 towards the Wadden Sea is somewhat larger for sole (6%) than for plaice and herring (<1%). These effects are still small compared with the natural variability. Moreover, only a small part of the sole larvae reaches the Wadden Sea. The effect on the transport success to all nurseries seems not to be influenced by the land reclamation for Maasvlakte 2.

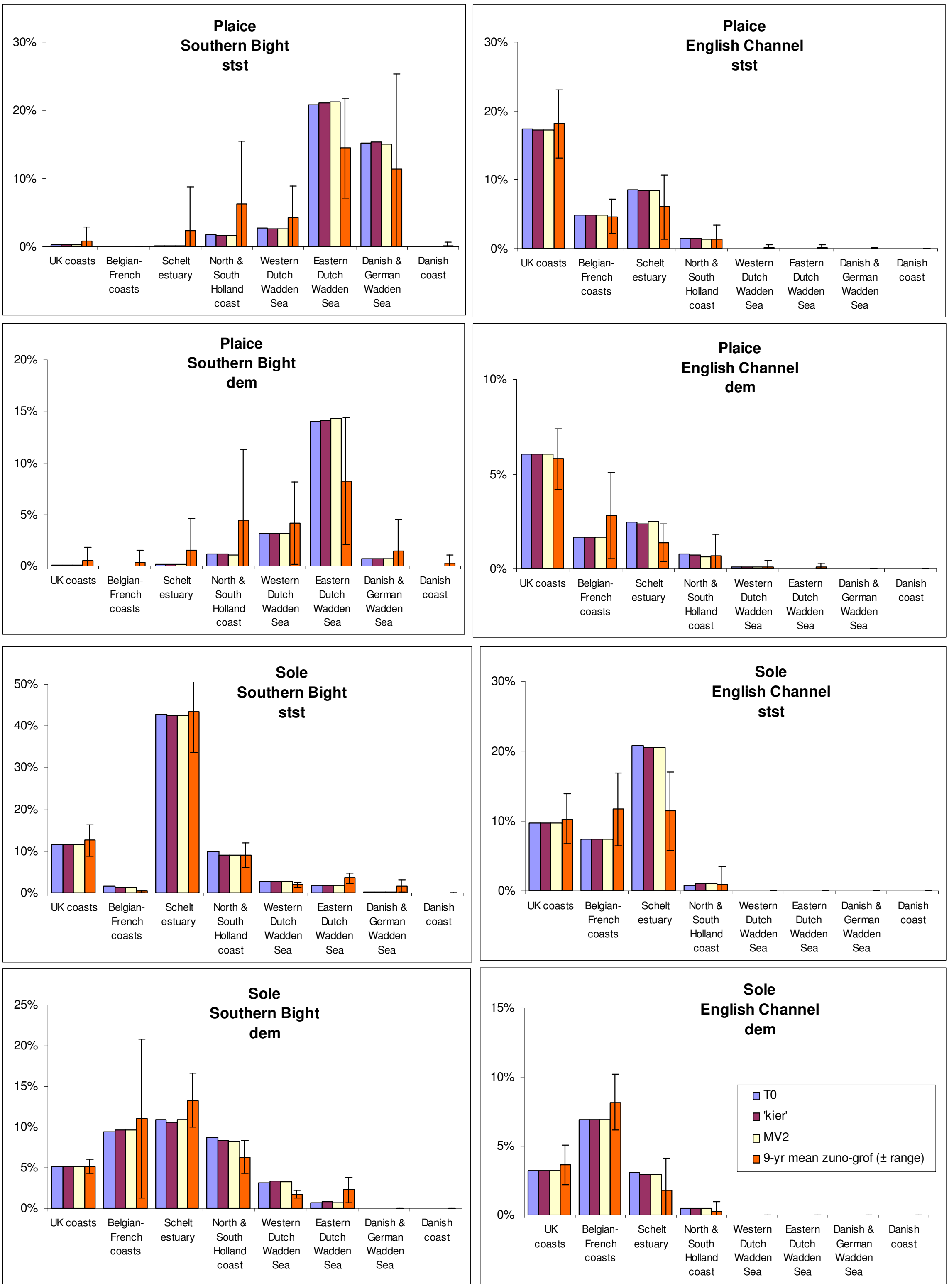


Figure 12: Delivery rates of plaice and sole larvae towards various areas in the present situation (T0), in the autonomous development without (“Kier”) and in the situation with Maasvlakte-2 (MV2), and mean (± range) for 9 years. The larvae originate from the spawning grounds in the English Channel and the Southern Bight. A distinction is made between the situation with selective tidal stream transport (‘stst’) and passive demersal transport (‘dem’).

The timing of the arrival in the Wadden Sea has been considered at a number of locations (e.g. Marsdiep). In some cases, the magnitude of the peak flux differs, but there is little difference between the times of arrival of the peak. In summary, it can be concluded that the impact of the Doorsteekvariant on the amount of fish larvae reaching the North Sea coastal zone and Wadden Sea and the timing of arrival in these areas is negligible.

The aforementioned effects have been computed for the Doorsteekvariant and are therefore comparable for the Reference Design I (GAN). No model results are available for Reference Design II (GAB). From the model results of the Doorsteekvariant, it follows that the transport towards the Wadden Sea is largely determined by the discharge through the English Channel and that this mainly occurs outside the coastal river. The land reclamation near Maasvlakte 2 only affects the local hydrodynamics around the outflow of the Rhine-Meuse and in the nearshore coastal zone at a larger distance. Therefore, it seems reasonable to conclude that the effect of Reference Design II (GAB) will also be negligible on the transport of fish larvae. Moreover, it is expected that sand mining has no effect on the transport of fish larvae because this activity does not change the large-scale hydrodynamics in the Southern North Sea.

4 DISCUSSION

4.1 Introduction

In the chapters above, the approach and results of the impact assessment were discussed in relation to the behaviour of mud, nutrients/primary production and fish larvae as a consequence of Maasvlakte 2. This model study was carried out in the context of the Appropriate Assessment for the Wadden Sea using state-of-the-art models. This chapter contains a review of this study and identifies the progress achieved, the existing uncertainties in the approach to the study and the results.

4.2 Scientific progress

During the study, progress was made in certain aspects and scientific boundaries were extended. Progress was made in the following areas:

- **"Southern North Sea model":** As part of the model study, a new 3D model was developed for the Southern North Sea. This model consists of eight grid domains with a very high resolution along the Dutch coast and in the Wadden Sea. This enables the processes in the coastal river to be described in fine detail. A relatively small intervention, such as the construction of Maasvlakte 2, can also be described accurately.

- **"Year computations":** In this study, the Southern North Sea model described above was used to carry out unique impact computations for the year 1988/1989. These computations are 3D and cover a full year with actual forcing by wind, tide and river discharge. Because of the high resolution in the coastal zone, the behaviour of the coastal river was modelled in fine detail. Three year computations were carried out on the WL|Delft Hydraulics cluster with 12 processors. The run time was about three weeks, and about 600 Gigabytes storage was required.

- **"Fish larvae model":** The existing fish larvae model was significantly extended in this study. This model takes account of the behaviour of fish larvae that is driven by both hydrodynamic factors (such as, salt, currents) and biological factors (such as, larval growth). This model was used to simulate the transport of fish larvae in the Southern North Sea. For the first time, nine years have been computed in order to investigate the variability between different years. These differences were in good agreement with the available data.

The above progress will be reported in various scientific publications.

4.3 Limitations and uncertainties in the model study

In addition to the scientific advances, certain choices had to be made before and during this study because of limitations in the available knowledge and time. Because of this, the results of the study itself and their interpretation are inherently uncertain and are open to discussion. The most important points of discussion on each part of the model study are summarized in the paragraphs below.

4.3.1 Introduction

"How representative is 1988/1989"[1]: This year was computed for all aspects using actual meteorological and hydrodynamic conditions in order to determine the effect of Maasvlakte 2 (*Doorsteekvariant* = cut-through variant). Various data series from the Wadden Sea show that there was a trend break in the system around that year as a result of a jump in temperature. The choice of that specific year is therefore not logical. However, an important argument in favour of selecting that year is that there are many measured data available for adjusting and validating the numerical models. For other years, these data are not available or are not immediately usable. Furthermore, the results are used in a relative sense rather than an absolute sense so that the representativeness of this specific year is less important. Finally, the year November 1988 – November 1989 was a reasonably typical year as regards the meteorological conditions and hydrodynamics (such as river discharges).

"Difference in effects between mud and nutrients": The impact assessment shows that the effects of the construction of Maasvlakte 2 on the flow of nutrients towards the Wadden Sea are much smaller than for mud. An important reason for this difference is that the underlying processes that affect the transport of mud and nutrients are not entirely the same. In contrast to nutrients, the distribution of mud is not uniform over the water column but the mud concentration is higher closer to the seabed. In combination with the residual currents resulting from the fresh/salt gradients, this gives a net transport of mud towards the coast. The result is the typical mud pattern with high mud concentrations close to the coast and lower concentrations further out to sea. The land reclamation changes the fresh / salt distribution and the pattern of residual currents along the Dutch coast. It is therefore logical that mud is more affected by Maasvlakte 2 than the transport of nutrients.

"Assessment of impact on fish larvae for Reference Design II ('GAB')": No model computations were made for the effect of Reference Design II ('GAB') on the transport of fish larvae, but an estimate was made on the basis of expert judgement. In the supporting reports on fish larvae, it is stated that – just as for the *Doorsteekvariant* – the effect is expected to be negligible. The thinking behind this is that the discharge through the English Channel is the most significant driving force for the transport of fish larvae through the Southern North Sea towards the Wadden Sea and this is not affected by Maasvlakte 2. Also, the transport of larvae does not occur very close to the coast, but somewhat further offshore. This means that even if the effects of Reference Design II ('GAB') on the water movements are slightly greater in the zone close to the coast the effects are still expected to be negligible.

4.3.2 Hydrodynamics

"Increased water level at the boundary with the English Channel": It was decided to raise the average water level at the boundary with the English Channel by 10 cm for the hydrodynamics computations. This was done in order to improve the match between the hydrodynamics off the Dutch coast (salinity, residual currents) and the measurements. The adjustment of the water level at this boundary is justified for various reasons. Firstly, the precise value of the average water level at that point is not known. Secondly, the focus of this study is the Dutch coastal zone. The increase was applied in order to match the model results to the measurements as closely as possible in the area of interest.

[1] This discussion point was dealt with in the workshops on track 2 and voiced by Alterra.

"Residual currents in the Marsdiep in the 14 days computation"[2]: This discussion is only relevant for assessing the impact on the mud and nutrients because the 14 days computation was not used for fish larvae. The residual flow through the Marsdiep was not well predicted in the 14 days computation: The residual flow on an annual basis is around 0 m^3/s in the model, while the measurements give around -2000 m^3/s (export). A good deal of effort was expended in an attempt to correct this, but without success (see the hydrodynamics report). On the basis of expert judgement, a residual flow that is more in line with the measurements probably has no effect on the impact assessment for mud and nutrients.

"14 days wind forcing": The representative 14 days wind forcing was based on the best possible match with the long-term wind statistics. Even though this selected period is statistically consistent with the long-term statistics, the choice is sensitive to the precise definition of the statistical parameters considered in the selection. Because it is known that the hydrodynamics along the Dutch coast are sensitive to the imposed wind climate, two steps were taken. Firstly, a number of computations were performed with different 14 days wind climates, based on different definitions of the statistical parameters. On the basis of these calculations it was concluded that the original 14 days wind climate gave the best match with the long-term average situation in the Dutch coastal zone with regard to salinity and residual currents. As a check, year computations were also performed with actual meteorological conditions (instead of representative meteorological conditions). The results show that the year computations and the 14 days computations with the original wind climate point in the same direction as regards effects and give the same results for the magnitude.

"Salinity pattern in the North Sea and the Wadden Sea": The salinity pattern in the North Sea and in the Wadden Sea is not well predicted by the hydrodynamic model. The salinity is too low (around 1 ppt) along the Dutch coast and in the Wadden Sea. The salinity field is an important indicator for the residual current pattern. Comparison with measurements from 1992 shows that there are differences from the measurements. The model predicts a slightly greater residual current in a northerly direction close to the surface and towards the coast close to the seabed. Such differences are acceptable for impact assessments as these only involve the differences between two model calculations.

4.3.3 Mud transport

"Neglecting seasonal water-seabed exchange"[3]: An important assumption in the mud study is that the seasonal seabed-water exchange can be neglected. This means that the storage of mud during quiet (summer) conditions and the release of mud again during rough (winter) conditions in the sandy bed of the North Sea is not included in the modelling. However, in this context, it is important to note that erosion and sedimentation of mud on the seabed as a result of tidal movements is included. The reason for the above assumption is that there are insufficient data and knowledge available at the moment to properly model this phenomenon and to calibrate/validate the

[2] The residual flow problems were extensively discussed in the meetings on the model study and separately discussed with experts from RIKZ, WL and NIOZ.

[3] In the context of the construction of the MER, new research is currently being defined in order to be able to include the effect of seasonal water-seabed exchange in the model calculations for sand mining.

parameters. The present approach is adequate for assessing the effects of the land reclamation since the reclamation itself only affects the water movement.

“Choice of boundary conditions”: The boundary conditions for the mud model were taken over from the Flyland study. These boundary conditions significantly affect the magnitude of the mud fluxes in the North Sea. There are many uncertainties associated with the boundary conditions. A comparison shows that the total mud flux through the English Channel and along the Dutch coast lies within the range of data from the literature. Despite the uncertainties in the boundary conditions, we can therefore argue that the present choice is the best available at the moment.

“Mud results for the present situation”: The concentrations from the mud model averaged over the year are too high. For the winter, however, they are too low. The mud fluxes along the Dutch coast are however on the low side. A possible reason for this could be the effect of storms generating very high mud concentrations. Large amounts of sediment are moved around during storms. The effect of storms has, however, been ignored in this study (see above). Because, in the end, this study is looking at the relative effects, the relatively low mud flux and the relatively high mud concentration are not significant.

“Quantification of uncertainties”: The quantification of the error band of the results was dealt with in the discussion of the results. The uncertainties relating to mud were quantified by comparing the impact assessment on the basis of the year computation with realistic meteorological and hydrodynamic conditions and the 14 days computations with idealised conditions. This comparison showed that the effects on mud are not sensitive to differences in forcing. The judgement of the experts is that the uncertainty around the results is about 50%. That figure is partly based on experience and partly on the quantitative analysis in this study.

4.3.4 Nutrients/primary production

“Mud concentrations for nutrient calculations”: Because the calculated mud concentrations were too high when compared with the measurements, the mud concentrations were halved for the nutrients and primary production computations. The reason for this is that errors in the mud concentration influence the results for the nutrients and primary production. The stationary mud concentrations were also modulated with a sine function for the seasonal variation and with a random function for the wind variation.

“The nutrients model is a 2DH approach”: A 2DH model (“averaged over depth”) was used to model the nutrients, while a 3D-model was used for the hydrodynamics and mud. Note, however, that the 3D effect was implicitly included in the 2DH model because both the hydrodynamics and the mud were based on 3D calculations. For nutrients and primary production, the processes are uniformly distributed over the vertical axis in such away that a 2DH approach is adequate.

“Quantification of uncertainties”: See the discussion of this topic under mud.

4.3.5 Fish larvae

“Impact assessment with one specific year (1988/1989)”: The impact assessment for fish larvae was based on a single computation for the year 1988/1989, with and without Maasvlakte 2, using a fine model (ZUNO-DD). A sensitivity analysis was also carried out for the present situation without Maasvlakte 2, using a coarse model (ZUNO-coarse) for nine different years. In view of the calculated variability between the different years, it is possible that the impact will also be different for different years. One reason for basing the impact assessment on a single year computation with ZUNO-DD is that the runtime did not permit the computation of more than one year. Computations with mud and nutrients showed that the use of a different hydrodynamic forcing had little effect on the relative effects. The results for fish larvae also showed that the year 1988/1989 is a reasonably typical year. On this basis it is to be expected that this also applies to the impact on fish larvae when using other years.

“Neglecting fish larvae mortality”: The computations for fish larvae were carried out without taking mortality into account. If the predation pressure changes, for example due to lower turbidity and hence a higher predation rate by sight feeders, this may affect the survival of the larvae during the transport phase. The survival may also be affected by changes in food availability related to changes in the productivity of the ecosystem. These potential indirect effects of Maasvlakte 2 on the survival of fish larvae have not been incorporated in the larval transport model. The study has focussed on the direct effects of Maasvlakte 2 on larval transport only. The experts expectation is that further development of the fish larvae model will not change the present conclusions regarding the effects of Maasvlakte 2 on the larval transport towards the Wadden Sea.

4.4 Evaluation

During the meetings with the experts, the progress and limitations of the current impact assessment with the aid of models were discussed. The progress with respect to the very detailed modelling of the North Sea, the computation of a realistic year instead of simplified meteorological conditions for a 14 days period, and the advanced fish larvae model are significant steps forward in these fields of knowledge. Besides the progress, the uncertainties in the model approach were discussed at length. This discussion identified the most important uncertainties as:

- salinity and residual current pattern in the North Sea
- seasonal water-seabed exchange
- quantification of the uncertainties relating to mud
- mud concentrations in the nutrients model
- relatively limited amount of measured data for calibration/validation

The removal of these uncertainties and limitations is crucial for gaining more insight into the behaviour of mud, nutrients/primary production and fish larvae in the North Sea in general and in the coastal river in particular. Despite the limitations in the model study and the related uncertainties in the model results, it is not expected that more insight would significantly change the conclusions of this study.

5 CONCLUSIONS

This report provides an overview of the effects of Maasvlakte 2 on the transport of mud, nutrients and fish larvae in the framework of the Appropriate Assessment for the Wadden Sea. Along with the results of earlier PMR studies, new studies have recently been initiated. The objective of this research is to quantify and explain the effects of Maasvlakte 2 on mud transport, nutrients and fish larvae for the Wadden Sea and the Dutch coastal zone, utilising all available knowledge and state-of-the-art tools. The various alternatives that have studied in this research are summarised in Figure 1.

Based on the present knowledge and results we conclude the following:

- **Model approach:** This study makes use of the best available model instruments for hydrodynamics, mud and nutrients. An important assumption is that the effect of wave action and the associated seasonal effect of water-bed exchanges (e.g. due to storms) has been neglected for the modelling of the North Sea. This is due to the lack of knowledge, and due to practical limitations of the computational capacity. Based on a literature survey, the existing fish larvae model has been extended to include state-of-the-art knowledge about the behaviour of fish larvae. Finally, it has been assumed in the model setup that the effects in the Eastern Wadden Sea are negligible. The model results do not indicate that this assumption is invalid.

- **Present situation:** Generally, the model results show good agreement with the measurements. For example, the typical high mud concentrations in the Dutch coastal zone are reproduced with the model. Moreover, the model results show that there exists a large natural variability in the patterns and transport of dissolved and particulate matter and organisms. These large variations are confirmed by measurements. The model results differ from the measurements for some aspects. For example, the computed salinity in the Dutch coastal zone is too low, the net discharge through the Marsdiep is a point of concern, and the instantaneous values of mud concentrations in the coastal zone are too high.

Based on the modelling results we conclude the following:

- **Mud:** The Doorsteekvariant causes a decrease in the mud concentration of the Western Wadden Sea of approximately 8% (5% - 15%) and in the North Sea coastal zone of approximately 10% (5% - 15%) The effect of Reference Design II (GAB) is a decrease of approximately 17% (10 – 25%) in the Western Wadden Sea and approximately 13% (5 – 15%) in the North Sea coastal zone. The effects of Reference Design II (GAB) are larger than the Doorsteekvariant.

- **Nutrients:** The effect of the Doorsteekvariant on nutrients in the North Sea coastal zone and the Western Wadden Sea is a decrease of approximately 2% (1 – 3%). For Reference Design II (GAB), this decrease is approximately 3% (1 – 5%). Organic carbon is considered to be one of the most important parameters for determining the subsequent effects on higher trophic levels in the ecosystem. The Doorsteekvariant shows an increase of organic carbon in the North Sea coastal zone of approximately +2% (bandwidth 1 – 4%) and in the Western Wadden Sea of approximately +1% (0.5 – 2%). For Reference Design II (GAB), these increases are approximately +4% (2 – 6%) in the North Sea coastal zone and +4% (2 – 6%) in the Western Wadden Sea. The effects on primary production are of the same order of magnitude. Similar results are obtained for Chlorophyll-a with the exception of the North Sea coastal zone for which the Reference Design II (GAB) gives an increase of approximately +8% (±4%).

- **Fish larvae:** The impact of the Doorsteekvariant on the amount of fish larvae reaching the North Sea coastal zone and Wadden Sea and the timing of arrival in these areas is negligible. No model computations have been carried out for Reference Design II (GAB). However, it seems reasonable to conclude that the effects on the transport of fish larvae due to Reference Design II will also be negligible due to its limited effect upon the large-scale hydrodynamics.

After carrying out the model study, there was a discussion with the experts concerned on the approach and results of this impact assessment using models. In addition to the scientific progress achieved in various fields of knowledge, the limitations in the current modelling approach and the related uncertainties in the impact assessment were also identified. Despite the uncertainties, the expectation is that improved insight will not essentially change the conclusions of this study with regard to the effects of the presence of the Reference designs or the Doorsteekvariant on mud, nutrients and fish larvae.

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