Large-scale sand extraction on sand ridges offshore of the Netherlands

Inventory of instruments to predict physical effects of sand extraction on the Zeeland ridges

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RIKZ/OS/2004.105W

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Directoraat-Generaal Rijkswaterstaat

Rijksinstituut voor Kust en Zee/RIKZ

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3 February 2004
Definitive version

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Workdocument:	RIKZ/OS/2004.105W
Project:	K2005*ZEEBODEM
Programme:	KUST2005

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Preface

This report is the result of my Master thesis of Civil Engineering at the University of Twente. I did my research at the Rijksinstituut voor Kust en Zee (RIKZ) in The Hague. I would like to take this opportunity to thank some people, who helped me to bring this research to a good ending. First, I want to thank the committee. Marien Boers, my supervisor at RIKZ, for his critical comments and help on the research strategy and the rest of the report and Ad Stolk, my supervisor of Rijkswaterstaat, Directie Noordzee (RWS, DNZ), for his useful contribution from a decision-makers perspective. Furthermore, Henriët van der Veen of the University of Twente for helping me get started with the research and checking the report. Finally, I want to thank Suzanne Hulscher for her difficult, but useful questions and critical comments.

During two weeks of my research, I did some model runs at the University of Twente. I want to thank Pieter Roos and Michiel Knaapen for letting me work with their models and for accompanying me. A highlight of my thesis was the workshop 'Modelling sand mining on the Zeeland ridges', which I organized on November 18th 2003 at RIKZ. I would like to thank all the participants of the workshop: Marien Boers, Job Dronkers, Dries van den Eynde, Suzanne Hulscher, Déborah Idier, Michiel Knaapen, Sonja Ouwerkerk, Leo van Rijn, John de Ronde, Pieter Roos, Teun Terpstra, Pieter Koen Tonnon, Henriët van der Veen and Dirk-Jan Walstra, for their presentations, co-operation and enthusiastic contribution to this day. I also want to thank Jan Mulder for leading the day as chairman.

Finally, I want to thank my colleagues at RIKZ, for their sociability and interest in my research during my stay at RIKZ. And last, but certainly not least, I am very grateful for my family and friends, who helped me through rough times of this research period and the rest of my study.

Saskia Hommes on board of the Zeeleeuw during a EUMARSAND campaign at the Belgian North Sea on December 5th 2003

Have fun reading!

The Hague, 3 February 2004

Saskia Hommes

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List of abbreviations

2D:	Two Dimensional
2DH:	Two Dimensional Horizontal
2DV:	Two Dimensional Vertical
3D:	Three Dimensional
ADCP:	Acoustic Doppler Current Profiler
BCS:	Belgian Continental Shelf
BUDGET:	Beneficial usage of data and geo-environmental techniques
CSI:	Coastal State Indicator
CZM:	Coastal Zone Management
DNZ:	Directie Noordzee; Directorate North Sea
EIA :	Environmental Impact Assessment
HISWA:	Hindcast Shallow WAter Waves
LLWL:	Low Low Water Level
MCL:	Momentaneous Coast Line
MUMM:	Management Unit of the North Sea Mathematical Models and the Scheldt estuary
NAP:	Normaal Amsterdams Peil
NCS:	Netherlands Continental Shelf
RBINS:	Royal Belgian Institute of Natural Sciences
RIKZ:	Rijksinstituut voor Kust en Zee; National Institute of Coastal and Marine Science
RON/MER:	Regionaal Ontgrondingenplan Noordzee
RON2:	Regionaal Ontgrondingenplan Noordzee 2
RWS:	Rijkswaterstaat; Directorate-General of Public Works and Water Management
SDN:	Stichting De Noordzee
SUTRENCH:	SUspended sediment transport in TRENCHes
SWAN:	Simulating WAves Nearshore
TAC:	Total Allowable Catch
UT:	Universiteit Twente; University of Twente

Summary

This Master thesis is accomplished at the Rijksinstituut voor Kust en Zee (RIKZ) as part of KUST2005, which is a morphological research programme of Rijkswaterstaat (RWS). The management question of RWS (Directie Noordzee, DNZ) concerns the effects of large-scale (> $10x10^6$ m^3) sand extraction on the Zeeland ridges. DNZ wants to gain knowledge on the physical effects of sand extraction on the Zeeland ridges. Therefore, the objective of this study is to make an inventory of instruments that can be used to predict the long-term physical effects of large-scale sand extraction on the Zeeland ridges, in order to support the Dutch decision-making process.

The Zeeland ridges is a group of ridges located in front of the coast of the Dutch provinces Zeeland and Zuid-Holland, seaward from the continuous -20 m NAP depth contour line. The characteristics of the Zeeland ridges are: 5-15 m height, 9-39 km length, transverse spacing 3-7 km, oriented 0-20 degrees clockwise with respect to the tide, (partly) covered with sand waves of 2-8 m height. The origin of the ridges is not clear. First, they were considered as drowned dunes, but others concluded that they were partly formed by erosion of older forms and partly by sand accumulation. Furthermore, there are no data that point to migration of the Zeeland ridges. At first sight, the Zeeland ridges seem to be tidal sand ridges. However, the ridges are oriented like shoreface-connected ridges, clockwise with respect to the tide. Except for the fact that the ridges are not connected to the shore. Therefore, no clear conclusion can be drawn on the classification of the Zeeland ridges.

To achieve the objective as formulated, we determine the information need of decision-makers and other stakeholders, using the 'Rugby ball method' from 'Meetstrategie 2000+' of RWS. An important aid in this process is the definition of a set of Coastal State Indicators (CSI's); a quantitative concept of the actual state of the system as a basis for objective and transparent decision-making. Each indicator is related to a specific coastal user function. In this research, we restrict ourselves to the user functions: coastal safety and maintenance, offshore infrastructure and navigation. For each of the selected coastal user function, research questions, CSI's and if possible assessment criteria are formulated. The result of the Rugby ball is the inventory of instruments (objective Master thesis). We selected state-of-the-art models: three analytical (non)-linear stability-type models (Twente model, Utrecht model, Amplitude-evolution model) and four numerical models (Delft3D, SUTRENCH, Telemac, mu-SEDIM) to include in this inventory. The current situation of these instruments on the modelling of sand extraction is investigated and the future possibilities of each model are estimated. The information on the models is gathered through interviews with model developers, literature study and organizing a workshop for model developers. Furthermore, with the Twente model and the Amplitude-evolution model some calculations are done.

In the inventory of instruments it is indicated for which CSI's the instruments are applicable and with what reliability. From this inventory it was clear that the a couple of instruments are capable to directly support the decision-making process on a few CSI's (but only on short-term effects) and on the remaining part of the CSI's qualitative and quantitative insight in a schematised situation is possible at this point. We conclude that the most important information missing are measurements on sand transport and knowledge on the long-term (morphological) evolution of the sea bottom. The Kwintebank on the Belgian Continental Shelf can form a good test case. From 1979 till 2003, sand was extracted on this ridge. During this period the Kwintebank was also monitored intensively. Since February 2003, there is a temporary extraction closure of three years, because two depressed areas on the ridge exceeded the permitted extraction depth. During the closure period intensive monitoring will take place, to evaluate the natural potential of restoration of the ridge. It would be worthwhile to propose an idealised configuration of the Kwintebank and its depressed areas. Then, we could run models on this idealised case and compare the results in between and the magnitude orders with the field observations.

Samenvatting

Dit afstudeeronderzoek is gedaan bij het Rijksinstituut voor Kust en Zee (RIKZ) binnen het project KUST2005, een morfologisch onderzoeksprogramma van Rijkswaterstaat (RWS). De beheersvraag van RWS (Directie Noordzee, DNZ) concentreert zich op het effect van grootschalige (> $10x10^6$ m^3) zandwinning op de Zeeland banken. DNZ wil kennis vergaren over de fysische effecten van deze zandwinning. Het doel van dit onderzoek is het maken van een inventarisatie van instrumenten, die gebruikt kunnen worden om de fysische lange termijn effecten van grootschalige zandwinning op de Zeeland banken te voorspellen, om het Nederlandse besluitvormingsproces te ondersteunen.

De Zeeland banken is een groep banken voor de kust van de Nederlandse provincies Zeeland en Zuid-Holland, zeewaarts van de doorgaande –20 m NAP diepte contour lijn. De karakteristieken van de Zeeland banken zijn:
5-15 m hoogte, 9-39 km lengte, afstand tussen banken 3-7 km, oriëntatie 0-20 graden met de klok mee ten opzichte van het getij, (gedeeltelijk) bedekt met zandgolven van 2-8 m hoogte. De oorsprong van de banken is onduidelijk. Eerst werden ze beschouwd als ondergelopen duinen, maar anderen concludeerden dat ze gedeeltelijk gevormd zijn door erosie van oude vormen en gedeeltelijk door aanzanding. Verder zijn er geen data die duiden op migratie van de Zeeland banken. In eerste instantie lijken de Zeeland banken getijdenbanken te zijn. Ze zijn echter georiënteerd zoals kustaangehechte banken, met de klok mee ten opzichte van het getij. Alleen zijn ze niet verbonden met de kust. Kortom, er kan geen duidelijke conclusie getrokken worden ten aanzien van de classificatie van de Zeeland banken.

Om het geformuleerde doel te bereiken, bepalen we de informatiebehoefte van beleidsmakers en andere belanghebbende. Hierbij wordt gebruik gemaakt van de 'Rugbybal methode' uit 'Meetstrategie 2000+' van RWS. Een belangrijk hulpmiddel hierbij is het definiëren van een set van Coastal State Indicators (CSI's); een kwantitatief concept van de werkelijke toestand van een systeem, dat de basis vormt voor objectieve en transparante besluitvorming. Elke indicator is gerelateerd aan een specifieke gebruiksfunctie van de kust. In dit onderzoek beperken we ons tot de gebruiksfuncties: kustveiligheid en –onderhoud, offshore infrastructuur en scheepvaart. Voor elk van de geselecteerde gebruiksfunctie worden onderzoeksvragen, CSI's en wanneer mogelijk beoordelingscriteria geformuleerd. Het resultaat van de Rugbybal is de inventarisatie van instrumenten (doel afstudeeronderzoek). We hebben een aantal state-of-the-art modellen geselecteerd voor deze inventarisatie: drie analytische (niet)-lineaire stabiliteitstype modellen (Twente model, Utrecht model, Amplitude-evolutie model) en vier numerieke modellen (Delft3D, SUTRENCH, Telemac, mu-SEDIM). De huidige situatie van de instrumenten ten aanzien van de modellering van zandwinning is onderzocht en de toekomstmogelijkheden van elk model worden bepaald. De informatie over de modellen is verzameld door middel van interviews met model ontwikkelaars, literatuurstudie en de organisatie van een workshop voor model ontwikkelaars. Verder zijn er met het Twente model en het Amplitude-evolutie model een aantal berekeningen gedaan.

In de inventarisatie van instrumenten wordt aangegeven voor welke CSI's de instrumenten toepasbaar zijn en met welke betrouwbaarheid. Uit de inventarisatie blijkt dat een aantal instrumenten in staat zijn om het besluitvormingsproces op een paar CSI's direct te ondersteunen (alleen op korte termijn effecten) en voor de overige CSI's is het mogelijk om kwalitatief en kwantitatief inzicht te verschaffen in een geschematiseerde situatie. We kunnen concluderen dat de belangrijkste informatie die mist zandtransport metingen zijn en kennis op het gebied van (morfologische) lange termijn ontwikkeling van de zeebodem. De Kwintebank op het Belgisch Continentaal Plat zou een goede test case zijn. Van 1979 tot 2003 is er op deze bank zand gewonnen. Gedurende deze periode is er ook intensief gemeten. Sinds februari 2003 is de Kwintebank tijdelijk gesloten voor zandwinning, omdat er zich twee depressie gebieden op de bank bevonden die de toegestane winningdiepte overschreden. Gedurende de sluiting wordt er intensief gemeten, om het natuurlijke herstel van de bank te evalueren. Het zou de moeite waard zijn om een geïdealiseerde configuratie van de Kwintebank en haar depressie gebieden te formuleren. Vervolgens kunnen we met de modellen rekenen aan deze geïdealiseerde situatie en de uitkomsten vergelijken met elkaar en de orde grootte met de veldmetingen.

1 Introduction, Research objective and strategy

1.1 Sand extraction offshore of the Netherlands

The North Sea may be a small, shallow pool compared with oceans, but nevertheless it is teeming with life. Water and sediment are home to a wide variety of plants and animals. The North Sea is also a sensitive ecosystem that is under a great deal of pressure from intense human activities such as fishing, sand and gravel extraction, shipping, oil and gas extraction, tourism and industry. On the Netherlands Continental Shelf (NCS) an average of 30 million m^3 of sand per year is extracted and used for filling sand, nourishments and large infrastructure projects. Nowadays only small-scale extractions take place. However, land reclamation projects (like Main Port Rotterdam; Maasvlakte 2) and sand extraction activities for the construction industry may lead to larger and deeper sand pits in the NCS and sand extraction at ridges, both seawards from the continuous –20 m NAP depth contour line. Furthermore, the use of sand resources on land provokes more and more resistance, by citizens and (local) politics. The authorities need information on the morphological effects of large-scale (> $10x10^6$ m^3) sand pits to make decisions on granting licenses. A judgement framework for granting licenses on large-scale sand extraction is however still in development (Rijkswaterstaat, 2003b).

1.2 Framework of the research

Policy on offshore sand extraction

In 1993, the regulations on extraction activities in the Dutch North Sea were formulated in the 'Regionaal Ontgrondingenplan Noordzee' (RON/MER). The most important statements in RON/MER were the following: sand extraction is only allowed seaward from the -20 m NAP depth contour line, except for harbour entrances and shipping channels; only deepening up to 2 m is allowed; an area that has been mined once is not allowed to be mined again. In 2004, the 'Tweede Regionaal Ontgrondingenplan Noordzee' (RON2) is released. RON2 differs from RON/MER on the following points: it distinguishes between small-scale extraction (< 10 million m^3) and large-scale extraction (> 10 million m^3); for large-scale extraction or extraction of an area greater than 500 hectares an Environmental Impact Assessment (EIA) is required; the –20 m NAP depth contour line as landward boundary for extraction is replaced by the continuous –20 m NAP depth contour line; for large-scale extraction it is possible to mine deeper than 2 m, if an EIA shows that this is acceptable (Rijkswaterstaat, 2004; Stolk, 2003). For further details on the policy of offshore sand extraction, we refer to Terpstra (2004).

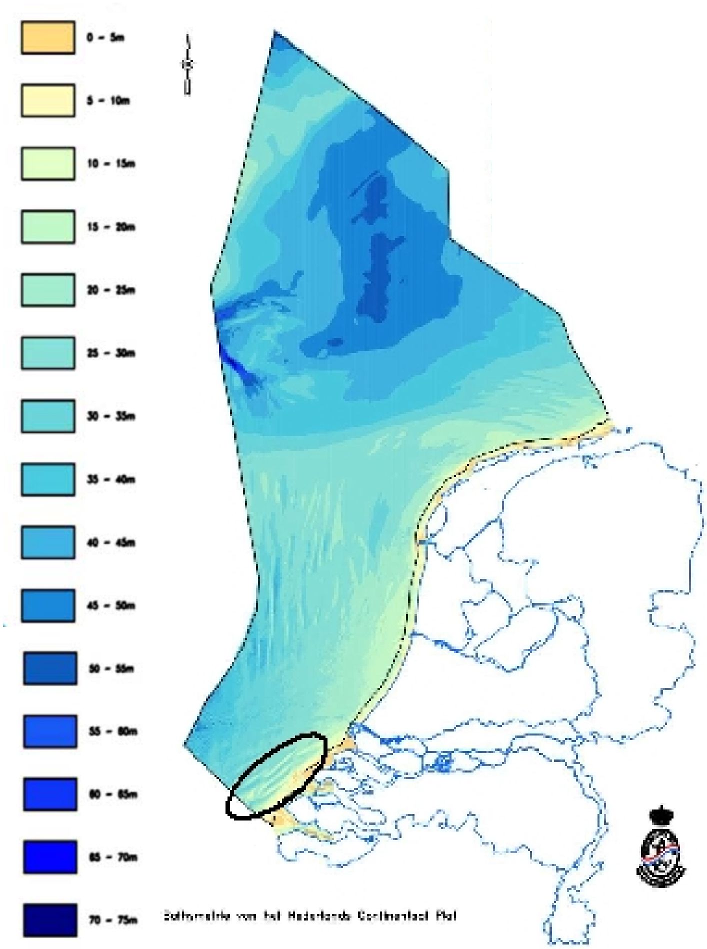


Figure 1.1: Water depth (m below LLWL) on NCS (TNO, 2003)

KUST2005

KUST2005 (COAST2005) is a morphological research programme of Rijkswaterstaat (RWS), which started in 2000 and lasts for five years. Based on an inventory of the major morphological coastal management problems on different timescales, COAST2005 aims: to contribute to the solution of specific coastal management problems; and to guarantee an improvement in quality of coastal engineering advice and models for the longer term. The specific problems concern four themes. This Master thesis is accomplished at the Rijksinstituut voor Kust en Zee (RIKZ) as part of the fourth theme, which focuses on the effects of (large-scale) sand extraction in the North Sea (Rijkswaterstaat, 2003a). In this research, we focus on the physical effects of large-scale sand extraction on the Zeeland ridges. The Zeeland ridges is a group of ridges located in front of the coast of the Dutch provinces Zeeland and Zuid-Holland, seaward from the continuous -20 m NAP depth contour line (marked by the circle in Figure 1.1).

1.3 Previous research on offshore sand extraction

Several studies related to the behaviour of navigation channels and sand extraction pits in the North Sea have been done recently and are still ongoing. Van Rijn and Walstra (2002) evaluated and summarised most of these studies, which generally focus on the flow and morphology of extraction pits in the North Sea using 2DV, 2DH and 3D hydrodynamic and morphodynamic models, as used by Delft Hydraulics, Svasek and University of Delft. The University of Twente uses bed instability models. These models have not yet been verified extensively due to the lack of field data. Field data sets at deeper water are almost completely missing (Van Rijn & Walstra, 2002).

Hoogewoning and Boers (2001) give an overview of the most important physical effects of offshore sand extraction, more specific: the influence on the flow, sediment transport and morphology. Furthermore, they relate these physical effects to involved user functions. Hoogewoning and Boers (2001) focus on three types of extractions: temporary sand extraction in the nearshore zone, large-scale sand extraction by widening of shipping channels and large-scale sand extraction in specific extraction areas (Hoogewoning & Boers, 2001).

Boers and Jacobse (2000) studied the influences of sand extraction on the Zeeland ridges on the wave conditions along the coast of Zeeland. This study was carried out within the framework of KUST2005. The research contributed to the insight in the possibilities of sand extraction on the Zeeland ridges. The conclusions of this research were that sand extraction on the Zeeland ridges has a very small, almost negligible influence on the wave conditions, direct after sand extraction, along the coast of Zeeland (Boers & Jacobse, 2000).

1.4 Research objective

The research on sand extraction at the Zeeland ridges started with a management question ('beheersvraag') of RWS, Directie Noordzee (DNZ). This management question concerns the effects of sand extraction on the Zeeland ridges. On one hand, we want to determine the user functions in the area and the value(s) of these ridges. This is the topic of the Master thesis of Terpstra (2004). On the other hand, we want to gain knowledge on the physical effects of sand extraction on the Zeeland ridges, the topic of this research. The objective of this Master thesis is:

> *Make an inventory of instruments that could be used to predict the long-term physical effects of large-scale sand extraction on the Zeeland ridges, in order to support the Dutch decision-making process.*

The main research question is:

> *In what way can instruments support the Dutch decision-making process on large-scale sand extraction in the area of the Zeeland ridges?*

Underlying questions are:

> - *What instruments can be used to predict certain physical effects caused by large-scale sand extraction on the Zeeland ridges?*
> - *Do the output parameters of these instruments support the decision-makers in their decision? If not:*
>   - *What information is missing?*
>   - *What knowledge is missing?*
>   - *What are the future expectations and challenges?*

1.5 Research strategy

To achieve the objective and to answer the main research question and underlying questions as stated in the previous section, we have to determine what information decision-makers and other stakeholders require. We do this using a strategy, which is developed by RWS and is called 'Meetstrategie 2000+'. The strategy is developed for users and suppliers of measurements in the water sector, to determine which field measurements are needed for certain projects or goals (Kinneging, 2001). In this Master thesis, we use the strategy to determine which instruments could be used to predict certain physical effects of large-scale sand extraction on the Zeeland ridges. The strategy consists of an information cycle, which is shown in Figure 1.2 (Kinneging, 2001).

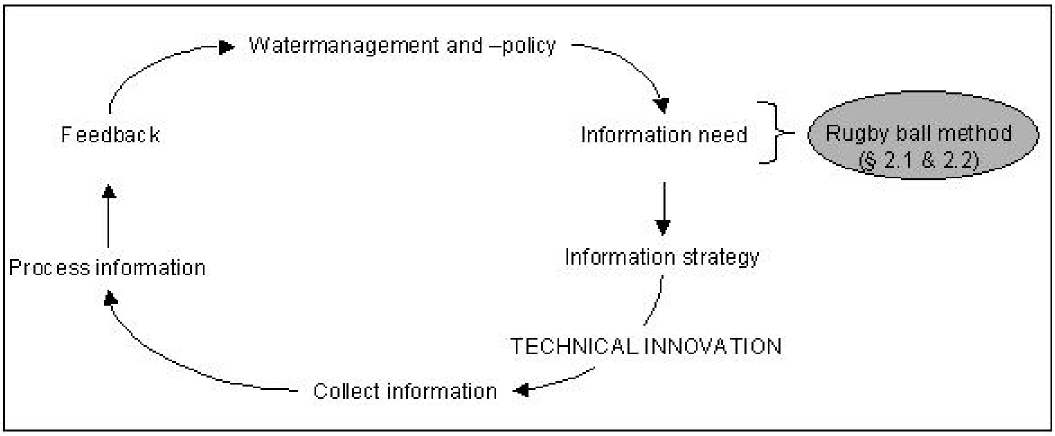


Figure 1.2: Information cycle (after: Kinneging, 2001)

The information cycle starts with a management question. To answer this question, we must first determine the information need of the stakeholders. Next an information strategy is designed, with which the information can be collected. The information that is gained has to be processed in the suitable format and delivered to the managers, who give feedback on the obtained information. Finally, the information need can be adjusted when needed and the cycle starts all over again. Note that the cycle can be run several times and on different levels of detail before the final goal is achieved.

Management and -policy

The information cycle starts with a management question, in this thesis the question of RWS (DNZ) on the physical effects of large-scale sand extraction on the Zeeland ridges.

Information need: Rugby ball method

The second step in the information cycle is the information need; this is the topic of this research. We determine this need using the so-called 'Rugby ball method'. This method is explained in Section 2.1 and 2.2.

Information strategy

The third step in the information cycle is the information strategy. In this step we indicate how different instruments should be used to collect the information that is needed. A short information strategy is given in Section 9.2.

Technical innovation

Depending on the mismatch between the information need and the possible techniques to collect the information, it can be necessary to search for new, innovative techniques (e.g. models).

Collect and process information

In these steps the designed information strategy is used to collect the information and the information is processed into the right format. This can consist of just presenting the results, but also combining, integrating and aggregating the information.

Feedback

In the last step of the information cycle the manager, gives feedback on the gathered information.

1.6 Reading guide

In the next chapter, the Rugby ball method is explained and the first two phases of this method are described. In Chapter 3, we investigate the research area, the area of the Zeeland ridges. In Chapter 4, we investigate the information need regarding the problem of sand extraction on the Zeeland ridges. Next in Chapter 5, we describe the current possibilities and limitations and the future possibilities of three analytical models, regarding the modelling of sand extraction on the Zeeland ridges. This is done for four numerical models in Chapter 6. In Chapter 7, we describe the results of the RIKZ workshop and the inventory of instruments. In Chapter 8, the results of this research are discussed. Finally, we draw conclusions and give recommendations for future research in Chapter 9.

2 Rugby ball method

2.1 Rugby ball method in general

The Rugby ball method is part of the strategy called 'Meetstrategie 2000+', which is developed by RWS. The Rugby ball method is used in this thesis to determine the information need regarding a large-scale sand extraction on the Zeeland ridges. In this chapter, we describe the Rugby ball adjusted for this research.

2.2 Rugby ball for this research

In Figure 2.1, the Rugby ball for this research is shown.

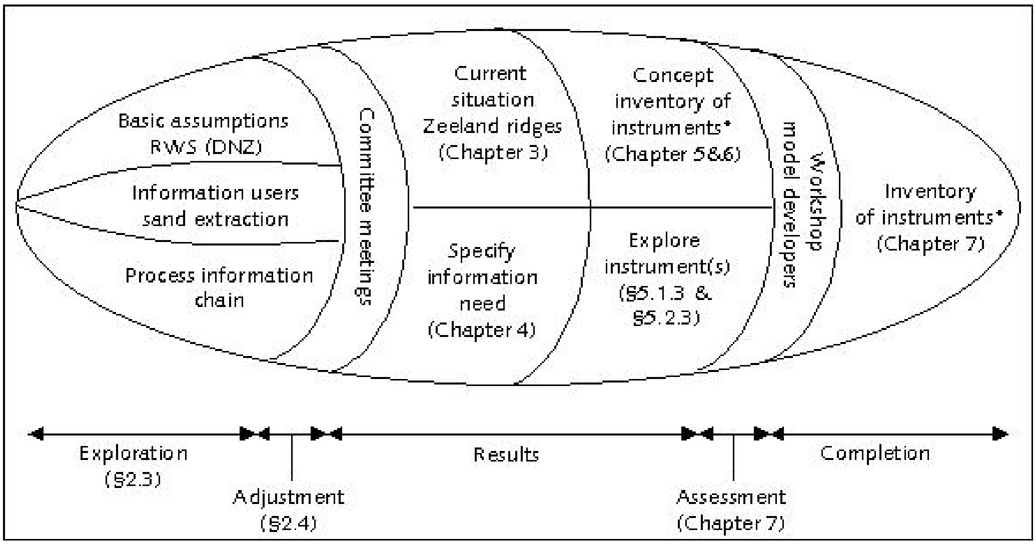


Figure 2.1: Rugby ball for this research (after: Rijkswaterstaat, 1998)
** In this research: instruments = models*

Phase 1: Exploration

In the first phase of the Rugby ball, the exploration phase, the basic assumptions of the research are determined, a list of information users is formulated and a process information chain is constructed.

Phase 2: Adjustment

The second phase of the Rugby ball is the adjustment phase. We adjusted the basic information need (Phase 1) during committee meetings with the supervisors of this research.

Phase 3: Results

Current situation Zeeland ridges

It is important to know the current situation before we can predict the influence of interventions, in this research sand extraction, on this situation. Therefore, we investigate the geomorphology, origin, sediments, physical processes and classification of the Zeeland ridges. For the current sand extraction market and policy in the Netherlands, the European legislation and the sand extraction plans in the area of the Zeeland ridges we refer to Terpstra (2004).

Specify information need

The information need of RWS (DNZ) and RIKZ is analysed by interviews with Ad Stolk (DNZ) and Marien Boers (RIKZ). Moreover, we use information from previous research, workshops and literature to determine the information need of other stakeholders. Finally, we make use of an indicator-concept to express the information need in quantifiable parameters, so-called Coastal State Indicators (CSI's).

Concept inventory of instruments & Explore instrument(s)

After an inventory of existing mathematical models, we selected three analytical models and four numerical models, to include in the inventory of instruments of this research. The current situation of these instruments is investigated. In order to explore the current possibilities and limitations of the different instruments, it would be ideal to do model runs with all models. However, it would take far too much time in the scope of this thesis to run all seven selected models. Therefore, we only did some exploratory model runs with two of the analytical models. We chose these models, because of practical reasons. The models were available for use at the University of Twente, where the model developers themselves supplied accompaniment.

Phase 4: Assessment

This phase is accomplished with the organisation of a workshop for model developers at RIKZ. At this workshop the participants gave a presentation on their model. After the presentations, a discussion was held, regarding modelling of sand extraction on one of the Zeeland ridges.

Phase 5: Completion

The result of the Rugby ball is an inventory of instruments, which can be used to predict the physical effects of large-scale sand extraction on the Zeeland ridges. In this inventory it is indicated for which CSI's the different instruments are applicable and with what reliability.

2.3 Exploration phase

2.3.1 Basic assumptions RWS (DNZ)

The basic assumptions are as follows: the final goal of RWS (DNZ) is to predict the long-term effects of large-scale sand extraction on the Zeeland ridges. This information can be used to decide whether to grant large-scale sand extraction on (these) ridges and under what conditions. Furthermore, this research focuses on the physical effects of sand extraction. The timescale on which we want to predict these physical effects is up to 100 years. However, in this research we do not include short-term effects, like silt plumes caused by dredging.

2.3.2 Information users sand extraction

The information users involved with the topic of offshore sand extraction are decision-makers, like DNZ who give permits on sand extraction, and water managers, like RIKZ who give advice on the effects of sand extraction. Further information users are: model developers, who want to know which output parameters their model must contain to be of practical use, and other stakeholders like environmental organizations, navigation, fishery, sand market, etc.

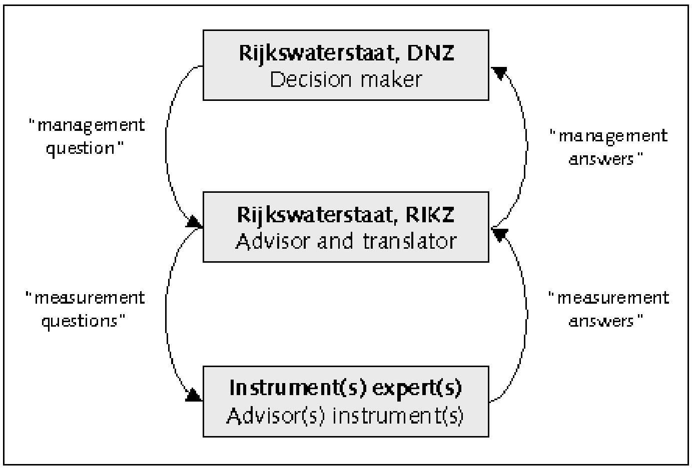


Figure 2.2: Process information chain

2.3.3 Process information chain

A process information chain is an aid to determine who undertakes what activities to achieve certain management goals and which information is needed to realise these goals. In Figure 2.2, the process information chain for this research is given. The process information chain starts with a "management question" of DNZ, who want to know the effects of sand extraction on the Zeeland ridges. With this question they come to RIKZ, where a graduating student (Saskia Hommes) is hired to investigate part of this problem. First, the "management question" is translated into "measurement questions" (research questions). RIKZ formulates parameters (CSI's; Section 4.2), which they want to determine using different instruments. With these "measurement questions" RIKZ turns to instrument experts, who can advice them on the possibilities and limitations of different instruments. Finally, RIKZ translates these "measurement answers" into "management answers", which can be used by DNZ in the decision-making process.

2.4 Adjustment phase

To adjust the basic information need (from the exploration phase) committee meetings were held with the supervisors of this thesis: Suzanne Hulscher (UT), Henriët van der Veen (UT), Marien Boers (RIKZ) and Ad Stolk (DNZ). In this phase, we discussed and adjusted the assumptions made in the exploration phase. The results of the committee meetings are processed in this report.

3 Research area: Zeeland ridges

In this chapter, we describe the area of the Zeeland ridges, which is the research area of this Master thesis. First, the general classification of tidal sand ridges and shoreface-connected ridges is described. After this, we investigate the geomorphology, origin, sediments, physical processes and user functions on the Zeeland ridges. In the last section, we aim to classify the Zeeland ridges.

3.1 Classification ridges

Sand ridge patches are significant features on many continental shelves and coastal regions. Their existence depends on the presence of tidal or other currents capable of moving the sand, and the availability of sand. In this section, we describe the general characteristics of tidal sand ridges and shoreface-connected ridges. In Figure 3.1, the location of several sand ridge patches in the North Sea is shown.

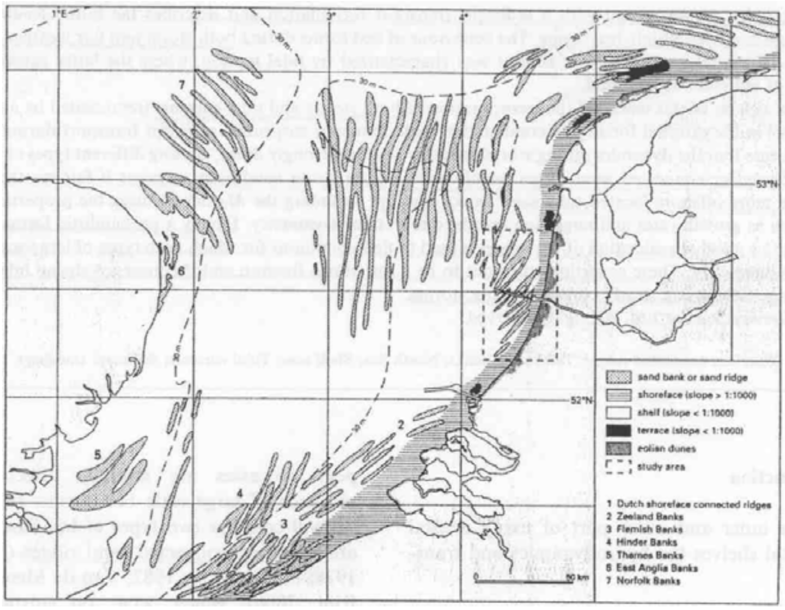


Figure 3.1: Sand ridge patches in the North Sea (Van de Meene, 1994)

3.1.1 Tidal sand ridges

Nearly all shallow tidal seas, where currents exceed 0.5 m/s and where sand is present, have tidal sand ridges. The sand ridges occur in trains, have an elongation of 8-65 km, and a regular transverse spacing of 1.6-10 km. In general the amplitude of sand ridges is between 2 and 20 m. The height-to-width ratio ranges from 1:200 to 1:300, but observations do not indicate a unique relationship between height and width. There are no indications that tidal sand ridges move. Furthermore, their crests are oriented slightly oblique (angles between 5 and 30 degrees) with respect to the principal tidal flow direction, nearly always in an anti-clockwise sense in the northern hemisphere (Figure 3.2). This suggests that the Coriolis force may be a significant factor in the dynamics of ridges (Dyer & Huntley, 1999). It is discussed that tidal sand ridges are relicts, or even moribund features. A feature is called relict if it is not formed by (present or former) flow-topography interaction. The definition of a relict feature does not exclude that its shape can significantly change due to flows and waves. If a feature is not influenced by the present hydrodynamical regime, it is called moribund (Hulscher et al., 2001).

3.1.2 Shoreface-connected ridges

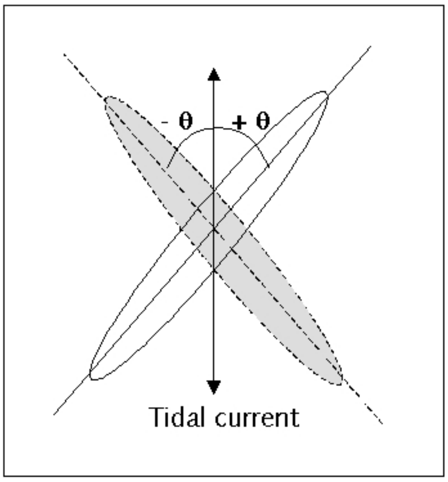


Figure 3.2: Orientation tidal sand ridges (gray; anti-clockwise) and shoreface-connected ridges (white; clockwise) with respect to tidal current

Shoreface-connected ridges are regular bars, which are connected to the lower shoreface with an oblique angle. Generally, patches of 4-8 ridges are observed in water depths of 5-20 m, located several kilometres offshore. The crests of shoreface-connected ridges are rotated clockwise with respect to the dominant axis of tidal motion, which is mirrored to the sense of direction of most tidal sand ridges (Figure 3.2). Furthermore, overall characteristics of these bed forms are: a height of 1-6 m, a width of 2-3 km, and a spacing between successive crests of 2-6 km, while crest lines can extend for several tens of kilometres. Side slopes of the ridge flanks are normally less than 1° and the ridges have an asymmetrical profile, i.e. they have a steeper slope on the seaward flank. The shoreface-connected ridges are associated with a temporal scale of decades to centuries and are present on shelves where storms contribute significantly to the mean longshore current, whereas the strength of the tidal current strongly varies over the regions of occurrence. Finally, the ridges migrate several metres (0.5-10 m) per year in the direction of storm-driven currents (De Swart & Calvete, 2003; Hulscher et al., 2001; Van de Meene, 1994; Walgreen, 2003).

3.2 Geomorphology of the Zeeland ridges

In this project, we focus on a group of ridges located in front of the coast of Dutch provinces Zeeland and Zuid-Holland, seaward from the continuous -20 m NAP depth contour line: the Zeeland ridges. The Zeeland ridges (Figure 3.3) consist of: Bollen van Goeree (1), Steenbanken (2), Middelbank (3), Schouwenbank (4), Buitenbanken (5), Schaar (6), Rabsbank (7) and Thorntonbank (8). In Appendix A, a geomorphological map of the Zeeland ridges is given.

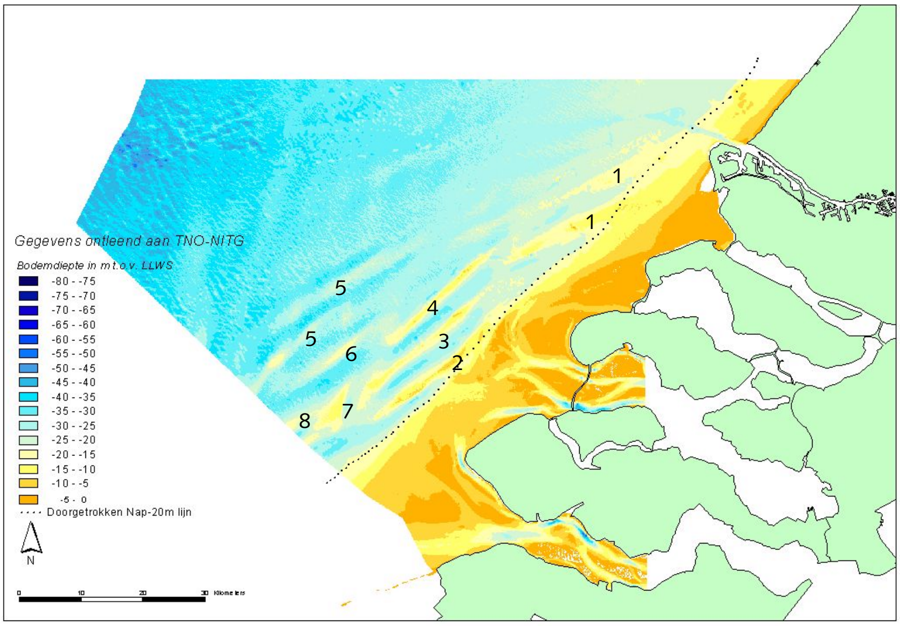


Figure 3.3: Bathymetry Zeeland ridges (TNO, 2003)

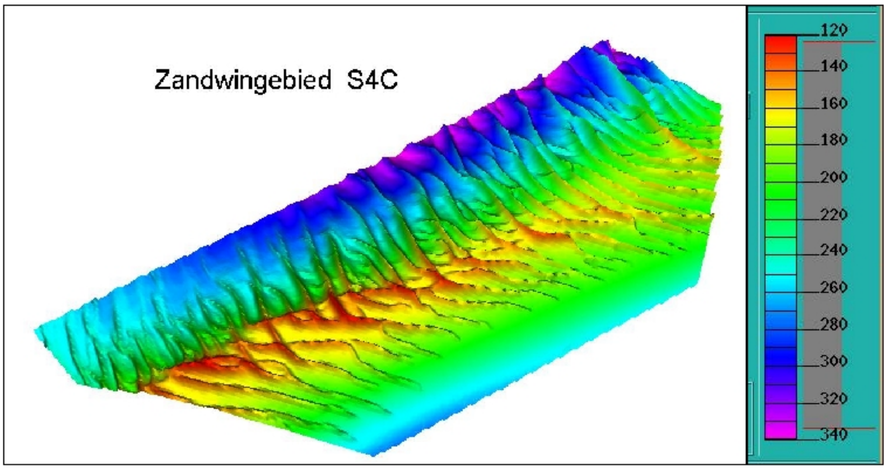


Figure 3.4: Bathymetry sand extraction area on the Middelbank, depth in dm – NAP (map from RWS, DNZ, 2003)

Most northwards, west of the islands Voorne-Putten and Goeree-Overflakkee, two large ridges are located: the Bollen van Goeree. These ridges are orientated in the WSW-ENE-direction, the distance between them is several kilometres, and the crest-trough height is 5 to 10 m and their length 29 and 39 km. The width of these ridges, which we define as half of the distance from the middle of the through on one side of the ridge to the middle of the other trough, is equal to 2-3 km. The ridges are located just seawards from the continuous -20 m NAP depth contour line. The Steenbanken, Middelbank and Schouwenbank are located west of Schouwen-Duiveland and Walcheren. The orientation of these ridges is in SW-NE-direction, the distance between them is around 3 km, and the crest-trough height is more than 10 m and their length 22-30 km. The width of the ridges is rather uniform (2-3 km). The ridges are located just seawards from the continuous -20 m NAP depth contour line. In Figure 3.4, the bathymetry of a sand extraction area on the Middelbank is shown. More offshore of the Schouwenbank, at a depth of -30 m NAP two large sand ridges are located: the Buitenbanken. These ridges are SW-NE oriented, the distance between them is around 3 km, and the crest-trough height is around 10 m and their length around 38 km. The width of the ridges is also rather uniform (2-3 km). Directly south of the Buitenbanken, three smaller ridges (in length) are located, the Schaar, Rabsbank and Thorntonbank. The Thorntonbank and Schaar are SW-NE oriented, the Rabsbank is SSW-NNE oriented. Their crest-trough height varies from 5 to 10 m and their length is 9-16 km.

The whole area, except for a nearshore zone of 5-14 km, is covered with sand waves. The height of these sand waves varies from 2 to 8 m (Figure 3.4). In general, the spatial scale of sand waves is smaller than that of sand ridges; their typical wavelength is between 100-800 m. The general amplitude of the sand wave patterns is of the order of 5 m. In most observed cases, the sand wave crests are almost perpendicular with respect to the major spring tidal current. Sand waves often have asymmetric shapes. Tidal sand ridges and sand wave fields sometimes partly overlap, sand waves fields occur on active ridges. Several authors have proposed estimates for the migration of sand waves. These vary between several metres per year up to 100 m per year. These results should be interpreted with care, due to the uncertainties in spatial location (Hulscher et al., 2001). The location of the sand wave fields in the area of the Zeeland ridges can be found in Appendix A.

3.3 Origin of the Zeeland ridges

The origin of the ridges in the Southern Bight of the North Sea, the Zeeland ridges, is not clear. Baak (1936; in Houbolt, 1968) considered the Zeeland ridges as drowned extensions of the barrier chain (dunes). These Old Dunes are shown in Figure 3.5. Houbolt (1968) concluded that the Zeeland ridges were in part erosional forms and were not formed by sand accumulation only. Furthermore, Houbolt draws the conclusion that the Zeeland ridges are nearly stationary. There are indeed no data on record that point to a significant displacement of the Zeeland ridges (Van Veen 1936 in: Houbolt, 1968). Laban and Schüttenhelm (1981) concluded that several of the Zeeland ridges are built on top of or are leaning against a core consisting of older deposits at least in part of (early) Atlantic age. These older deposits, provisionally named 'initial ridges', appear to be elongated in shape. Finally, we are not aware of any research on the Zeeland ridges after the research of Laban and Schüttenhelm (1981). In Appendix B, more details on the researches on the origin of the Zeeland ridges are given.

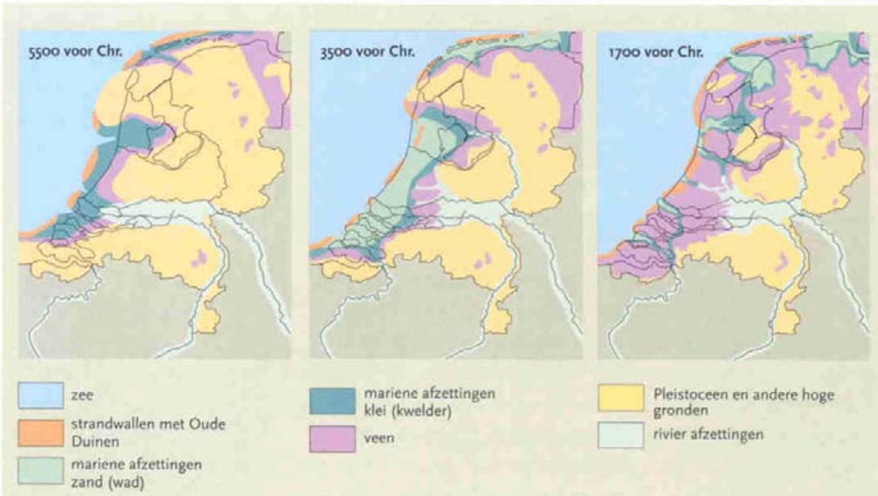


Figure 3.5:Distribution of Holocene deposits in the years 5500, 3500 and 1700 before Chr. (ICID, 2003)
blue = sea
orange = barrier chain with Old Dunes
pale green = river deposits
grass green= marine sand deposits
dark green = marine clay deposits
yellow = Pleistocene and other high grounds

3.4 Sediments on the Zeeland ridges

The sea bottom of the North Sea in the area of the Zeeland ridges mostly consists of sand. The surface sediment of the Zeeland ridges consists of moderate coarse sand (diameter = 210-300 μm) and very coarse sand (diameter = 300-420 μm). In general, sand ridges consist of sand, with coarser sand on the top and finer sand on the bottom of the ridges. In the troughs, gravel (diameter = 2-63 mm) and silt (diameter < 63 μm) can be found. In Appendix C, the grain size of the sediment in the first metre is shown for the area of the Zeeland ridges.

3.5 Physical processes on the Zeeland ridges

3.5.1 Tides

The North Sea is a tidally dominated shelf sea. The tide in the Southern Bight of the North Sea is semidiurnal with a period of around 12 hours and 25 minutes. Three tidal waves enter the North Sea: one through the English Channel, one along the Scottish coast and the Shetland Islands and a third along the Norwegian coast (Appendix D, Figure D.1A). The combined constraint of ocean basin geometry and the influence of the Coriolis force result in the development of amphidromic systems, in each of which the crest of the tidal wave at high water circulates around an amphidromic point once during each tidal period. The tidal range is zero at each amphidromic point, and increases outwards away from it. Interference between the three tidal waves in the North Sea results in two amphidromic points (Appendix D, Figure D.1A). Tidal waves in amphidromic systems are a type of Kelvin wave, in which the amplitude is greatest near the coasts. Kelvin waves occur where the deflection caused by the Coriolis force is either constrained (as at the coast) or is zero (as at the Equator). The typical tidal range in the North Sea varies from 0 to 6.5 m. In the area of the Zeeland ridges the typical tidal range varies, from north to south, from 2.5 to 3.5 m (Appendix D, Figure D.1C). At spring tide the tidal range at Vlissingen is around 4.5 metres and at neap tide it is around 2.5 metres (Appendix D, Figure D.2). We assume that the tidal range in the area of the Zeeland ridges is more or less the same as the tidal range at Vlissingen (Houbolt, 1968; Open University, 1999).

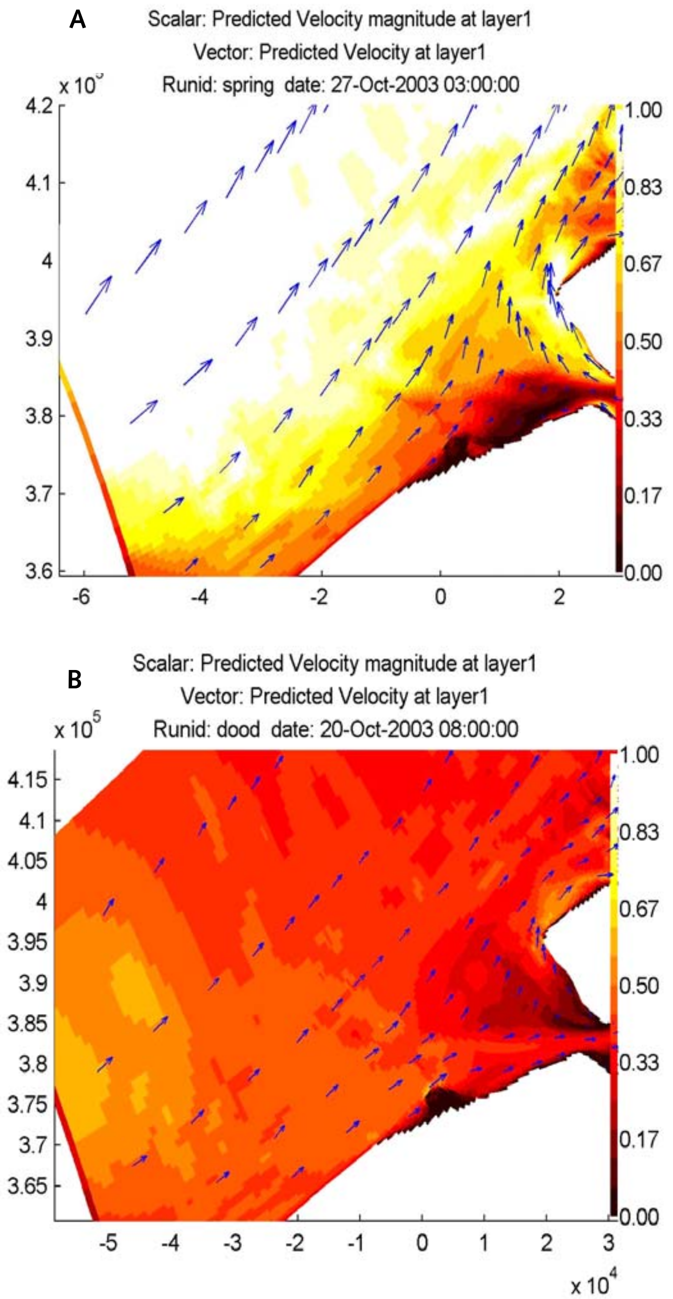


Figure 3.6: Maximum tidal currents at the water surface (m/s) in the area of the Zeeland ridges; spring tide (A); neap tide (B) (from Kustzuid model, 2003)

3.5.2 Tidal currents

The strength of the tidal currents in the North Sea is generally moderate (Appendix D, Figure D.1B), in the area of the Zeeland ridges it is around 0.75 m/s (1.5 knots). During spring tide maximum tidal currents of around 1.0 m/s can occur and during neap tide the maximum lies around 0.6 m/s (Figure 3.6). However, during storms much greater velocities can occur. The residual currents resulting from the tidal movements are shown in Appendix D, Figure D.1D. The influence of meteorological conditions on the tidal currents is difficult to determine, the more so as also weather conditions at a greater distance (e.g. off the Norwegian coast) may affect the horizontal water movement near the Dutch coast. The principal meteorological conditions which give rise to changes of the tidal currents are wind fields and to a lesser extent air pressure differences above the North Sea area (Koninklijke Marine, 2001).

3.5.3 Tidal currents over ridges

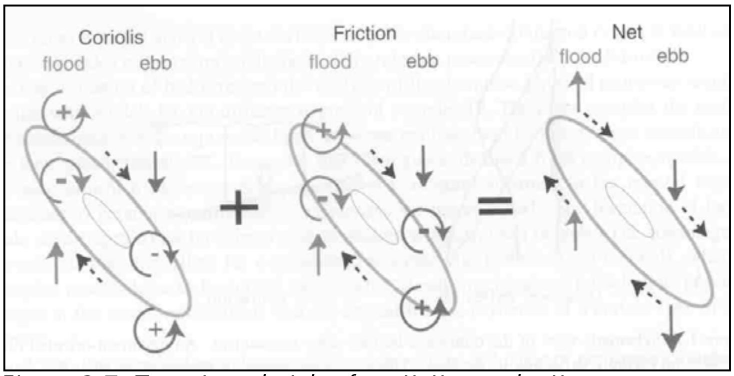


Figure 3.7: Top view sketch of vorticity production (anticyclonic = -; cyclonic = +) resulting from a tidal current flowing over a ridge. The vorticity during flood (left side of ridge) and ebb (right side of ridge), as well as the resulting (averaged over tidal period) current direction (dashed arrows) are indicated. (Walgreen, 2003)

If a tidal current moves over a ridge, in this case the Zeeland ridges, continuity effects cause an acceleration of the flow over the shallower area. Furthermore, the Coriolis force experienced by the water parcel on the crest is higher than in the deeper water and produces a torque. Conservation of potential vorticity results in the production of anticyclonic (clockwise on the Northern Hemisphere) vorticity over the ridge crest, during both ebb and flood. Vorticity is a measure for rotation and the refraction degree of the flow. A net anticyclonic circulation around the ridge, following the contours, and irrespective of the orientation of the ridge is the result (Figure 3.7, left). In addition, the bottom friction causes a strong deceleration of the flow on shallower areas, which produces torques over the flanks of the ridge (Figure 3.7, middle). This vorticity is advected by the tide. For a ridge oriented cyclonically (anti-clockwise on the Northern Hemisphere) with respect to the tidal flow, anticyclonic residual vorticity is generated over the crest during the tidal period (Figure 3.7, right). In that case both torques enhance each other and the strongest residual circulation is found. Whereas for a ridge of which the crest is rotated anticyclonically (like the Zeeland ridges, see Section 3.7), the Coriolis and frictional torques have opposite directions above the crest and a weak residual circulation is induced.

3.5.4 Waves

The wave climate is rather uniform along the Dutch coast: the dominant wave direction is southwest. Some values of the probability of occurrence (duration in % of time) for waves in deep water are:

- South-west (180°-270°): 15% waves of 1-2 m, 4-5% between 2-3 m, 1-2% between 3-5m;
- North-west (270°-360°): 10% between 1-2 m, 4-5% between 2-3 m, 1-2% between 3-5m.

The wave heights mentioned above are significant wave heights (Van Rijn & Walstra, 2002).

3.5.5 Wind

In general, wind can increases or decreases the rates of tidal currents depending on the directions of the wind and currents. To determine the effect of wind in open sea the following rule applies: a current of 2% of the wind velocity should be applied to the tidal currents (thus a wind of 20 m/s generates a current of 0.4 m/s). The wind-generated current is about ten degrees veered with respect to the direction in which the wind blows (a NW-wind generally generates a SE-S-current) (Koninklijke Marine, 2001).

3.5.6 Sediment transport

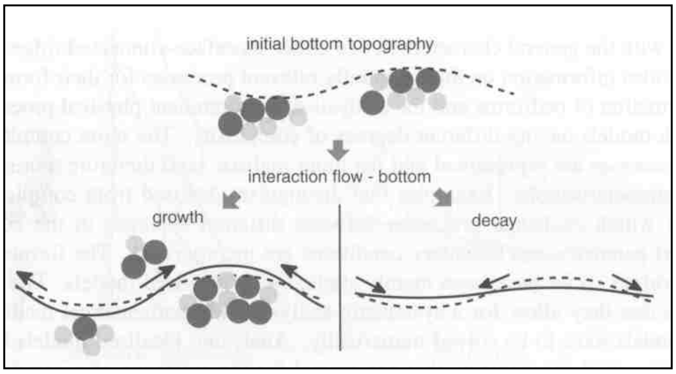


Figure 3.8: Schematic view of the growth or decay of bottom perturbations through transport of sediment (Walgreen, 2003)

An essential aspect of a coastal system, like the area of the Zeeland ridges is that currents and waves are capable of transporting water and sediment. In the case of sediment, the currents must exceed a certain threshold value before the sediment is transported. The interaction between the water motion and bottom topography through the transport of sediment can result, in some cases, in a positive feedback due to which small perturbations in the bottom start to grow (Figure 3.8). A morphological change in the seabed, e.g. the development of a sand ridge, is the result. A bottom topography that does not change in time under a certain forcing is in equilibrium with this forcing (Walgreen, 2003). For the research area of the Zeeland ridges, no measurements on sediment transport are available. Therefore, we investigate the sediment transport on the Belgian and Netherlands Continental Shelf from literature. We focus on sand transport (and exclude silt transport), because this determines the long-term evolution of sand ridges after mining, which is the topic of this research.

Belgian Continental Shelf

On the Belgian Continental Shelf (BCS), a variety of sediment dynamical studies have been performed. In the course of the BUDGET project, an overview has been produced of all these studies. Most of the data has been re-evaluated and the results were compiled in a synthesis map to characterise the natural sand transport on the BCS. However, using the existing data it is difficult to set up a quantitative sediment balance of the BCS (Lanckneus et al., 2001). Van Lancker et al. (2000) and Van Lancker and Jacobs (2000) (in: Kleinhans, 2002) studied sediment transport on the Flemish banks (Figure 3.9, location C) at water depths of 0-15 m. They found out that the spring-tidal flood current alone can transport sediment of 0.42 mm at least, but sediment of larger grain sizes when the sediment is stirred by waves as well. The coarsest sediments (up to 0.5 mm) with the best sorting are found on the tops of the banks. Vincent et al. (1998) studied the suspended sediment transport under waves and currents in more detail. They did measurements on the Middelkerke Bank (one of the Flemish Banks) during two winters. The wave heights were 1-4.3 m, and were observed to increase the suspension but have no effect on the transport direction. The following sand transport rates were obtained: 0.9 tonnes/m/day (≈ 200 m^3/m/year) up to 0.3 m above the bed, along the northern steep slope of the Middelkerke Bank. The southern side of the bank appeared to be more wave-sheltered, which explains the lower suspended transport rates of about 0.05 tonnes/m/day (≈ 10 m^3/m/year). The transport on the steep slope was mainly in the size range of 100-140 μm (fine sand), which is not significantly present in the bed material, indicating that it was advected by upstream wave- and current action. Excluding the finer component, the transport rates of coarser sand (> 200 μm) at the two sites were similar over the measuring period. Finally, the transport rates are consistent with a timescale of 100-1000 years for the formation of the bank (Kleinhans, 2002; Lanckneus et al., 2001).

Netherlands Continental Shelf

Van de Meene (1994), Van de Meene et al. (1996) (in: Kleinhans, 2002) and Van de Meene and Van Rijn (2000) (in: Kleinhans, 2002) studied the sediment dynamics of the shoreface-connected ridges off the Holland coast at a water depth of 10-20 m. In fair weather, the current-driven bed load transport is dominant and low, whereas in storm, the waves stir up the sediment and the sediment transport is dominantly in the suspended mode, driven by the mean currents. From measurements it could be concluded that both currents and waves rework the seabed to a depth of 0.1-0.2m in the bed. The sediment on top of the sand ridges is coarser and better sorted due to wave action (winnowing of fines) (Kleinhans, 2002). Van Rijn (1995 and 1997 in: Van Rijn & Walstra, 2002) presented estimates and variation ranges of the net annual longshore transport rates at the –20 m depth contour at several stations along the Holland coast, based on state of the art mathematical computations with the UNIBEST-TC model. UNIBEST-TC is designed to compute sediment transports and the resulting profile changes along any coastal profile of arbitrary shape under the combined action of waves, longshore tidal currents and wind. The longshore sediment transport (total load) at Noordwijk (about 45 km north of Hoek van Holland) is 35±10 m^3/m/year, the longshore transport at Scheveningen (about 20 km north of Hoek van Holland) is equal to 25±10 m^3/m/year both in northeast direction. The computed transport rates are compared with transport rates derived from available data of the middle and lower shoreface. Net annual longshore transport rates derived from sand dump sites near Hoek van Holland and about 70 km northwards, near Wijk aan Zee are in the range of 30 to 100 m^3/m/year for depths between 10 and 20 m. So, the results obtained from the model computations are in the same order of magnitude (Van Rijn & Walstra, 2002; Website WL Delft Hydraulics, 2003).

Conclusions

From the studies on the BCS and NCS, it follows that the average longshore total transport rate is in the order of 10-100 m^3/m/year at a depth of 10-20 m. We assume that the transport in the area of the Zeeland ridges is in the same order of magnitude. However, the transport on the top of a ridge (e.g. Middelkerke bank) can be much higher, in the order of 200 m^3/m/year. This is probably also the case on the top of the Zeeland ridges. These transport rates will change after a large-scale extraction on a ridge has taken place. It is difficult to determine the exact transport rates after a large-scale extraction on a ridge, because there is very little experience on such interventions. However, an extraction pit on a ridge will decrease the flow velocity over the ridge and thereby the sediment transport. The recovery period of a dredged ridge could be of the same order of magnitude as the formation of ridges (decades to centuries), depending on the volume and geometry of the pit,.

3.6 User functions in the area of the Zeeland ridges

In the area of the Zeeland ridges different user functions are observed (Appendix E, Figure E.2). A pipeline crosses the southern part of the area. Furthermore, there are a couple of cables (in use and not in use) running through the middle of the area. There are also some parts of the ridges on which extractions have taken place. Finally, shipping routes and an anchor area lie around and on the Zeeland ridges. In Appendix E, two maps with the user functions on the NCS and the in the area of the Zeeland ridges are given. For a detailed description of the user functions and 'values' in the area of the Zeeland ridges, we refer to Terpstra (2004).

3.7 Classification of the Zeeland ridges

In this section, we aim to classify the Zeeland ridges. First, we compare the Zeeland ridges with the ridges on the BCS. Next we give an overview of the statistics (height, length, orientation, etc.) on the Zeeland ridges and the environment. Finally, we draw conclusions on the classification of the Zeeland ridges.

3.7.1 Comparison with Belgian ridges

The BCS is characterised by a couple of sand ridge systems. In this section, we compare the Zeeland ridges (A) on the NCS to the Hinder Banks (B) and Flemish Banks (C) (Figure 3.9).

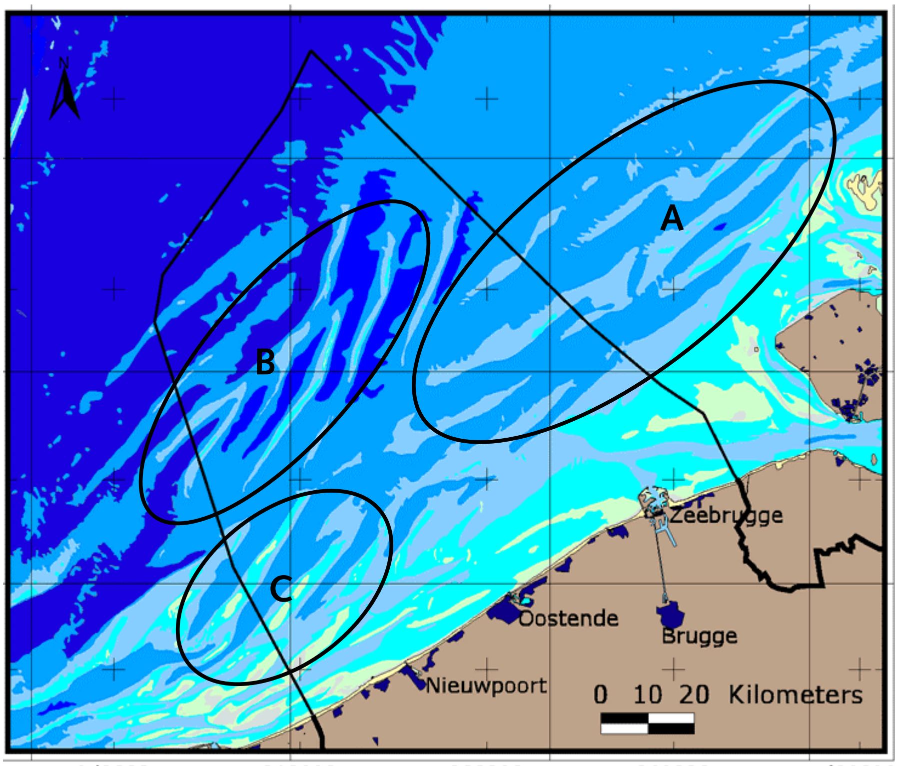


Figure 3.9: Sand ridge systems on the BCS and NCS (Website MUMM, 2003)
A = Zeeland ridges; B = Hinder Banks; C = Flemish Banks

Hinder Banks

About 50 km west of Walcheren a group of sand ridges occurs; the Hinder Banks. These ridges are separated from the Flemish Banks by a narrow zone of deeper water. To the east they truncate the Zeeland ridges. To the north and west they are bordered by a flat or almost flat sea bottom. The ridges of the Hinder Group are elongated, isolated ridges between 17 km and 34 km long, which rise up to 30 m above the surrounding sea floor. Furthermore, the Hinder Banks are oriented anti-clockwise with respect to the tide (Houbolt, 1968). Dyer and Huntley (1999) classified these ridges as open shelf ridges.

Flemish Banks

Offshore of Flanders a complex series of ridges occurs, commonly known as the Flemish Banks. They consist of elongated ridges of 30-50 km length and up to 30 m height. The Flemish Banks show a strong degree of parallelism but they are connected in a complicated pattern, especially in the north. Van Veen (1936, in: Houbolt, 1968) attributes this complex morphology to a system of ebb and flood channels. Furthermore, the Flemish Banks are also oriented slightly anti-clockwise with respect to the tide. Dyer and Huntley (1999) classified these ridges also as open shelf ridges. In Table 3.1, a few parameters of the three sand ridge systems, Zeeland ridges, Hinder Banks and Flemish Banks are summarised.

Parameter	Zeeland ridges	Hinder Banks	Flemish Banks
Height ridges	5-15 m	30 m	30 m
Length ridges	9-39 km	17-34 km	30-50 km
Orientation ridges with respect to tide	clockwise	anti-clockwise	anti-clockwise

Table 3.1: Characteristics Zeeland ridges, Hinder Banks and Flemish Banks

From Table 3.1, we can see that the length of the Hinder Banks and Flemish Banks is of the same order of magnitude as that of the Zeeland ridges. Their height is however two times (or more) the height of the Zeeland ridges. Furthermore, the two systems on the BCS are oriented anti-clockwise with respect to the tide, whereas the Zeeland ridges are oriented clockwise with respect to the tide. Finally, Houbolt (1968) concluded that the Hinder Banks and the Flemish Banks were formed by sand accumulation, whereas he concluded that the Zeeland ridges were formed by erosion of older deposits. However, the origin of the Zeeland ridges is not clear (Section 3.3) (Houbolt, 1968).

3.7.2 Characteristics of the Zeeland ridges

In Table 3.2, an overview on the characteristics of the Zeeland ridges and the environment of the ridges is given.

Parameter	Description	Magnitude
Height ridges	trough – crest	5 – 15 m
Length ridges		9 – 39 km
Width ridges	half of distance trough to trough	2 – 3 km
Transverse spacing	between crests	3 – 7 km
Orientation ridges with respect to tide	clockwise	0 – 20 degrees
Bed forms	sand waves	2 – 8 m (height)
Bottom slope		< 1:1000
Tidal range: typical spring (at Vlissingen) neap (at Vlissingen)	 from north to south -2.0 to 2.5 m + NAP -1.0 to 1.5 m + NAP	 2.5 – 3.5 m 4.5 m 2.5 m
Tidal current : average maximum	 at spring tide at neap tide	 0.75 m/s 1.0 m/s 0.6 m/s
Grain size sediments: - top of ridges - troughs	 moderate coarse sand very coarse sand gravel silt	 210 – 300 μm 300 – 420 μm 2 – 63 mm < 63 μm
Migration	ridges	Not observed
Sediment transport: - average total load - on top of ridges	 BCS and NCS Middelkerke bank	 10 – 100 m^3/m/year 200 m^3/m/year

Table 3.2: Characteristics Zeeland ridges and environment

3.7.3 Conclusions

At first sight, the Zeeland ridges seem to be tidal sand ridges. According to their length and their height this would be the right conclusion. Comparing the Zeeland ridges to the Hinder Banks and Flemish Banks shows that they have about the same length, only they are not as high as the latter two groups of ridges. Furthermore, the orientation of the Zeeland ridges is not the same as that of the Hinder Banks and Flemish Banks, these are oriented anti-clockwise with respect to the tide like most tidal sand ridges. The Zeeland ridges are however oriented like shoreface-connected ridges, clockwise with respect to the tide. Except for the fact that the ridges are not connected to the shore. An explanation for the mirrored orientation can be found in the origin of the banks. According to the most recent research (Laban & Schüttenhelm, 1981) they were formed partly by erosion of older (dune) forms and partly by sand accumulation. So, this could be the explanation for the orientation of the ridges. However, no clear conclusion can be drawn on the classification of the Zeeland ridges.

4 Information need

In this chapter, the information need of the different stakeholders, regarding sand extraction on the Zeeland ridges, will be specified (Section 4.1), which results in research questions and Coastal State Indicators (Section 4.2).

4.1 Information need stakeholders

4.1.1 Information need RWS (DNZ)

The information cycle, as described in Section 1.5, starts with a management question. From a Coastal Zone Management (CZM) perspective, like the perspective of DNZ, the context of sand extraction is determined by: the physical context (i.e. the physical- and ecological environment); the socio-economic context (i.e. socio-economic functional uses of the coastal zone) and the administrative context (i.e. the institutional arrangements, regulations, legislations and directives). Rational CZM will be based on an integrated analysis of this context (Website Sandpit, 2003). Thus, related to sand extraction the overall management question of DNZ is:

What are the long-term effects of large-scale sand extraction on the Zeeland ridges?

A rational coastal manager will aim for a rational decision-making process that is transparent and reproducible. The (vague) strategic CZM objectives must be translated into (specific) operational objectives. An important aid in this process is the definition of a set of Coastal State Indicators (CSI's) (Soulsby, 2003). A CSI is defined as:

A quantitative concept of the actual state of the system as a basis for objective and transparent decision-making; or a well defined physical and/or ecological variable quantifying a socio-economic functional use of the coastal zone.

Each indicator is related to a specific coastal user function. Examples of coastal user functions are: coastal safety and maintenance, offshore infrastructure, navigation, recreation, ecosystem and fishery. For convenience, we have decided to restrict ourselves in this research to the first three coastal user functions and to the physical effects of sand extraction on them. Using this indicator-concept, the overall management question can be (re)phrased as:

What are the probable long-term physical effects, caused by large-scale sand extraction on the Zeeland ridges, which affect the coastal user functions: coastal safety and maintenance, offshore infrastructure and navigation?

4.1.2 Information need RIKZ

RIKZ is engaged with all the salty and brackish waters in the Netherlands, and the coast. RIKZ is one of the six specialist departments of RWS. It gathers and provides knowledge and advice to support solving all kinds of sea related problems. In this research, RIKZ has two interests. Firstly, they want to gain (general) knowledge on how to deal with human interventions in the North Sea. Secondly, they need (specific) knowledge on the case of sand extraction on the Zeeland ridges and which instruments can be used to predict the physical effects, to advice RWS (DNZ).

4.1.3 Information need other stakeholders

Sandpit cycle

The Sandpit cycle (Figure 4.1, left) was developed for the European project Sandpit (see Website Sandpit) and presented at the RIKZ workshop (Hommes, 2004). The cycle starts with a request for sand extraction (mining). The first step in the cycle is to identify the problem, by determining stakeholders and investigating their concerns. Stakeholders define the spatial scale, which is the distance between the sand extraction and their concern. And the spatial scale determines the timescale of their concern. This is presented in the Scale graph (Figure 4.1, right). For example: a citizen is concerned that the beach will erode, the spatial scale of this topic is the coastline. Changes in the position of the coastline occur on the scale of years or decades, this is the timescale. The second step in the Sandpit cycle is to develop an assessment strategy with CSI's and assessment criteria, which express the concerns of the stakeholders. The next step is to make predictions on the effects of sand extraction, using measurements and models. The last step of the cycle is to assess the predictions on the CSI's and formulate a judgement, the decision on the request for sand extraction.

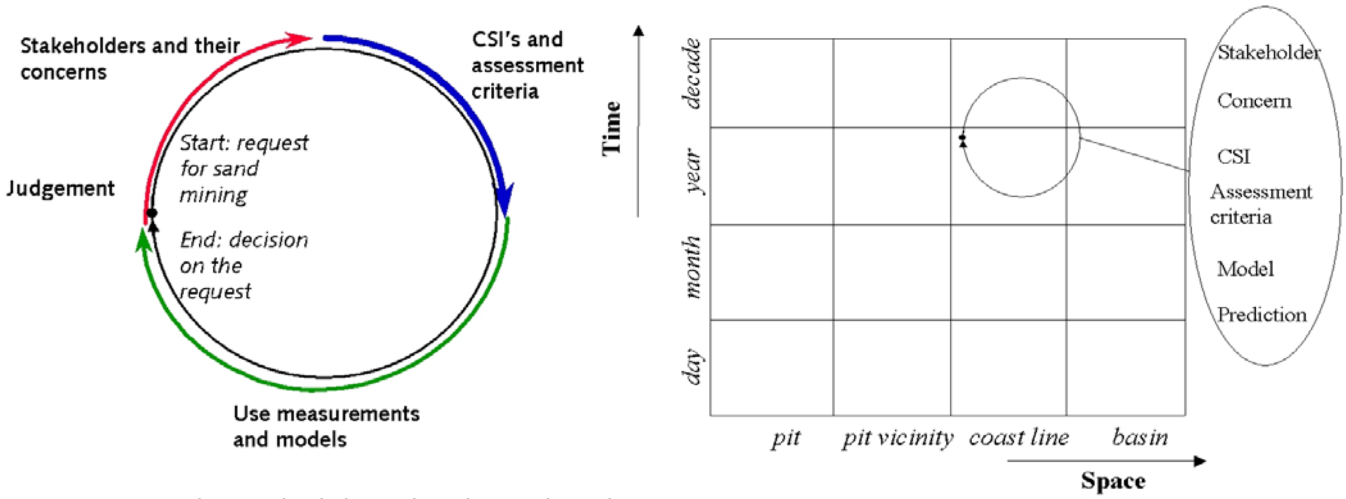


Figure 4.1: Sandpit cycle (left) and Scale graph (right) (Hommes, 2004)

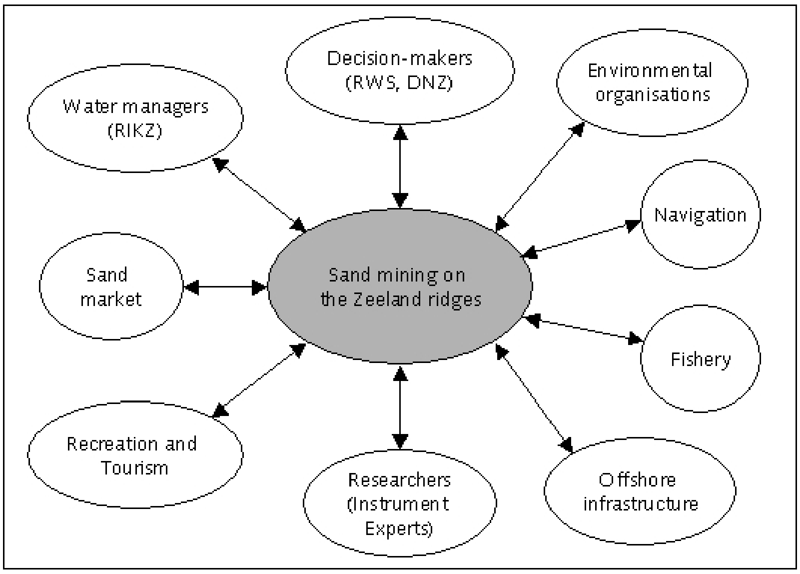


Figure 4.2: Environmental information model

Environmental information model

From the Sandpit cycle it follows that it is important to determine the information need of all stakeholders, to prevent conflicts., The environmental information model, which shows all the stakeholders involved in the problem, is given in Figure 4.2. We already determined the information need of the decision-maker (RWS, DNZ) and the water managers (RIKZ) in the previous sections. For the other stakeholders this is done briefly in this section. Furthermore, some points of concern are given; these are derived from workshops held by RWS in the framework of large-scale deep sand extraction (Van Woerden, 2002).

Environmental organizations

An example of an environmental organisation is 'Stichting De Noordzee' (SDN). SDN is non-governmental organisation that stands up for the North Sea and the ecosystem in particular. They aim at better regulations for the North Sea, expose misuse on the North Sea and communicate with governmental and non-governmental organisations about a clean and sustainable use of the North Sea. The public opinion is playing a key-role in these issues. The main points of concern for environmental organisations regarding the long-term effects of large-scale sand extraction are the following: insufficient recovery of sea bottom fauna (e.g. by oxygen deficit), extreme changes in algal communities (poisonous algae, etc.) and harmful effects on Bird- and Habitat areas (Van Woerden, 2002; Website SDN, 2003). In this research, we do not take the user function ecosystem into account. Therefore, these points of concern are not included.

Navigation

The Netherlands has one of the largest harbours of the world, Mainport Rotterdam. This generates a lot of traffic on the North Sea, which is regulated by deep-water routes and shipping channels. These routes and channels prevent conflicts between navigation and other user functions (Website Noordzee Atlas, 2003). The aim of the Dutch policy on sea navigation is to enlarge the sustainable additional value by the establishment of maritime activities in the Netherlands. Furthermore, the environment and safety are important issues of the Dutch policy on sea navigation. Finally, the use of the space on sea is an important issue. The points of concern for navigation regarding the effects of large-scale sand extraction focus on the issues: accessibility of harbours (sand accumulation in harbours by silt plumes) and safety (changes in water depths and currents) (Van Woerden, 2002; Website Noordzeeloket, 2003). The first issue focuses on the short-term and is therefore not included in this research. The point of concern safety is taken into account in the formulation of the CSI's (Section 4.2).

Fishery

The fishery sector in the Netherlands has the highest productivity per vessel in the European Union and has a very strong export position. The fishery on the North Sea is regulated by European regulation ('Gemeenschappelijk Visserijbeleid') and in the Dutch regulation ('Structuurnota zee- en kustvisserij'). The policy on fishery on the North Sea aims to find a good balance between fishery and nature. The government and business community collectively strive for responsible fishery based on sustainable management of fish stocks. The Total Allowable Catches (TAC's) are yearly settled on European level. The Dutch Fishing Association promotes the interests of the professional fisherman in the offshore and coastal fishing industry. The points of concern for fishery, regarding the effects of sand extraction, are: the possibility of fishing and the availability of fish (Van Woerden, 2002; Website Directie Noordzee, 2003; Website Nederlandse vissersbond, 2003; Website Noordzeeloket, 2003). In this research, we do not take the user function fishery into account. Therefore, these points of concern are not included.

Offshore infrastructure

The stakeholder offshore infrastructure includes the organisations that are responsible for cables, pipelines and offshore constructions, like oil platforms and windmill parks. In the framework of large-scale sand extraction these stakeholders are mainly concerned with the maintenance of their offshore infrastructure. This point of concern is accounted for in the Dutch policy and legislation and also taken into account in the formulation of the CSI's in the next section.

Recreation and tourism

A lot of recreation takes place in and around the North Sea. Citizens and tourists are sailing, fishing, surfing and swimming. During the swimming season the water quality is measured at several places. The main issue is the bacteriological quality of the water. The points of concern for recreation and tourism, regarding the effects of large-scale sand extraction, are: beach erosion and changes in current regimes at the coast (Van Woerden, 2002; Website Noordzeeloket, 2003). In this research, we do not take the user function recreation and tourism into account. Therefore, these points of concern are not included.

Researchers

Researchers want to know what output parameters their model should have to be of practical use in the decision-making process. Therefore, their information need/concern is of a different level than that of other stakeholders. We take the possibilities of the selected models (thus researchers) into account as input, from another point of view than the decision-makers, for the formulation of the CSI's (Section 4.2).

Sand market

According to Peters (2000), it is expected that in the future the overall need for sand will increase. The demand for sand used for activities on land will increase, especially the demand for filling sand. Furthermore, the possibilities to supply sand by extraction from land decreases because regions in the Netherlands are less willing to allow sand extraction. To supply the amount of sand needed, other sources have to be used. This can be sand extracted from sea, but also sand extracted from other surface waters. However, the latter source is limited and therefore it is no structural solution to the problem. As a consequence, the pressure to extract sand offshore increases. Furthermore, we should take into account the large amounts of sand needed for large infrastructure projects, which will be extracted offshore. The pressure to extract concrete and construction industry sand offshore also increases, because the sources on land are limited. Offshore extraction of concrete and construction industry sand is far more difficult than that of filling sand. Concrete and construction industry sand needs to have a certain quality. This kind of sand is only available in large enough quantities in the deeper layers of the seabed, and therefore a deep large sand extraction is required. Terpstra (2004) studied the area of the Zeeland ridges for interesting concrete and construction industry sand extraction locations and classified these locations. However, if entire layers will be dredged, a lot of filling sand can be extracted which can be used for filling sand. Therefore this alternative can be a solution for both deficits (Peters, 2000). The main concern of the sand market is to get enough sand of the desired quality to supply different industries. The sand market is not really concerned with the effects of large-scale sand extraction as long as they can extract enough sand and get their licenses. They are however interested in the answer to the question if it will be permitted to carry out (large-scale) sand extraction on the Zeeland ridges. The last is the motive and topic of this research.

4.2 Research questions and Coastal State Indicators

For each of the three selected coastal user functions we formulate research questions, CSI's and if possible assessment criteria in the following sections. The input, which determines the research questions, is the information need of the stakeholders, discussed in the previous section. Another input are the possibilities of different instruments described in Chapter 5 and 6. In this research, we use both ways to determine research questions and CSI's. Some of the CSI's are derived from the Sandpit project (Website Sandpit, 2003). Furthermore, we use the CSI's to qualify the different instruments on their practical relevance, in the RIKZ workshop (Hommes, 2004) and further on in the inventory of instruments (Chapter 7). Note that we do not aim at a complete overview of all possible physical effects caused by sand extraction. Our goal is however, to give insight into some physical effects and which (of the selected) models can be used to predict them.

4.2.1 *Coastal safety and maintenance*

The coastal user function ‘Coastal safety and maintenance’ focuses on the nearshore area. By the nearshore area, we mean the Voordelta and the coastline. The Voordelta consists of: Hinder, Ooster, Banjaard, Hompels, Kaloo and Raan (see geomorphological map, Appendix A). The research questions, corresponding CSI’s and assessment criteria, are given in Table 4.1.

	Research question	CSI	Assessment criteria	
INFORMATION NEED STAKEHOLDERS	1. Will a large-scale extraction pit act as a sediment sink? 1.1. What impact will it have on nearshore sediment transport regimes? 1.2. Will it lead to an increase in coastal erosion?	- Coastline position (MCL) as a function of time - Sand budget in the nearshore zone as a function of time	- Maintain MCL - Maintain sand budget	INSTRUMENTS
	2. Will large-scale sand extraction in the area of the Zeeland ridges affect the tidal flow and wave regime? 2.1. What is the effect of large-scale sand extraction on the nearshore tidal currents? 2.2. What is the effect of large-scale sand extraction on the waves in the nearshore area?	- Erosion profile as a function of time - Coastline position (MCL) as a function of time	- Minimum erosion profile - Maintain MCL	

Table 4.1: Coastal safety and maintenance parameters

The ‘Momentaneous Coast Line’ (MCL) is the CSI for ‘Coastline Position’. The MCL is defined as the coastline position with respect to a fixed reference point. It follows from the sand volume underneath a settled beach profile. The MCL should be maintained. Figure 4.3 shows the trends (seaward=green or landward=red) in the coastline of Schouwen and the nourishment locations in 2003 (yellow circles). The CSI ‘Sand budget in the nearshore zone’ is defined as the sand budget per coastal cell from –20 m NAP till the dune foot. This budget should also be maintained. Finally, the CSI ‘Erosion profile’ (‘afslag lijn’) is defined as the line that indicates which part of the dune erodes due to a certain storm (TAW, 2002). The minimum erosion profile for the research area cannot be quantified at this point.

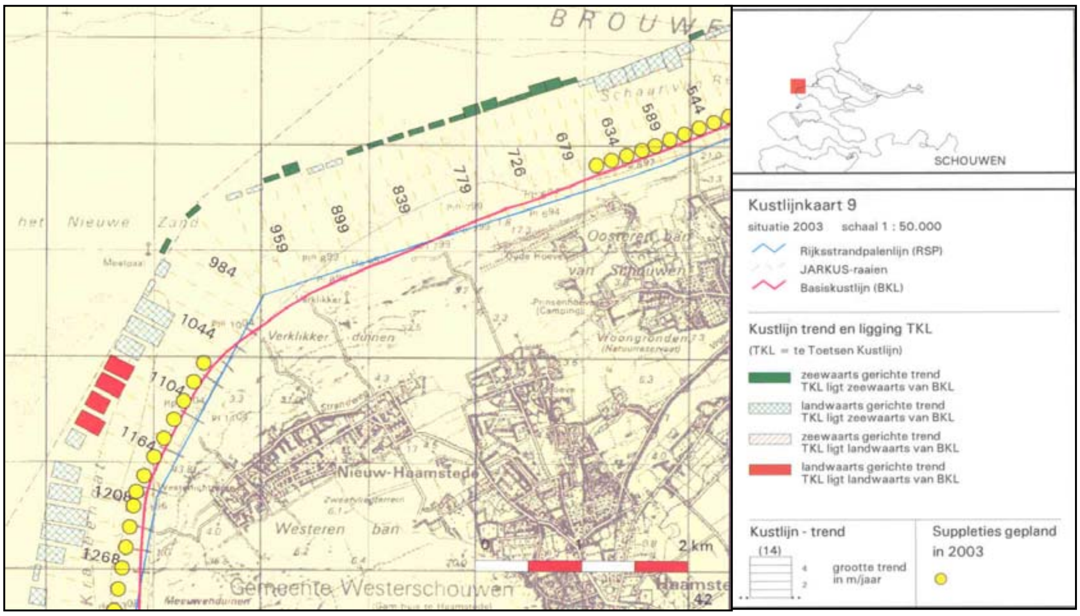


Figure 4.3: Coastline map of Schouwen (RIKZ, 2003)

4.2.2 Offshore infrastructure

The coastal user function ‘Offshore infrastructure’ takes cables, pipelines and offshore constructions, like oil platforms and windmill parks into account. This coastal user function focuses on the offshore area, the area of the Zeeland ridges. In Table 4.2, research questions, corresponding CSI’s and assessment criteria for this function are given.

	Research question	CSI	Assessment criteria	
INFORMATION NEED STAKEHOLDERS	3. Will the extraction pit act as a sediment sink and thereby have a particularly marked impact on the seabed in the area of the pit? 3.1. What is the sand transport regime in relation to the current outside the dredged pit (sand ridge)? 3.2. What is the deformation of the pit (changes in pit shape, formation of bed patterns, etc.) per year and over 50-100 years? What is the influence area? 3.3. What is the migration rate of the pit per year?	- Coverage of cables and pipelines as a function of time - Distance from pit to cables, pipelines and offshore constructions as a function of time	- Minimum coverage of cables = 1 m - Minimum coverage of pipelines = 0.2 m or 40% excavation - Minimum distance to offshore infrastructure = 500 m (with pit depth of 2 m)	INSTRUMENTS

Table 4.2: Offshore infrastructure parameters

In general, cables should be covered with 1 m of sand. The minimum coverage of pipelines with a diameter smaller than 0.4 m is equal to 0.2 m. If the diameter is larger than 0.4 m the pipeline must lie stable and should be excavated for 40% of the diameter (Figure 4.4). The minimum distance from a extraction pit to offshore infrastructure is 500 m, with a pit depth of 2 m. If the pit is deeper it could be necessary to increase this distance. This should be taken investigated in the EIA that is obligatory for large-scale extraction pits deeper than 2 m. Note that all assessment criteria for the offshore infrastructure CSI’s apply to the period over which the offshore infrastructure is in use, the life span of a construction.

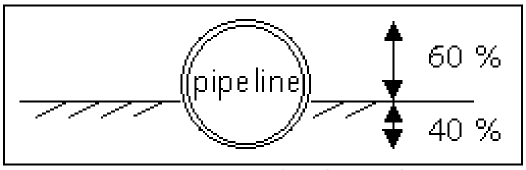


Figure 4.4: Excavation depth pipelines diameter > 0.4 m

4.2.3 Navigation

The coastal user function 'Navigation' focuses on the local navigation in the area of the Zeeland ridges and the navigation through adjacent shipping channels, like the Euro-Maas channel. In Table 4.3, the research questions, CSI's and (if possible) assessment criteria for this function are given.

	Research question	CSI	Assessment criteria	
INFORMATION NEED STAKEHOLDERS	4. Will the Zeeland ridges recover after they have been mined away? If yes: 4.1. Within what period will they recover? 4.2. Will the recovery affect other nearby sand ridges?	- Position ridge(s) as a function of time - Height ridge(s) as a function of time	- Not determined	INSTRUMENTS
	5. Will an offshore extraction pit (mined sand ridge) modify the local flow and wave fields in the area? 5.1. What is the change in maximum tidal current velocity due to the presence of a dredged sand ridge? 5.2. What is the change in wave height during a storm due to the presence of a dredged sand ridge?	- Tidal current along nearby shipping channel(s) and at anchor areas as a function of time - Wave height along nearby shipping channel(s) and at anchor areas as a function of time	- Minimum change in current velocity - Minimum change in wave height	
	6. Will the extraction pit act as a sediment sink and thereby have a particularly marked impact on the seabed in the area to the pit? 6.1. What is the change in water depth in the area of the ridges due to the presence of a dredged sand ridge? 6.2. What is the deformation of the pit (changes in pit shape, formation of bed patterns, etc.) per year and over 50-100 years? What is the influence area? 6.3. What is the migration rate of the pit per year?	- Water depth in the area of the ridges as a function of time - Depth and width of nearby shipping channel(s) as a function of time - Distance from pit to nearby shipping channel(s) and anchor areas as a function of time	- Minimum change in water depth - Minimum change in depth shipping channel - Minimum change in width shipping channel	

Table 4.3: Navigation parameters

For the recovery of ridges no assessment criteria could be determined yet. Furthermore, for the hydrodynamic and morphodynamic influence of an extraction pit (Research question 5 and 6) we cannot quantify the assessment criteria. However, it is important that the shipping channels and anchor areas stay usable after a large-scale sand extraction. Therefore, the assessment criteria are formulated as minimum change in the different CSI's.

4.2.4 Parameter values and accuracy

In the previous sections, we formulated CSI's for each of the three selected user functions. In this section, we describe which kind of values (average, worst case, etc.) decision-makers want to determine and with what accuracy.

Parameter values

CSI's that focus on morphological developments, like pit migration and recovery of sand ridges, should be determined as an average year value. This means that seasonal influences do not have to be determined. For CSI's that deal with safety parameters, like safety of constructions and safety for navigation, the worst-case scenario should be assessed.

Accuracy parameters

The temporal accuracy with which we want to determine the CSI's, is equal to a time series like for example: 1, 2, 5, 10, 50, 100 years after sand extraction. The spatial accuracy is already veiled in most CSI's, for example "Distance from pit to cables and pipelines as a function of time". For the other CSI's a grid of 500 m - 2 km will be used. Moreover, it is very important that each model output parameter is presented with a range of variation.

5 Analytical models

In this chapter, we give an overview of three analytical models (Twente model, Amplitude-evolution model, Utrecht model). First, a model description of each model is formulated, after this we describe the current situation on the modelling of sand extraction for each model. With the Twente model and the Amplitude-evolution model some runs are done, the results of these runs are also described in this chapter. Finally, we estimate the future possibilities of each model. The information on the models is gathered through interviews with model developers, literature study and organizing a workshop for model developers.

5.1 Twente model

5.1.1 Description Twente model

Flow, Sediment Transport, and Bed Evolution

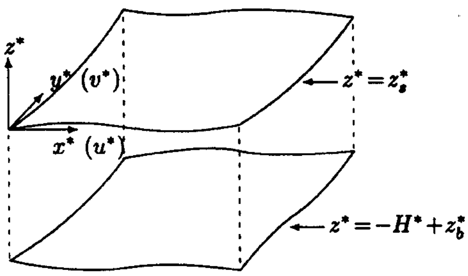


Figure 5.1: Definition sketch of the model geometry (Roos & Hulsher, 2003)

The Twente model described by Roos and Hulscher (2003) is an extension to the class of simple offshore models that describe large-scale bed evolution in shallow shelf seas. In Appendix F, the general concepts of morphodynamic modelling in a tidally dominated environment are given. A shallow sea of undisturbed depth H* is considered, in which a tidal wave of frequency σ* and maximum velocity U* is active. An orthogonal coordinate system is used, with horizontal coordinates **x*** = (x*, y*) and z*-axis pointing upward. The free surface is denoted by $z^* = z_s^*$ and the bed level by $z^* = -H^* + z_b^*$. The boundaries of the offshore system are taken infinitely far away. In Figure 5.1, the model geometry is shown.

Unsteady flow can be described by the depth-averaged shallow water equations, i.e., by two momentum equations and a mass balance. The seabed is assumed to consist of cohesionless sediment of uniform size, which is transported as bed load or as suspended load. The volumetric bed load sediment flux is described by a generalization of an empirical relationship, which includes a slope correction (see e.g. Van Rijn, 1993). Suspended load transport requires a different description. The depth-averaged volumetric concentration can be described by an advection equation (De Vriend, 1990 in: Roos & Hulscher, 2003). The diffusion of suspended sediment is neglected. The local rate of bed change is due to both the divergences in bed load transport and the difference between deposition and entrainment.

Scaling and Timescales

In Appendix G, all equations of the Twente model are given. In Equation G.1-G.6, the variables and morphodynamic model are given. The model contains two timescales, the fast hydrodynamic timescale (t) and the slow morphodynamic timescale (τ). We assume that the flow and sediment transport quantities evolve on both timescales, whereas the seabed evolves only on the slow timescale. Hence, the fast bed changes within the tidal cycle are neglected, which effectively decouples the hydrodynamics and sediment transport (Equation G.2-G.5) from the bed evolution (Equation G.6); this is a quasi-stationary approach (Roos & Hulscher, 2003).

Basic State and Linearization

The morphodynamic model consists of a set of non-linear equations, which cannot be solved in closed form. Hence, we resort to an approximation technique. Equation G.7, denotes the state of the system and equation G.8 is a solution of the set of equations. It describes a flat bed subject to a spatially uniform tidal flow and is called the basic state. We consider a tidal flow that is a generalization of the M_2-tide and add an M_0-component (a residual current) along with an M_4-component (periodic with double frequency $2\sigma^*$), thus allowing for tidal asymmetry (Equation G.9 and G.10) (Roos et al., 2001).

Linear Stability Analysis

The stability of the basic state is investigated by considering a small wavy perturbation of the flat seabed (Equation G.11). We expand the solution around the basic state (ϕ_0) according to Equation G.12. Furthermore, the bed evolution equation has the structure shown in Equation G.13, in which the growth rate is a complex number. The real part of the growth rate is related to the amplitude growth of the perturbation, while a nonzero imaginary part causes a nonzero celerity, thus migration of the wavy bed features (Equation G.14). In a linear stability analysis, the mode with the largest growth rate (ω_r) is usually considered to be the most interesting one. This mode is called the fastest growing mode (Roos et al., 2001).

5.1.2 Modelling sand extraction with Twente model

A sand pit can be seen as a superposition of wavy bed perturbations of small amplitude, which enter the problem as an initial bed profile at order γ (Equation G.15). The depth of the pit is given by the expansion parameter γ, so varying the depth merely affects the validity of the theory and does not provide qualitative physical insight. Equation G.16 describes a circular Gaussian pit shape. Here the diameter L is defined such that the volume of the pit is simply given by $V = \gamma L^2$. This means that a circular Gaussian pit with a volume of for example $10\text{x}10^6$ m^3 (large-scale sand extraction) and a depth of 2 m has a diameter L of 2.2 km. The problem will be solved in the Fourier spectrum. Each point in the Fourier spectrum grows or decays exponentially with an individual growth rate (Equation G.17). A straightforward numerical procedure is applied to transform the results in Fourier space back into physical space (Roos et al., 2001).

Limitations of the model

The most important limitation of the model is that it starts from a flat bed. Therefore, it is not possible to include ridges (e.g. Zeeland ridges) and extraction on ridges. Furthermore, the model predicts (exponential) growth of bed patterns, which does not turn to equilibrium. Finally, the model cannot predict the influence of the pit depth on the effects, because it uses a linear approach.

Uncertainty

The greatest uncertainty lies in predicting the magnitude of the bed load sediment transport rate. This has forced Roos et al. (2001) to consider a range of values of the bed load transport parameter (α_b). To get an idea of the morphodynamic timescale, within the range of α_b ($0.5\text{x}10^{-6}$–$0.5\text{x}10^{-5}$), $\tau = 1$ corresponds to a time of 45-450 years.

5.1.3 Modelling results with Twente model

During one week of the research period, some exploratory model runs were done with the model. This was carried out at the University of Twente. We calculated the bed evolution after extraction. In Section 5.1.4 other results like hydrodynamic effects are shown. In this section, the input parameters and different model scenarios (sensitivity analysis) are described and the results are shown and discussed.

Input parameters

In Appendix H, Table H.1 the input parameters and standard values of the Twente model are given. The diameter (L) is scaled with the morphological length scale $l_m \equiv U^*/\sigma^*$, which is the particle excursion of an M_2-tide with velocity amplitude U^*. The angular frequency (σ^*) of the M_2-tide in the Dutch North Sea is equal to 1.41×10^{-4} rad s^{-1}.

Description	Scenario
Influence of Coriolis force	1-2
Influence of M_4- tide	3
Influence of residual current (M_0)	4-5
Different shapes of the pit:	6 (L = 2xB) 7 (L = 4xB)
Pit (L=2xB) under different angles	8-12

Table 5.1: Scenarios Twente model

Sensitivity analysis

In order to determine the sensitivity of the model to changes in different parameters, we did model runs with several scenarios (Table 5.1 and Table H.2-H.3, Appendix H). All scenarios have a pit with a volume of 145×10^6 m^3, which is equal to the external need for Project Mainport Rotterdam. Furthermore, the pits all have a depth of 2 m.

Results

In Appendix H, the bed evolution and streamlines for each scenario are shown. Comparing Scenario 1 and 2 (without and with Coriolis force respectively) shows that including the Coriolis force has a considerable influence. When no Coriolis force is included a symmetrical bed pattern emerges around the pit. However, when the Coriolis force is present the patterns become asymmetrical and are more elongated. Around the pit three circulation cells form and four crests and two (circular) troughs emerge. The Coriolis force changes these four crests into two crests along the side of the pit and the pit itself elongates. Scenario 3 shows the influence of the M_4-tide. We used the tidal parameters of the M_4-tide at Vlissingen (from Rijkswaterstaat, 2003c). Comparing Scenario 3 with Scenario 2 shows that an asymmetrical tide (M_2 + M_4-tide) causes the pit (and patterns) to migrate. Furthermore, in Scenario 4 and 5 we added two different residual currents (u_{res}=0.1 m/s and u_{res}=0.05 m/s respectively). Adding a residual current has a large effect on the streamlines around the pit and also causes the pit (and patterns) to migrate; the larger the residual current, the more the pit migrates. Scenarios 6 and 7 are examples of oval shaped pits, placed along the direction of the tide. Comparing these oval pits to the circular one (Scenario 2) shows that the longer the pit the narrower the crests, which emerge around the pit. In Scenario 8-12, we investigated the influence of the pit angle. The scenario plots show that the bed patterns around the pit evolve more under certain angles than under others. When the pit is placed under an angle of 30 or 60 degrees clockwise with respect to the tide the largest troughs and crests evolve. When the pit is placed under an angle anti-clockwise (30 or 60 degrees) with respect to the tide, the patterns are smaller. Finally, when the pit is placed perpendicular to the tide the magnitude of the patterns is between the two former scenarios.

Conclusions

The main conclusion is that creating a large-scale offshore sand pit has a significant morphodynamic impact, both on the pit itself and on the surrounding area. The pit itself elongates and around the pit a pattern of sand ridges appears. Furthermore, an asymmetric tide causes the pit and the patterns to migrate. Finally, when a pit is placed under an angle anti-clockwise with respect to the tide, smaller crests and troughs evolve than with pits under clockwise angles.

5.1.4 Other results with Twente model

Some other preliminary results, gained from the linear model, were presented at the RIKZ workshop (Hommes, 2004). These results can be found in Appendix H.

Description results

In Figure H.1, the hydrodynamic effects of a rectangular pit of 3x2 km placed under an angle of 30 degrees with respect to the tide are shown. The two top plots show the response of the flow velocity. On one hand, the flow velocity decreases in a pit due to continuity. On the other hand, the flow velocity increases in a pit due to the decrease of bed friction. It depends on the pit geometry and the place in the pit, which mechanism is stronger. The plots in Figure H.1 show that in this case the flow in x-direction (u) decreases in the pit, while the flow in y-direction (v) slightly increases in the middle of the pit. The bottom left plot shows the change in water level, which increases in the pit and slightly decreases left and right from the pit. The bottom right plot gives the vorticity caused by the pit. Theory shows that vorticity in the system is created in two ways: friction-topography interaction in the case of a lateral slope (perpendicular to the flow) and Coriolis-topography interaction in the case of a longitudinal slope (in the direction of the flow). For a pit both mechanisms are simultaneously active, the plot in Figure H.1 shows that in the case of anti-clockwise slopes they strengthen each other. Figure H.2 shows the flow contraction of a pit as a function of the width and length of the pit. It is clear that an elongated pit is more flow contracting, than a wide pit. Finally, Figure H.3 shows the pit migration of a rectangular pit of 3x2 km placed under an angle of 30 degrees, subject to an M_2-tide and a residual current. The pit migrates around 2.5 km in about 35-350 years ($\tau = 0.75$), which is equal to 7-70 m per year.

Conclusions

We conclude that a large-scale pit has a significant effect on the hydrodynamics, like flow velocity, water level and vorticity. Furthermore, the pit shape influences the degree of flow contraction, an elongated pit is more flow contracting, than a wide pit. The migration numbers presented above strongly depend on morphological timescales, which are related to the magnitude of the sediment transport. As a result, the rates of migration and the patterns spreading are proportional to the parameter α, for which we merely have a range of estimates.

5.1.5 *Future possibilities with Twente model*

In the previous section, we concluded that the model predictions strongly depend on the magnitude of sediment transport. Therefore, further investigating the uncertainties in the parameterisation of sediment transport is a suggestion for future research. Finally, the presented theory is linear, and another suggestion is to include non-linear effects of pit evolution as well. At this moment the UT is developing a non-linear model (eQwin), which describes sand ridges in an equilibrium position and can be used to model sand extraction on ridges. In Appendix I, the concept of the eQwin model is described.

5.2 Amplitude-evolution model

5.2.1 *Description Amplitude-evolution model*

Knaapen and Hulscher (2002) developed a model to predict the regeneration of sand waves after dredging. Komarova and Newell (2000) performed a non-linear stability analysis for a 2DV tidal model. As a result, they found two coupled evolution equations of the Ginzburg-Landau type, which predicts sand waves superimposed on sand ridges. If the large spatial modulations are neglected, this model reduces to the Landau equation. Based on these findings, Knaapen and Hulscher (2002) assumed that the growth of sand waves is described by the real Landau equation (Equation J.1-J.3, Appendix J). The amplitude of the bed form and the maximum amplitude are described by Equation J.4 and J.5 (Appendix J), respectively. Note that the migration of the sand waves is not taken into account. This simplification, to treat amplification apart from migration, is justified by measurement data from the Bisanseto Sea (Japan) (Knaapen & Hulscher, 2002).

5.2.2 *Modelling sand extraction with Amplitude-evolution model*

The model was designed to predict the regeneration of sand waves after dredging, e.g. in navigation channels. In this research, we adjust and use it to predict the regeneration of sand ridges after dredging. To do so, we determine the linear growth velocity (α_0) and the long timescale (T), which defines the morphological timescale ($\hat{t}$). From these parameters the third model parameter (α_1), can be calculated (Equation J.5, Appendix J). The output of the model is the time it takes for a dredged ridge to regenerate to its former (equilibrium) height; the recovery period.

Limitations of the model

The most important limitation of the model is that its possibilities are very limited. The only output parameter of the model at this moment is the recovery period of dredged sand ridges. Other limitations are the following: in the model long spatial modulations are neglected, only bed load transport is included and the migration of sand ridges is not taken into account. Finally, the model can only be used for simulations of dredged crests/troughs and not for the extraction of a pit on a ridge (e.g. on the flank).

Uncertainty

The model is very sensitive to changes in the parameter α_0 (and thus $\hat{t}$). In the next section (sensitivity analysis), we show how the linear grow velocity (α_0) influences the model output. It can be stated that the accuracy of the model output highly depends on the model parameters α and τ. However, as Knaapen and Hulscher (2002) showed, when the model is tuned to measured data, the results are good. The model accurately reproduces the measured growth of the sand waves in the Bisaneto Channel (Japan). The results show that the difference between the model and the data is considerably smaller than the noise in the signal (standard deviation of the noise varies between 3% and 30% of the signal). The model was tuned based on constructed predredging data and the amplitude evolution was measured over two years. After tuning, the predictions were accurate for about 10 years (Knaapen & Hulscher, 2002). However, there is no experience with the model on dredging of ridges.

5.2.3 Modelling results Amplitude-evolution model

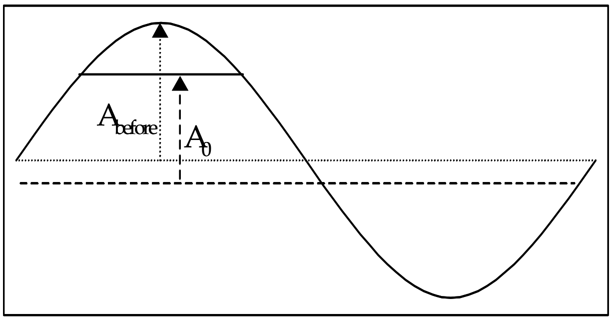


Figure 5.2: Definition amplitude

During one week of the research period, we adjusted the model and did some exploratory model runs with the Amplitude-evolution model. This was carried out at the University of Twente. In this section, the input parameters and different model scenarios (sensitivity analysis) are described and the results are discussed.

Input parameters

In Appendix K, Table K.1, the input parameters of the model are given. In Figure 5.2, we defined the amplitude before (A_{before}) and after dredging (A_0).

Sensitivity analysis

In order to determine the sensitivity of the model to changes in different parameters, we formulated and did model runs with several scenarios (Appendix K, Table K.2-K.3).

In/Output parameter	A_{before} (m)	A_0 (m)	α_0 (s^{-1})	α_1 ($s^{-1}m^{-2}$)	T (years)	Recovery period (years)
Scenario 1	7.5	6.5	0.37[a]	0.0066	70 [a]	$4x10^2$
Scenario 2	7.5	5	0.37[a]	0.0066	70 [a]	$5x10^2$
Scenario 3	7.5	3	0.37[a]	0.0066	70 [a]	$6x10^2$
Scenario 4	7.5	5	0.185	0.0033	70 [a]	$10x10^2$
Scenario 5	7.5	5	0.37[a]	0.0066	70 [a]	$5x10^2$
Scenario 6	7.5	5	0.74	0.0132	70 [a]	$3x10^2$

Table 5.2: Results Amplitude-evolution model
[a]after Hulscher (1996)

Results

In Table 5.2, the results of the model runs with the Amplitude-evolution model are summarised. In Figure K.1 and K.2 (Appendix K), the results are plotted. In the first three scenarios, we investigated the influence of the dredging depth on the recovery period. As expected, the recovery period increases with an increasing dredging depth. The recovery period of a ridge with a height of 15 m (A_{before} = 7.5 m), like the Zeeland ridges, is rather long in the order of hundreds of years. In order to determine the sensitivity of the model to changes in the parameters α (α_0 and α_1) and T, we formulate different scenarios. However, the parameters α_0 and T both determine the morphological timescale $\hat{t}$ (Equation J.2, Appendix J). Therefore, we only formulate scenarios with different values for α_0, Scenarios 4-6. As one can see, the model is very sensitive to changes in the linear grow velocity (α_0) and thus the morphological timescale ($\hat{t}$).

Conclusions

It can be concluded that the model output is very sensitive to the magnitude of the morphological timescale, which determines the sediment transport. Furthermore, the model is very simple, but therefore also transparent and it could be used as a quick management tool.

5.2.4 Future possibilities Amplitude-evolution model

Morelissen et al. (2003) presented a new method for identifying potential pipeline problems, such as hazourdous exposures due to the migration of sand waves. This method comprises a newly developed sand wave amplitude and migration model, which is also based on the (complex) Landau equation, and an existing pipeline-seabed interaction model (Morelissen et al., 2003). In the future, we can include such a method in the sand ridge Amplitude-evolution model described in this section. This way, we could predict the influence of sand extraction on pipelines and probably also on cables, offshore constructions, shipping channels and anchor areas. Furthermore, the model could be extended with the sediment flux. However, this parameter is proportional to the recovery period after dredging. Finally, other shape functions (e.g. asymmetric shapes) of the ridges could be included in the model.

5.3 Utrecht model

5.3.1 Description Utrecht model

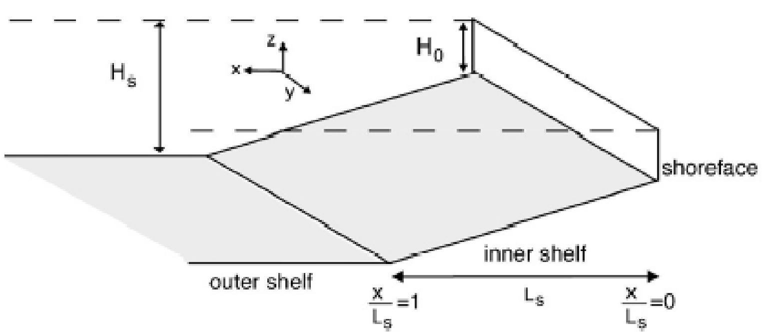


Figure 5.3: Shelf geometry (De Swart & Calvete, 2003)

Model formulation

An idealized morphodynamic model can be used to gain understanding about the formation and characteristics of shoreface-connected sand ridges and tidal sand ridges on the continental shelf. Following earlier studies, Walgreen et al. (2002) hypothesize that tidal sand ridges and shoreface-connected ridges form as inherent instabilities of a morphodynamic system. The shelf geometry is schematised as a semi-infinite domain, bounded on the landward side by the transition from the shoreface to the inner shelf (Figure 5.3). The reference bathymetry is uniform in the longshore direction (y). In the cross-shore direction (x) it consists of an inner shelf (linearly sloping bottom) and an outer shelf represented by a horizontal bottom. The water depth at the landward side of the inner shelf (x = 0) is H_0, L_s the inner shelf width and the depth of the outer shelf is indicated by H_s. Representative values for the central Dutch coast are H_0 = 15 m, H_s = 20 m and L_s = 12 km. In Appendix L, all equations of the model are given. The model uses the 2DH shallow water equations to describe the water motion (Equation L.1 and L.2). The evolution of the bottom is a result of convergences and divergences in the sediment flux (Equation L.3). A sediment transport formulation, based on expressions derived by Bailard (1981, in: Walgreen et al., 2002), is used in the model. Bailard (1981) applies the idea that part of work done by shear stresses acting on the sediment is used for transport, the rest is lost by frictional collisions. These considerations result in expressions for the bed load and suspended load sediment transport (Equation L.4 and L.5).

Basic state

The basic state is a morphodynamic equilibrium (i.e., a fixed bed level). It should be remarked that it is a consequence of the fact that in this model the transverse slope of the reference bathymetry does not cause a net seaward flux. It is assumed that this flux is compensated by the net landward fluxes, which are caused by physical processes not explicitly accounted for in the model (such as wave asymmetry). The basic state velocity consists of a steady component V_0 (residual current) and a tidal component, due to the M_2 and M_4 tidal wave (Equation L.6-L.12).

Linear stability analysis

The stability properties of the basic state can be considered by studying the dynamics of small perturbations evolving on this basic state. In case of a positive feedback between flow and bottom topography, rhythmic bottom features will develop. The linearised momentum and mass conservation equations can be solved at the tidal timescale to find the perturbed velocity field as a function of the bottom topography. The flow variables can be substituted in the bottom elevation equation and solved at the morphodynamic timescale, which is in the order of several hundreds of years. This problem is then governed by an eigenvalue problem. The stability analysis then yields the growth rate of the topographic features as a function of the longshore wavelength. The interest is in perturbations having positive growth rates. The perturbation corresponding to the wave number for which a maximum in the growth rate curve is found, is defined as the initially most preferred mode.

Conclusions

The model described in this section is able to explain the formation of both shoreface-connected ridges and tidal sand ridges due to inherent instabilities of the coupled water-bottom system. Shoreface-connected sand ridges appear to be formed mainly during storm conditions. Tidal currents turn out to be of minor importance in this case. Offshore tidal sand ridges on the other hand require strong tides and they form during fair weather conditions (Walgreen et al., 2002).

5.3.2 Modelling sand extraction with Utrecht model

A non-linear variation of the morphodynamic model, described in the previous section, can be used to study the response of shoreface-connected sand ridges and the net sand balance of the microtidal coastal shelf to large-scale interventions, like large-scale sand extraction. In an experiment, a total amount of 1.3×10^6 m^3 of sand was extracted from a ridge. The results of the experiment show that the response of the system is such that it returns to its original situation. These findings agree, at least qualitatively, with field observations (in: Knaapen & Hulscher 2002 and Pattiaratchi & Harris, 2002). Thus, the system does not tend to a new equilibrium, which could be present in such a highly non-linear system. An important implication of the response is that the inner shelf (where the ridge is located) must import sand. Results show that sand is transferred both from the nearshore zone and outer shelf to the inner shelf, although the largest contribution is from the outer shelf (De Swart & Calvete, 2003). In Appendix M, the results are shown.

Assumptions in the model

A few assumptions have been made in the model described before. The first assumption is that the sediment is uniform, although a newer version of the model (Walgreen, 2003) can now explicitly deal with grain sorting. Second, no tidal currents are included in the model, as Walgreen et al. (2002) demonstrated that tides have a negligible effect on the evolution of shoreface-connected ridges. The third assumption is that the coastline is straight; no tidal inlets are included. Finally, the sea level rise is not included in the model, the influence of this phenomenon seems however small.

Limitations of the model

The experiments with the model were performed for a transverse bottom slope β, which is only 15 % of its commonly measured value. This was done in order to avoid numerical problems in the model, if the bottom slope is taken too large solutions of the model become unbounded before the non-linear saturation regime is reached. The model thus has a limited validity in this regime. At the same time, model simulations support the conjecture that the response of the model will be similar in the case of a larger value of β being used. The second limitation of the model is that the number of eigenmodes is (too) limited, although this does not influence the accuracy of the output with small bottom slopes (e.g. β = 15 % of real value) for the purpose of predicting the recovery of ridges after a large-scale sand extraction (De Swart & Calvete, 2003).

Uncertainty

The model predictions (ridge height, wave length of ridges, grain sorting on ridges) correspond well to observations. However, the uncertainty of the model lies in the estimation of the sediment transport/flux. As described in the previous sections, this is also a problem of the Twente model and the Amplitude-evolution model. Moreover, data on sediment transport are very limited and not very reliable, which makes it difficult to validate the model(s) on this point.

5.3.3 Future possibilities with Utrecht model

In the model described in this section, the effect of bed forms on the wave stirring is not taken into account; this could be a valuable extension of the model. To account properly for these effects a sophisticated wave transformation model, based on e.g. the eikonal equation, would be required. Application of such a method to the nearshore region of a straight barred coast already showed successful results (Calvete et al., 2003 in: Walgreen, 2003). Walgreen (2003) also suggested that a more realistic representation of the bottom layer is needed to represent the grain size pattern correctly, e.g. by introducing an exchange layer to the one-layer model that is now included. However, the present knowledge on vertical sorting processes is very limited and a verification of the model results would be very difficult. Finally, the analysis of a 3D flow over an uneven bed, which is a complicated problem, is one of the most important topics for further research. Wind effects, like up welling, and other 3D aspects could then be taken into account (Walgreen, 2003).

6 Numerical models

In this chapter, we give an overview of four numerical models (Delft3D, SUTRENCH, Telemac, mu-SEDIM). First, a short description of each model is formulated, after this we describe the current situation on the modelling of sand extraction for each model. Finally, the future possibilities of each model are estimated. The information on the models is gathered through interviews with model developers, literature study and organizing a workshop for model developers.

6.1 Delft3D

6.1.1 Description Delft3D

Delft3D is an 2D/3D integrated numerical model for calculation of: hydrodynamics, waves, sediment transport, bottom morphology, water quality and ecology. Delft3D simulates the temporal and spacial variations of these six components and their interconnections. Delft3D consists of a number of modules, which are linked to and integrated with one-another. The hydrodynamic, wave and morphodynamic modules are described below.

Hydrodynamic module (Delft3D-FLOW)

This module basically simulates non-steady flows (2D or 3D) in relatively shallow water. It incorporates the effects of tides, winds, air pressure, density (due to salinity and temperature) differences, waves, turbulence and drying and flooding of tidal flats. The output of the module is used in all the other modules of Delft3D. Delft3D-FLOW can also be used independently, without other modules.

Wave module (Delft3D-WAVE)

This module computes the non-steady propagation of short-crested waves over an uneven bottom, considering wind action, energy dissipation due to bottom friction, wave breaking, refraction (due to bottom topography, water levels and flow fields), shoaling and directional spreading. The second generation, quasi-stationary HISWA (Hindcast Shallow WAter Waves) model is in the process of being replaced by the third generation, spectral model SWAN (Simulating Waves Nearshore). Both models are developed by Delft University of Technology.

Morphodynamic module (Delft3D-MOR)

Delft3D-MOR is a module for morphological computations. This module computes morphological bottom changes due to sediment transport gradients and time dependent boundary conditions. Both wind and waves act as driving forces and a number of transport formulae have been built in. An essential feature of this module is the dynamic feedback with the Delft3D-FLOW and WAVE modules, which allow the flows and waves to adjust to the local bathymetry (Website WL Delft Hydraulics, 2003).

6.1.2 Modelling sand extraction with Delft3D

Research Klein (1999)

Klein (1999) studied the behaviour of large-scale sandpits with Delft3D. This study was divided in two parts: the water movement in and around sandpits and the morphological behaviour of sandpits. The emphasis in the hydrodynamic part lies on the influence of the Coriolis force and on the orientation of the sandpit with respect to the main tidal current direction. For the hydrodynamic study the tidal boundary condition was schematised to one harmonic component. The results show the development of large tide-averaged circulation patterns. An important parameter for the flow in the sandpit is the length-width ratio of the sandpit. The influence of the Coriolis force on this tide-averaged current pattern is very limited.

For the morphological computations Klein (1999) used a depth-averaged model (2DH) and assumed a flat bottom. In the morphological part the tidal movement is schematised with the M_0, M_2 and M_4-components. Wind waves have been implemented in the model to stir up sediment from the sea bottom. The breaking of waves and refraction are not specified. The morphological computations were performed over a period of 1000 years. The software automatically determines the morphological timesteps, which are necessary to calculate significant bottom changes over the period. About 80 bottom calculations are necessary to cover 1000 years. The morphological calculations focus on: the development of pit shapes and the area around pits; the migration of pits and the comparison of the behaviour of pits to that of tidal sand banks. The results of the development of pit shapes and the area around pits are compared with the results of Walstra et al. (1999) who used the Euro Maas trench as a reference trench in their study (see also Section 6.2.2). Comparison of these results show that the qualtitative results are similar. However, one has to be careful with the quantitative results. The long simulation time and the influence of the boundary conditions lead to inaccuracies (Klein, 1999). We refer to Klein (1999) for figures of the hydrodynamic and morphological results.

PUTMOR project

Between October 1999 and March 2000 an extensive measuring campaign was held by RWS to collect data concerning water movement, water quality and morphology in and around a large sand pit at the North Sea some 10 km off the Dutch coast near Hoek van Holland (Appendix N, Figure N.1). The dimensions of the pit are 1300 m x 500 m x 10 m (relative to the seabed, at an approximate depth of 24 m water depth) yielding a total volume of around 6.5×10^6 m^3. The current velocities were measured continuously through the vertical with ADCP's at the centre of the pit (Location M) and 500 m south of the pit (Location A). Additionally, eight flow track measurements were carried out along four tracks (Appendix N, Figure N.2). The preparation and execution of the measuring campaign as well as the processing and analysing of the measurements are part of the PUTMOR project (Svasek, 2001; Walstra et al., 2003). The field data of the PUTMOR project were used to evaluate the performance of Delft3D-Online (upgraded Delft3D model). The model uses a 3D grid with a horizontal resolution varying from 40 m in the pit to 1500 m at the model boundaries and 10 equidistant layers in the vertical.

In Appendix O (Figure O.1-O.5), some modelling results, which were presented at the RIKZ workshop (Hommes, 2004), are shown. It can be concluded that the model is able to give a good representation of the measured velocities. The largest deviations are present near the water surface, but are in general less than 10% of the maximum velocities (Walstra et al., 2003).

Limitations of the model

The long computational time is one of the main limitations of the model, regarding the modelling of long-term (up to 100 years) physical effects of sand extraction. The temporal scale of Delft3D is equal to 10 years. Knowledge of applying the model on longer timescales is very limited. Delft3D includes a module (Delft3D-RAM) that can be used to upscale morphological predictions to longer timescales. However, this negatively influences the accuracy of the predictions.

Uncertainty

There is no experience on the modelling of sand ridges with Delft3D. Furthermore, the spatial scale on which Delft3D can be applied is equal to 50-100 km. This influences the capability to predict the bathymetry of bed forms, which occur on a smaller spatial scale (e.g. sand ridges, sand waves) and thus the accuracy of predictions of modelling sand extraction on ridges. Another uncertainty of the model lies in the prediction of the sediment transport. Experiments already showed that significant deviations with measured transports occur.

6.1.3 Future possibilities with Delft3D

A robust modelling approach for the case of the Zeeland ridges is not (yet) available. First, a schematisation of the boundary conditions must be formulated. Furthermore, the upscaling of the morphological predictions and the respresentation of sand ridges with the model should be investigated. Finally, one must consider whether to do a large number of simulations with a simple model or a limited number of simulations with a complex model.

6.2 SUTRENCH

6.2.1 Description SUTRENCH

The SUTRENCH (SUspended sediment transport in TRENCHes) software package has been developed by WL | Delft Hydraulics. It is a two-dimensional vertical (2DV) mathematical model for the simulation of bed load and suspended load transport under conditions of combined quasi-steady currents and wind-induced waves and the related sedimentation and erosion of dredged channels and trenches perpendicular or at oblique angle to the flow. The most relevant processes which have been taken into account are the convection of the particles by the horizontal and vertical fluid velocities, the diffusion or mixing of the particles due to the current-related and wave-related mixing processes, the settling of the particles due to gravity and the pick-up of the particles from the bed by bottom shear stress induced by the flow.

The computation of the sediment concentrations and transport is based on the solution of the convection-diffusion equation. This basic equation of SUTRENCH can be solved numerically when the fluid velocities, the mixing coefficient distribution, the fall velocity of the sediment and the geometrical and physical boundary conditions of the considered situation are known. When the concentration field is known, the new bed levels are computed from the continuity equation for the total (cross-section integrated) sediment transport (Walstra et al., 1999; Website WL Delft Hydraulics, 2003).

Applicability

SUTRENCH is restricted to well mixed gradually varying flow conditions over a sediment bed consisting of fine particles with narrow size gradation. The model is applicable with or without waves. The tidal flow can be represented by schematising the tidal period to quasi-steady flow periods. All processes (parameters) in the direction normal to the computation direction are assumed to be constant. This can impose limitations to the applicability of SUTRENCH if 2DH or 3D effects play a dominant role. SUTRENCH can be applied at a spatial-scale of 1-10 km and at a timescale of 1-100 years. It is applicable in regions outside the surf zone where wave breaking is limited. SUTRENCH has been verified extensively using flume and field data for currents and waves (e.g. Van Rijn, 1986a and b; Walstra et al., 1999). To determine the most important controlling parameters of the program detailed sensitivity analyses have been carried out (Walstra et al., 1999; Website WL Delft Hydraulics, 2003).

6.2.2 Modelling sand extraction with SUTRENCH

Morphological modelling of shoreface-connected ridges

Van de Meene and Van Rijn (2000) studied the long-term morphological behaviour of the shoreface-connected ridges along the central Dutch coast with a simplified modelling approach, consisting of a 1D current model (Trenchflow), combined with SUTRENCH. The analysis focused on a cross-section of a single sand ridge. The morphological changes were calculated from the sediment budgets for each morphological unit (up-current flank, top and down-current flank) in which the sand ridge is divided. The modelling shows that the ridges are stable on a time scale of years to decades, while they may be considered active on the time scale of thousand of years. Calculated migration rates of the ridges are in the order of 1m/yr. Morphological timescale and migration rate correspond to the results from a geological reconstruction of Van de Meene (1994) (Van de Meene & Van Rijn, 2000).

Research Walstra et al. (1999)

Walstra et al. (1999) used SUTRENCH in their study. The central theme in this study was the knowledge and modelling of sand transport processes on the lower shoreface (seaward of –20 m depth contour) of the Dutch coast with the aim of predicting the morphological behaviour of large-scale sand extraction pits. The performance of SUTRENCH was first evaluated against laboratory data. It was found that the model showed good agreement with measurements. The results of these laboratory tests are shown in Appendix P (Figure P.1-P.4).

Next, a model was set up of the Euro-Maas channel to study the effects of various large-scale sand extraction pits. With this calibrated model the morphological development of various trench geometries was investigated over a period of 50 years. According to Walstra et al. (1999), the morphological timescale for the complete filling of a trench (10-14 m depth) is in the order of centuries. Furthermore, they concluded that if the stability (minimum migration rate) is considered as the main criterion, narrow relatively deep pits are preferred over wide relatively shallow pits. The definition of the morphological timescale in the order of centuries seems to give reliable results. However, these are first order estimates of the morphological timescale, for more reliable predictions simulations in the order of 500 years have to be made. This was outside the scope of this study (Walstra et al., 1999).

To further determine the validity of applying SUTRENCH to simulate the longshore morphology of relative large-scale pits, Walstra et al. (2002) made a comparison between SUTRENCH and the Delft3D used in the PUTMOR project (Section 6.1.2). To that end, the predicted morphological developments of the PUTMOR pit made by the two models, are compared after one year. The overall behaviour of both models is very similar; the main differences are caused by the fact that flow contraction was not accounted for in the SUTRENCH simulation. This causes that the backfilling rates are over-estimated in the SUTRENCH simulations and will probably result in an over-estimation of the migration rates of the pit and an under-prediction of the morphological timescale of pits where flow contraction plays an important role (Walstra et al., 2002). The results of the comparison between Delft3D and SUTRENCH are shown in Appendix P (Figure P.5).

Limitations of the model

SUTRENCH is developed for the simulation of sedimentation and erosion of dredged channels and trenches, but also used for morphological modelling of shoreface-connected ridges. However, there is no experience with the modelling of sand extraction on ridges. Furthermore, it is a 2DV model and thus it cannot be used to predict 2DH and 3D effects of a pit. Also the spatial scale on which SUTRENCH can be applied is limited from 1-5 km and the pit depth, which can be modelled, is very small ($\approx$ 0.2 m).

Uncertainty

As described before, the morphological timescale of the filling of a trench/pit is determined only by first order estimations. This creates high uncertainties in the predictions.

6.2.3 Future possibilities with SUTRENCH

At the RIKZ workshop (Hommes, 2004) it was concluded that SUTRENCH is probably unsuitable for the modelling of sand extraction on the Zeeland ridges. However, Van de Meene and Van Rijn (2000) showed that it is possible to model (shoreface-connected) ridges with SUTRENCH. This gives future opportunities to model sand extraction on ridge, but the problem of the small spatial scale on which SUTRENCH is applicable poses limitations on the predictions.

6.3 Telemac

The system Telemac is developed by the National Hydraulics and Environment Laboratory of France and is distributed by SOGREAH Consultants.

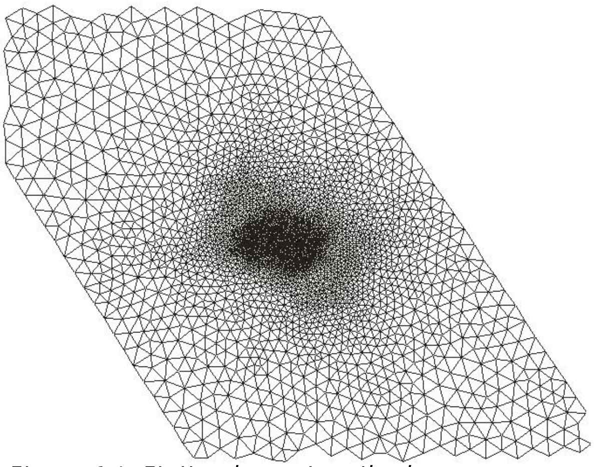


Figure 6.1: Finite-element method

6.3.1 Description Telemac

The Telemac system is an integrated modelling tool for use in the field of free-surface flows. The various simulation modules use algorithms based on the finite-element method (Figure 6.1). Space is discretised in the form of an unstructured grid of triangular elements, which means that it can be refined particularly in areas of special interest. This avoids the need for systematic use of embedded models, as is the case with the finite-difference method.

Hydrodynamics

Telemac consists of several hydrodynamic modules. TELEMAC-2D is used to simulate free-surface flows in two dimensions of horizontal space. At each point of the mesh, the program calculates the water depth and the two velocity components. TELEMAC-2D solves the Saint-Venant equations. TELEMAC-3D simulates the three dimensional flows, solving the Navier-Stokes equations. ARTEMIS is a module to simulate wave propagation towards the coast or into harbours. COWADIS is used to model wave propagation in coastal areas. The BOUSSINESQ module is a 2D module, used to simulate short waves solving the Boussinesq equations.

Transport/Dispersion

Telemac consists of three transport/dispersion modules. SUBIEF-2D is used for water quality modelling; it models the 2D suspended sediment transport. SISYPHE is a module for the modelling of 2D bed load transport. And SEDI-3D is used for 3D suspended sediment transport (Website Telemac, 2003).

6.3.2 Modelling sand extraction with Telemac

Modelling sandbank dynamics

Idier and Astruc (2003) introduced a two-dimensional morphodynamic model based on a bottom evolution equation using a generic formula for bed load sediment flux, coupled with depth-integrated shallow-water formulation, including a quadratic friction law, for the fluid flow. The numerical resolution of the bed evolution equation relies on the SISYPHE software. The hydrodynamic equations are solved using the TELEMAC-2D software. As the boundary conditions, a stationary fluid discharge is imposed upstream, a stationary free surface level downstream and a slip condition at the lateral boundaries. Idier and Astruc (2003) first showed that the numerical model is accurate enough to properly simulate the dynamics of the bottom free instability waves and at the same time to analyse the physical mechanisms of the instability. This is achieved for a steady current over a flat bottom.

Figure Q.1 (Appendix Q) shows that the results for the growth rate estimated with the numerical morphodynamic model are very similar to those obtained by the (analytical) stability analysis. However, the growth rate is underestimated by 18% in the numerical computations. This difference is almost exclusively due to the hydrodynamic computation whereas the bed evolution model and the coupling scheme appear to contribute only marginally to the error.

The second goal of this work is to gain insight into finite-amplitude dynamics of large bottom perturbations, and in particular into the saturation process, with the numerical model. The computation of the long-term evolution of small bottom perturbations would require years of computer time. Therefore, Idier and Astruc (2003) assume that only one unstable mode will survive at finite amplitude, so that the studied bed form will be sinusoidal. The growth rates are plotted in Figure Q.2 (Appendix Q) for different values of the bottom slope effect. The saturation amplitude is estimated to be 81% of the undisturbed water depth. Compared with English Channel and North Sea field data, the saturation time seems to be in good agreement whereas the saturation height is slightly overestimated (saturation amplitude from data of North Sea = 71-83%). The migration due to the steady component of the current has also been estimated and appears to be reasonable (Idier & Astruc, 2001; Idier & Astruc, 2003).

Modelling sand extraction

Idier and Astruc (2003) showed that morphodynamic numerical modelling with Telemac, despite the limitations due to the large computational resources needed, may provide insight into the dynamics of bed forms, like sand ridges and extraction pits. However, they did not (yet) model sand extraction (on ridges). In the framework of the EU project SANDPIT, SOGREAH (distributor of Telemac) is involved to do mathematical modelling work with Telemac on sand transport and morphology of sand extraction pits. This project is still ongoing and unfortunately no modelling results with Telemac are published yet (Website Sandpit, 2003).

Limitations of the model

As described before, the most important limitation of Telemac regarding the modelling of long-term morphological effects is the large computational time. Furthermore, a limitation of the model is that it does not (yet) contain a coupling between the changes in bathymetry (SISYPHE) and the hydrodynamics (TELEMAC2D) and waves (COWADIS).

Uncertainty

The greatest uncertainty of the model lies in the prediction of the sediment transport.

6.3.3 Future possibilities with Telemac

In the near future Telemac will be extended with the following aspects: extended granulometry in SISYPHE, internal coupling between SISYPHE, TELEMAC2D and TELEMAC3D and non-cohesive sediment in TELEMAC3D. Another possibility for the future is the internal coupling between SISYPHE and the wave module COWADIS.

6.4 mu-SEDIM

6.4.1 Description mu-SEDIM

The model described in this section, is developed at MUMM. MUMM is a department of the Royal Belgian Institute of Natural Sciences (RBINS), a federal scientific establishment that comes under the Federal Science Policy. In the framework of the BUDGET project Van den Eynde (2003) developed a 2D total load sediment transport model, mu-SEDIM. Mu-SEDIM is coupled with a hydrodynamical model and a wave model. These models are described below, after which we describe the mu-SEDIM model.

Hydrodynamic model: mu-BCZ

The hydrodynamic model mu-BCZ forecasts currents and sea surface elevation induced by the tide, the atmospheric pressure and the wind stress. Mu-BCZ is based on the COHERENS model, which is a multi-purpose 3D hydrodynamic model for coastal and shelf seas resolving meso scale to seasonal scale processes. The hydrodynamic part is coupled to biological, resuspension and contaminant models. The governing equations of the physical part express conservation of mass and momentum. These equations are numerically solved using finite differences and the mode-splitting technique on a staggered grid (Arakawa C-grid). Predictor and corrector steps are also applied to the horizontal momentum equation to insure that the depth-integrated currents obtained from the 2D and 3D mode are identical. The model is implemented on the same grid as the grid for the sediment transport and includes the Belgian nearshore zone and the Flemish Banks with a resolution of about 750 m x 750 m. At the boundaries, the model is coupled with a 2D model mu-STORM, which encloses the North Sea and the Channel. Furthermore, at the mouth of the Western Scheldt mu-BCZ is coupled with a 1D model of the estuary (Van den Eynde, 2003; Website MUMM, 2003).

Wave model: mu-WAVE

The wave climate on the BCS is calculated using the wave model mu-WAVE. The HYPAS model, a second-generation wave model, forms the basis of this model. HYPAS computes at each grid point and at each time step the whole wave spectrum taking into account the wave generation by atmospheric energy input, energy dissipation by bottom friction and wave breaking, wave propagation and non-linear interaction between various wave components. The HYPAS model has a spatial resolution of 50 km x 50 km. In order to account for the complex bathymetry in the southern North Sea, a high-resolution model (5 km x 5 km) is coupled to the coarse grid model through two open boundaries (Van de Eynde, 2003; Website MUMM, 2003).

Sediment transport model: mu-SEDIM

The mu-SEDIM model is based on a local total load formula in each grid point. The bottom stress in this formula is calculated under currents and waves and accounting for the roughness in the grid point, using a 2D hydrodynamic model (mu-BCZ) and a second-generation wave model (mu-WAVE). The total roughness is calculated from the median grain size, from the calculated ripple height and steepness and the calculated bottom load. A total load sediment transport formula (Ackers and White) is used to calculate the sediment transport vectors. Finally, using the sediment transport calculated in each grid point, the changes in the bed level can be estimated, which shows the erosion- and deposition zones (Lanckneus et al., 2001; Van den Eynde, 2003).

6.4.2 Modelling sand extraction with mu-SEDIM

The mu-SEDIM model has been used to model the sediment transport on the BCS. In Appendix R, the results of mu-SEDIM for the BCS and the Westhinderbank are shown. However, no modelling of sand extraction (on ridges) has been done with mu-SEDIM yet. At the RIKZ workshop (Hommes, 2004) it was stated that desspite the sensitivity of the different modules, mu-SEDIM could be used to give (qualitative) information on the sediment transport in a certain zone after extraction. Furthermore, from the first Belgian researches on the Kwintebank, from which a lot of sand has been extracted, it seems that the stability of a ridges could be disturbed by large-scale extraction.

Limitations of the model

The main limitation of mu-SEDIM regarding the modelling of long-term morphological effects is the large computational time. Furthermore, a limitation of the model is that it does not contain a coupling between the changes in bathymetry (mu-SEDIM) and the hydrodynamics (mu-BCZ) and waves (mu-WAVE).

Uncertainty

Like in all the models described before, the greatest uncertainty lies in the sediment transport parameter. This parameter determines the timescale on which the morphological changes of the seabed occur.

6.4.3 Future possibilities with mu-SEDIM

In the future the mu-SEDIM model will be implemented with a third generation wave model (WAM or SWAN). Furthermore, a coupling between the changes in bathymetry (mu-SEDIM) and the hydrodynamics (mu-BCZ) and waves (mu-WAVE) can be included in the model.

7 Results

In this chapter, we describe the results of this research. In Section 7.1, the results of the RIKZ workshop are summarised. In Section 7.2, the prediction force of the models, regarding the different CSI's of the three selected coastal user functions, is investigated in the inventory of instruments.

7.1 RIKZ Workshop

For the full report on the RIKZ workshop for model developers we refer to Hommes (2004). In Appendix S, some details of the RIKZ workshop (aim, participants, programme, guidelines presentations, discussion case and results) are included. In this section, we summarise the conclusions and recommendations, which followed from the workshop.

7.1.1 Conclusions workshop

The aim of the workshop was:

Get an objective judgement of the possibilities, limitations and accuracy of different instruments, now and in the future, regarding the modelling of sand extraction on the Zeeland ridges.

The first part '*current possibilities and limitations*' was achieved successfully; the results are processed in Chapter 5 and 6. The second part '*accuracy*' is very difficult at this point, because there are no data available to validate the instruments. Furthermore, there are very few calculation results on large-scale sand extraction pits, so it is quite hard to validate and evaluate them. Therefore, we have to think about other ways to inspire the decision-makers with confidence in the model predictions. From a decision-makers perspective, it is necessary to calculate the worst-case scenario besides average predictions and to determine the uncertainty interval of the predictions. To inspire the decision-makers with confidence in the model predictions, it is important to determine which processes most influence an extraction pit and to look at the spatial scales. We have to keep in mind that we are dealing with a non-linear system, which means that the system could turn to another equilibrium after a large intervention. Therefore, we cannot use a linear approach to make predictions. Finally, one does not know what far field effects a large-scale sand extraction will cause. This forms a great difficulty in the prediction of long-term morphological effects.

Furthermore, we investigated the '*future possibilities*'. Firstly, we concluded that it is very important to describe a realistic seabed, with patterns like sand ridges, with the models. The eQwin model (Section 5.1.5) can describe sand ridges in their equilibrium position. And it is also possible to describe sand ridges with process-based models, like Telemac (Section 6.3.2). A stable equilibrium state should be the starting point of each model, assuming that the present state of the sea bottom is in equilibrium. Secondly, we need to couple different models to predict the effects of large-scale sand extraction. The models can be coupled to describe the starting point and to find better estimations of model parameters, e.g. the growth rate in instability models. The question remains, how the coupling of models can be achieved in a feasible way. It would be a step forward to run a test case, then organize another discussion and try to couple different models.

7.1.2 Recommendations

In the previous section, we concluded that it would be a great step forward to run a test case on large-scale sand extraction on a ridge. The Kwintebank on the BCS can form a good test case. From 1979 till 2003, 0.9-1.2x10^6 m^3/year (total 21.6-28.8x10^6 m^3) of sand was extracted from this ridge. During this period the ridge was also monitored intensively. Since February 2003, there is a temporary extraction closure of three years, because two depressed areas on the ridge exceeded the permitted extraction depth (Figure 7.1). During the closure period intensive monitoring (4 surveys/year) will take place, to evaluate the natural potential of restoration of the ridge.

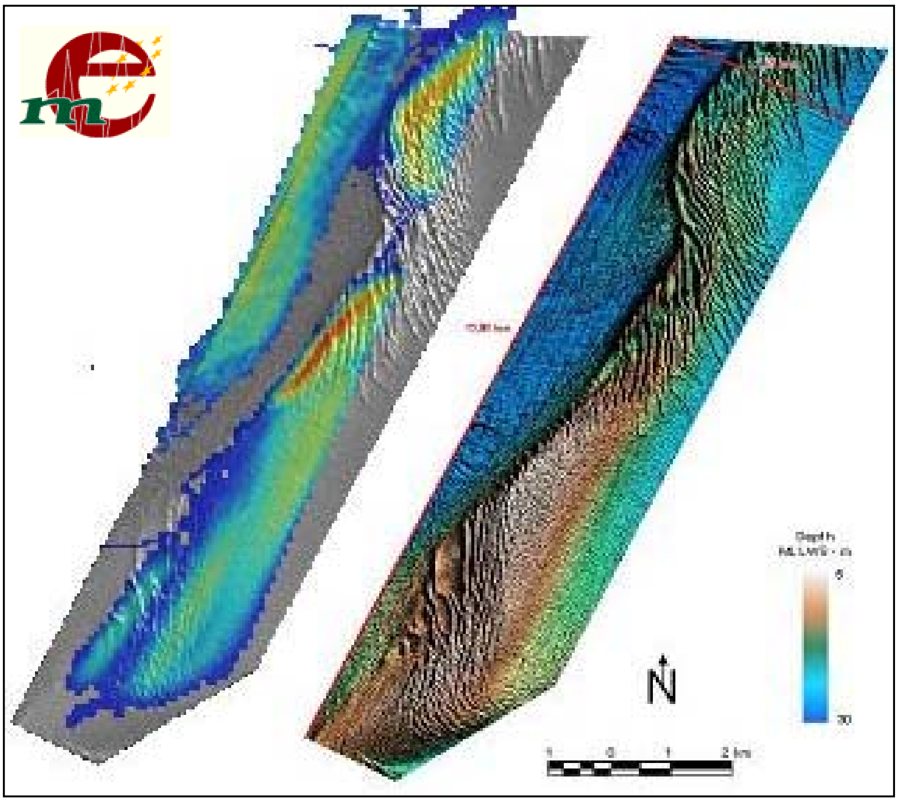


Figure 7.1: Kwintebank on the BCS; two depressed (red) areas (left); bathymetry (right) (maps from the Ministry of Economic Affairs, Belgium, 2003)

We recommend investigating the opportunities of running this case in the near future. And, actually run the test case with several instruments and organize another discussion after some period. Then, also the coupling of models can be tried and the models can be validated with the Belgian measurements. Finally, the test case can be used to determine which processes most influence a pit. It is a challenge for research managers (RIKZ) and model developers, to respectively organize and run the Kwintebank case. It would be practical to couple this with the ongoing European project EUMARSAND, which runs till end 2005 (see Website EUMARSAND).

7.2 Inventory of instruments

In this section, we formulate the inventory of instruments, the last phase of the Rugby ball (Section 2.2). We can compare this inventory with the manual of a toolbox. For instance, if we want to nail a painting on the wall, what equipment do we need? We look at the manual (inventory of instruments) and see we should use a hammer for this purpose.

7.2.1 Method of judgement

Each model is judged on their prediction force regarding the CSI's of the three coastal user functions: coastal safety and maintenance, offshore infrastructure and navigation. We split this judgement in 'applicability' and 'reliability' and formulate scores to judge the instruments on these two parameters. The applicability of an instrument shows for what purpose it can be used. We qualify the applicability by looking at the representation of processes, which are important to predict the CSI's. Furthermore, the reliability of an instrument shows how reliable a prediction, on a CSI, with this instrument is. We qualify reliability on two points: spatial scale on which the predictions apply (schematised or realistic) and representation of the situation (schematised or realistic). These two parameters together determine the scores on reliability. In Appendix T, the categories for 'applicability' and 'reliability' are explained.

The next step is to determine the scores of the models regarding the CSI's. To objectively judge the models we use the following method: we look at a CSI and investigate the applicability of the model to the CSI. In Table T.1 and T.2 (Appendix T), an explanation for the scores on applicability of each model is given. Next we determine the reliability of the model results. In Table T.3 and T.4 (Appendix T), an explanation for the scores on reliability of each model is given. Finally, an overview of the prediction force of the selected models, regarding the different CSI's, is given in the inventory of instruments in Table 7.1.

Coastal user function	Research question	CSI	Prediction force instruments: Twente Model		Amplitude evolution model		Utrecht model		Delft3D		Su-trench		Telemac		mu-SEDIM	
Coastal safety and maintenance	1. Will pit act as sediment sink?		A	R	A	R	A	R	A	R	A	R	A	R	A	R
	- What impact will it have on nearshore sediment transport regimes?	- MCL	1	2	F		2	2	2	2	X		2	2	2	2
	- Will it lead to an increase in coastal erosion?	- Sand budget in nearshore zone	1	2	F		2	2	2	2	X		2	2	2	2
	2. Will pit affect tidal flow and waves?		A	R	A	R	A	R	A	R	A	R	A	R	A	R
	- What is the effect on the nearshore tidal currents?	- Erosion profile	X		X		1	2	1	2	X		1	2	1	2
	- What is the effect on waves in nearshore area?	- MCL	1	2	F		2	2	2	2	X		2	2	2	2
Offshore infra-structure	3. Will pit act as sediment sink?		A	R	A	R	A	R	A	R	A	R	A	R	A	R
	- What is the sand transport regime in relation to the current outside the pit?	- Coverage cables & pipelines	2	2	F		X		2	1	2	1	2	2	2	1
	- What is the deformation of the pit? Influence area? - What is the migration rate of the pit?	- Distance pit to offshore infrastructure	2	2	F		X		2	2	2	1	2	2	2	2
Navigation	4. Will the ridges recover after extraction?		A	R	A	R	A	R	A	R	A	R	A	R	A	R
	If yes: - Within what period?	- Position ridge(s)	X		X		X		?		X		F		?	
	- Will recovery affect other nearby sand ridges?	- Height ridge(s)	F		2	2	2	2	?		F		F		?	
	5. Will pit modify the local flow and waves in the area?		A	R	A	R	A	R	A	R	A	R	A	R	A	R
	- What is the change in maximum tidal current velocity?	- Tidal current	1	2	X		X		1 3*	2 3*	1	1	F		F	
	- What is the change in wave height during a storm?	- Wave height	X		X		F		1 3*	2 3*	1	1	F		F	
	6. Will a pit act as a sediment sink?		A	R	A	R	A	R	A	R	A	R	A	R	A	R
	- What is the change in water depth?	- Water depth in area	1	2	1	2	1	2	2	1	2	1	2	2	2	1
	- What is the deformation of the pit? Influence area?	- Depth and width shipping channel(s)	X		X		X		?		2	1	?		?	
	- What is the migration rate of the pit?	- Distance pit to channel & anchor area	2	2	F		X		2	2	2	1	2	2	2	2

Table 7.1: Inventory of instruments

A = applicability; X = not applicable; does not represent processes (red), 1= qualitative; qualitative insight (orange), 2 = moderate; quantitative insight (yellow), 3 = good; direct support decision-making process (green), ? = no experience (purple), F = possible to apply in near future (purple)

R = reliability; X = not applicable (red), 1 = not reliable; represents processes on schematised spatial scale with schematised situation (orange), 2 = moderate; represents processes on realistic spatial scale with schematised situation (yellow), 3 = good; represents processes with realistic situation (green), ? = no experience (purple), F = possible in near future (purple)

* for short-term predictions

7.2.2 *Coastal safety and maintenance*

From Table 7.1, we can see that the applicability of the instruments to the CSI's of coastal safety and maintenance differs a lot. The numerical models Delft3D, Telemac and mu-SEDIM and the Utrecht model seem to be best applicable for these CSI's. However, we must keep in mind that predictions on long timescales (50-100 years) require large computational time with the numerical models. Therefore, the Twente model and in the near future the Amplitude-evolution (although both not applicable for CSI 'Erosion profile') are also interesting to use for fast qualitative insight. Furthermore, SUTRENCH is not applicable for these CSI's, because it is a 2DV model and these CSI's deal with horizontal effects.

7.2.3 *Offshore infrastructure*

From Table 7.1, we can see that the Utrecht model is not applicable to the CSI's for offshore infrastructure. The Amplitude-evolution model could be used for these CSI's in the near future by including the method of Morelissen et al. (2003) (Section 5.2.4). Based on the possibilities described in Chapter 6, we are to believe that Delft3D, Telemac and mu-SEDIM are capable to give quantitative insight in a schematised situation (i.e. flat sea bottom), although no calculations of this kind have been done (yet) with these models. However, also here we are dealing with large computational time for predictions on longer timescales. Furthermore, the predictions of Delft3D and mu-SEDIM on the CSI 'Coverage of cables and pipelines' are probably not reliable, because these models are not (yet) capable to predict bed forms like sand ridges, which evolve due to a large-scale extraction pit. SUTRENCH can also provide quantitative insight in the CSI's. These predictions are however not reliable, because the spatial scale on which SUTRENCH can be applied (1-5 km) is too small. Finally, the Twente model can give quantitative insight in the effects of large-scale sand extraction on offshore infrastructure and presents the processes on a realistic spatial scale, but with a schematised situation (starts from a flat bottom).

7.2.4 *Navigation*

The coastal user function navigation deals with three (main) research questions (Table 7.1, questions 4-6). Research question 4 deals with the recovery of ridges after extraction. Only the Amplitude-evolution model and Utrecht model are capable to predict the recovery of ridges after extraction (only CSI 'Height ridge(s)'). The other models could be applied for the CSI 'Height ridge(s)' in the near future (Twente model, SUTRENCH, Telemac) or there is a lack of experience with the models on this point (Delft3D and mu-SEDIM). Research question 5 deals with the effects of sand extraction on the hydrodynamics. For the CSI's of this research question Delft3D, and in the near future Telemac and mu-SEDIM can directly support the decision-making process and give good reliable results, but only on short-term predictions. On the longer term (up to 100 years), Delft3D, SUTRENCH and the Twente model (only CSI 'Tidal current') can give qualitative insight. The predictions of SUTRENCH are however not reliable because the spatial scale of the model is too small. Furthermore, Telemac and mu-SEDIM can be used to predict long-term hydrodynamic effects, when an internal coupling between the morphology and waves and tides is included in the models. Moreover, the Utrecht model could be extended with a wave transformation model in the near future (Section 5.3.3). Finally, the Amplitude-evolution model is not applicable for these CSI's.

Research question 6 deals with the morphological effects of an extraction pit. In the inventory of instruments we see that all models can be applied to predict the changes in water depth in the area after extraction. The Twente model, Amplitude-evolution model and Utrecht model can give qualitative insight, whereas the other models (Delft3D, SUTRENCH, Telemac and mu-SEDIM) can give quantitative insight to this CSI, all using a schematised situation. However, the Amplitude-evolution model and SUTRENCH can only predict the water depth along one cross-section and the predictions with SUTRENCH are not reliable, due to the schematised spatial scale. Furthermore, the predictions with Delft3D and mu-SEDIM are not reliable, because these models are not (yet) capable to predict bed forms like sand ridges, which evolve due to a large-scale extraction pit. Moreover, at this moment there is no model that can be used to predict the influence of a pit on the depth and width of adjacent shipping channels. SUTRENCH can only predict the filling of the trench itself. The Twente model, Amplitude-evolution model and Utrecht model are not applicable and with the other models (Delft3D, Telemac, mu-SEDIM) there is a lack of experience on this point. Finally, to predict the distance from the pit to shipping channel(s) and/or anchor areas, only the Utrecht model is not applicable. The Twente model, Delft3D, SUTRENCH, Telemac and mu-SEDIM are capable to give quantitative insight in a schematised situation. However, the problem with large computational time for predictions with the numerical models on longer timescales and non-reliable results with SUTRENCH arises also here. Therefore, the Twente model is probably most suitable for this CSI.

8 Discussion

In this chapter, we first discuss the main goal of this thesis; the inventory of instruments, which can be used to predict the long-term physical effects of large-scale sand extraction on the Zeeland ridges. After this, we briefly investigate the influence of the coastal user functions that were not taken into account, on the decision-making process. In Section 8.3, the RIKZ workshop (Hommes, 2004), that was organized within the framework of this research, is evaluated. Finally, we discuss the match between the end user's information need and specialists knowledge.

8.1 Inventory of instruments

Applicability and reliability instruments

In the previous chapter, we judged the selected instruments on their applicability to predict the different CSI's and on the reliability of these predictions. Although we formulated rather objective scores for applicability and reliability, it is hard to determine these scores for each instrument on each CSI because there is very little experience with calculations on large-scale sand extraction pits on ridges. Furthermore, the calculations that were done on this topic (modelling sand extraction, modelling ridges) with different instruments all have a very different character. Therefore, it is difficult to compare and judge the possibilities of the instruments in the exact same way. To achieve a more objective judgement of the instruments, it would be favourable to run a test case and compare the model results to each other and to field measurements.

Selection instruments

We selected three analytical and four numerical models to take into account in the inventory of instruments of this research. However, this selection was quite arbitrary and it is not self-evidently a selection of the best instruments, which can be used to model sand extraction on the Zeeland ridges. Therefore, it is not inconceivable that there are more instruments available to model this case.

8.2 Coastal user functions

We have decided to restrict ourselves in this research to the three coastal user functions: Coastal safety and maintenance, Offshore infrastructure and Navigation. This way we neglect the impact of large-scale sand extraction on the user functions: Ecosystem, Recreation and Fishery. Especially, the impact on the coastal user function 'Ecosystem' is very important in the decision-making process (besides the impact on the three selected user functions). Terpstra (2004) investigated the ecosystem on the Zeeland ridges by comparing it to the ecosystem on the ridges of the BCS. Before a decision on large-scale sand extraction on the Zeeland ridges can be made, CSI's for the function ecosystem should be formulated and quantified. Furthermore, the impact on recreation is also important. However, this impact is probably mostly covered by the CSI's for 'Coastal safety and maintenance', because most important for recreation is the maintenance of the beach. Finally, also the impact on fishery is important to include, before making a decision on sand extraction. However, if the impact on the ecosystem would be taken into account, it is probably not necessary to look at the impact on fishery separately.

8.3 RIKZ Workshop

Presentations

We asked all model developers, who participated in the workshop, to give a presentation on their model. The maximum duration of each presentation was 20 minutes, after which there was some time for questions. To stimulate a similar representation of each model, we formulated a few guidelines for the presentations in the invitation for the workshop. The programme and the guidelines for the presentations are given in Appendix S. The guidelines were more or less followed by each participant. This was very practical for the comparison of the different models.

Case: 'Large-scale extraction on the Schouwenbank'

At the end of the day, we held a discussion on the case of a large-scale sand extraction on the Schouwenbank and how the long-term physical effects, caused by such an extraction, can be modelled now and in the future. The case is described in Appendix S. We tried to focus on the research questions and CSI's as formulated in Section 4.2. However, it was very hard to focus the discussion on the CSI's, because they did not match directly with the model results and all model developers were therefore very cautious with their statements. So, the discussion was more about the model possibilities and how we could use them now and improve them in the future. The conclusions of the discussion are summarised in Section 7.1.

8.4 Bridging a gap?

During this research and from literature (e.g. Van Koningsveld, 2003) we noticed a suboptimal cooperation between specialists (e.g. model developers) and users of specialists' knowledge (e.g. coastal managers, decision-makers). In this research, we tried to bridge this "gap" between the coastal managers (RIKZ & DNZ) and the model developers. A key element is to use the end user's (in this case DNZ) information need as an explicit starting point for knowledge development and to continuously match specialist research with the information need of end users. In this research, we used the Rugby ball method (Section 2.2) to make the information need explicit, this resulted in quantifiable parameters; CSI's (Section 4.2). On the other hand, we gathered information on the selected instruments by interviewing experts, literature study and organizing a workshop for model developers. This way, we determined the possibilities and limitations of the different models regarding the end user's information need; this resulted in the inventory of instruments (Section 7.2).

It can be said we made an explicit match between coastal management and research. However, this does not mean that the "gap" was bridged. From the inventory of instruments it is clear there are still a lot of end user (research) questions that cannot be answered with the selected instruments at this point. But we can conclude that a start has been made, the fundaments for a bridge are built. Now it is a challenge to coastal managers and researchers to keep on building this bridge from two sides.

9 Conclusions and Recommendations

The main question of this research is the following:

In what way can instruments support the Dutch decision-making process on large-scale sand extraction in the area of the Zeeland ridges?

9.1 Conclusions

What instruments can be used to predict certain physical effects caused by large-scale sand extraction on the Zeeland ridges?

9.1.1 Inventory of instruments

We selected three coastal user functions to take into account in this research: 'Coastal safety and maintenance', 'Offshore infrastructure' and 'Navigation'. Furthermore, we selected state-of-the-art models: three analytical (non)-linear stability-type models (Twente model, Amplitude-evolution model, Utrecht model) and four numerical models (Delft3D, SUTRENCH, Telemac, mu-SEDIM) to include in the inventory of instruments. In this section, we draw conclusions on the prediction force of the selected instruments, regarding the physical effects, which affect the coastal user functions. We formulated Coastal State Indicators (CSI's) for each selected user function, to quantify these physical effects.

Coastal safety and maintenance

The CSI's for 'Coastal safety and maintenance' are: 'Coastline position' (MCL), 'Sand budget in the nearshore zone' and 'Erosion profile'. The numerical models Delft3D, Telemac and mu-SEDIM and the Utrecht model seem to be best applicable for these CSI's. However, we must keep in mind that predictions on long timescales (50-100 years) require large computational time with the numerical models. Therefore, the Twente model and in the near future the Amplitude-evolution (although both not applicable for CSI 'Erosion profile') are also interesting to use for fast qualitative insight.

Offshore infrastructure

The CSI's we formulated for 'Offshore infrastructure' are: 'Coverage of cables and pipelines as a function of time' and 'Distance from pit to cables, pipelines and offshore constructions as a function of time'. Based on the model possibilities, we are to believe that Delft3D, Telemac and mu-SEDIM are capable to give quantitative insight in a schematised situation (i.e. flat sea bottom), although no calculations of this kind have been done (yet) with these models. However, also here we are dealing with large computational time for predictions on longer timescales. Furthermore, the predictions of Delft3D and mu-SEDIM on the CSI 'Coverage of cables and pipelines' are probably not reliable. Finally, the Twente model can give reliable quantitative insight in the effects of large-scale sand extraction on offshore infrastructure with a schematised situation (starts from a flat bottom) and the Amplitude-evolution model could be used for these CSI's in the near future.

Navigation

The first CSI's for 'Navigation' focus on the recovery of the Zeeland ridges after extraction, these are: 'Position ridge(s)' and 'Height ridge(s) as a function of time'. Only the Amplitude-evolution model and Utrecht model are capable to predict the recovery of ridges after extraction (only CSI 'Height ridge(s)'). The other models could be applied for the CSI 'Height ridge(s)' in the near future (Twente model, SUTRENCH, Telemac) or there is a lack of experience with the models on this point (Delft3D and mu-SEDIM). The second CSI's for 'Navigation' deal with the hydrodynamic effects of sand extraction. For the CSI's of this research question Delft3D, and in the near future Telemac and mu-SEDIM can directly support the decision-making process and give good reliable results, but only on short-term predictions. On the longer term (up to 100 years), Delft3D and the Twente model (only CSI 'Tidal current') can give qualitative insight. Finally, the Utrecht model could be extended to predict the influence of a large-scale extraction on the wave height in the area.

The last CSI's for 'Navigation' focus on the morphological effects of sand extraction: 'Water depth in the area of the ridges as a function of time', 'Depth and width of nearby shipping channel(s) as a function of time', 'Distance from pit to nearby shipping channel(s) and anchor areas as a function of time'. All models can be applied to predict the changes in water depth in the area after extraction. The Twente model, Amplitude-evolution model and Utrecht model can give qualitative insight, whereas the other models (Delft3D, SUTRENCH, Telemac and mu-SEDIM) can give quantitative insight to this CSI, all using a schematised situation. However, the Amplitude-evolution model and SUTRENCH can only predict the water depth along one cross-section and the predictions with SUTRENCH are not reliable. Also the predictions with Delft3D and mu-SEDIM are not reliable, because these models are not (yet) capable to predict bed forms like sand ridges, which evolve due to a large-scale extraction pit. Moreover, at this moment there is no model that can be used to predict the influence of a pit on the depth and width of adjacent shipping channels. Finally, to predict the distance from the pit to shipping channel(s) and/or anchor areas, Twente model, Delft3D, SUTRENCH, Telemac and mu-SEDIM are capable to give quantitative insight in a schematised situation. However, the problem with large computational time for predictions with the numerical models on longer timescales and non-reliable results with SUTRENCH arises also here. Therefore, the Twente model is probably most suitable for this CSI.

9.1.2 Decision-making process

Do the output parameters of these instruments support the decision-makers in their decision? If not:

- *What information is missing?*
- *What knowledge is missing?*
- *What are the future expectations and challenges?*

From the inventory of instruments it was clear that some instruments are capable to directly support the decision-making process on the CSI's 'Tidal current along nearby shipping channel(s) and at anchor areas as a function of time' and 'Wave height along nearby shipping channel(s)', but only on the short-term effects. On the remaining part of the CSI's no direct support, but qualitative and quantitative insight in a schematised situation, is possible at this point. From the discussion at the RIKZ workshop, it follows that the most important information missing are measurements on sand transport and knowledge on the long-term (morphological) evolution of the sea bottom. The applicability and reliability of practical sand transport models are largely based on the quality and quantity of the underlying data sets. Therefore, it is extremely important to have information provided by available data sets from laboratory and field experiments. Hardly any data sets are available for deep water with depths larger than 10 m at this moment. If these field and/or laboratory measurements were carried out, this would be a great step forward in the validation of the model results.

Furthermore, there are also CSI's were a lack of experience with the instruments is observed. Firstly, the recovery of ridges after extraction, with Delft3D and mu-SEDIM there is no experience on this point. However, it is shown that it is possible to model sand ridges with these process-based models (Section 6.3.2). Secondly, at this moment there is no experience to model the impact on the depth and width of shipping channels due to an extraction pit. The Twente model, Amplitude-evolution model, Utrecht model are not applicable for this purpose and with the other models there is a lack of experience on this point. It is a challenge for the future to gain (more) knowledge on these two points.

9.2 Recommendations

Research strategy

In this research we used a strategy called 'Meetstrategie 2000+'. The strategy is developed for users and suppliers of measurements in the water sector, to determine which field measurements are needed for certain projects or goals. In this Master thesis, we use the strategy to determine which instruments could be used to predict certain physical effects of large-scale sand extraction on the Zeeland ridges. The strategy consists of an information cycle (Section 1.5), which contains the following steps: watermanagement- and policy (management question), information need, information strategy, collect information, process information and feedback. The second step, information need is the topic of this research. We determine the information need, regarding a large-scale sand extraction on the Zeeland ridges, using the Rugby ball method (Section 2.2), which results in the inventory of instruments. It is the first time the Rugby ball method was used for this kind of research, but it proved to be very useful and successful to accomplish a structured research and to clearly determine the information need of (coastal) managers and other stakeholders (although the last was only determined from literature and previous research). Therefore, it is recommended to use this strategy more often in similar researches.

Inventory of instruments

In the inventory of instruments, we judged the selected models on their prediction force (applicability and reliability) regarding the different CSI's. We gathered information on the models by interviews with model developers, literature study and organizing the RIKZ workshop for model developers. This information forms the input on which we based the judgement of the different models. It would be worthwhile to ask the model developers to give feedback on the judgement of their model and the other models. This would be a valuable extension of the research.

Information strategy

The third step in the information cycle is the information strategy. In this step we indicate how different instruments should be used to collect the information that is needed. From the inventory of instruments (Table 7.1) one can determine, which instrument should be used for what purpose (research question). So, if it is clear what information is needed, we can pick the best possible instrument, gather the input parameters, run the model and collect the output. However, as concluded before, at this moment we are not capable to answer all research questions on a level of direct support to the decision-making process. One should keep this in mind, when interpreting the model results.

Coastal user functions

As discussed in the previous chapter, the impact of sand extraction on the coastal user function ecosystem, which is not taken into account in this research, is very important in the decision-making process. Therefore, before a decision on large-scale sand extraction on the Zeeland ridges is made, we recommend to formulate and quantify CSI's for this user function. We could think about CSI's like 'Size of shoal area of the Voordelta as a function of time'. The impact on recreation and fishery (the other user functions not taken into account) is considered less important to investigate.

Test case

As described in the previous section, on the recovery of ridges after extraction and the impact on the depth and width of shipping channels due to an extraction pit a lack of experience with some of the models is observed. On these points further research is recommended. It would be a great step forward to run a test case on large-scale sand extraction on a ridge. This was also concluded at the RIKZ workshop for model developers.. The Kwintebank on the BCS can form a good test case (Section 7.1.2). However, it will probably be hard to model the complex reality of the Kwintebank as a test case. Therefore, it would be worthwhile to propose an idealised configuration of the Kwintebank and its depressed areas. For instance: make a simply bathymetry, propose a representative tidal current for the area (e.g. mean spring tide) and tidal elevation, propose a fair weather and storm scenario (wave height, wave direction, surges) and a representative grain size. Then, we could run the models on this idealised case. Then, also the coupling of models can be tried. And we can compare the results in between and the magnitude orders with the Belgian field observations (Section 7.1.2). Finally, the test case can be used to determine which processes most influence a pit and we can gain knowledge on the recovery of ridges. It is a challenge for research managers (RIKZ) and model developers, to respectively organize and run the Kwintebank case. For the impact on shipping channels another research, including a pit nearby a shipping channel, would probably more suitable.

References

Literature

Boers, M. and J.J., Jacobse, 2000, *Zandwinning op de zeebanken – Effecten op golfcondities langs de kust van de Zeeuwse en Zuid-Hollandse eilanden*, KUST*2005, Rijksinstituut voor Kust en Zee/RIKZ, Ministerie van Verkeer en Waterstaat (in Dutch).

De Swart, H.E. and D. Calvete, 2003, 'Non-linear response of shoreface-connected sand ridges to interventions', *Ocean Dynamics 53*, 270-277.

Dyer, K.R. and D.A. Huntley, 1999, 'The origin, classification and modelling of sandbanks and ridges', *Continental Shelf Research 19*, 1285-1330.

Houbolt, J.J.H.C., 1968 , 'Recent sediments in the southern bight of the North Sea', *Geologie en Mijnbouw*, volume 47 (4) , p. 245-273.

Hulscher, S.J.M.H., 1996, 'Tidal-induced large-scale regular bed forms patterns in a three-dimensional shallow water model', *Journal of Geophysical Research,Vol. 101, No. C9*, 727-744.

Hulscher, S.J.M.H., J.S. Ribberink and M.A.F. Knaapen, 2001, *Marine Dynamics II*, reader, Civiele Technologie & Management, University of Twente.

Hommes, S., 2004, *Workshop: 'Modelling sand mining on the Zeeland ridges'*, Rijksinstituut voor Kust en Zee/RIKZ, intern document.

Hoogewoning, S.E. and M. Boers, 2001, *Fysische effecten van zeezandwinning*, KUST*2005, Rijksinstituut voor Kust en Zee/RIKZ, Ministerie van Verkeer en Waterstaat (in Dutch).

Idier, D. and D. Astruc, 2001, *Numerical modelling of large scale rhythmic bedforms in shallow water*, IAHR conference, Obihiro, Japan, 10-14 sept. 2001, pp 565-574.

Idier, D. and D. Astruc, 2003, 'Analytical and numerical modeling of sandbanks dynamics', *Journal of Geophyshysical Research, 108(C3)*, 3060, doi:10.1029/2001JC001205.

International Commission on Irrigation and Drainage (ICID), 2003, *Leefbaar laagland – Geschiedenis van de waterbeheersing en landaanwinning in Nederland*, Vijfde geheel herziene druk, Uitgeverij Matrijs, Utrecht (in Dutch).

Kinneging, N.A., 2001, *Van vraag naar antwoord,* Ministerie van Verkeer en Waterstaat, Directoraat-Generaal Rijkswaterstaat, Meetkundige Dienst (in Dutch).

Klein, M.D., 1999, *Large-scale sandpits – Hydrodynamic and morphodynamic modelling of large-scale sand pits*, M.Sc. Thesis, WL Delft Hydraulics, prepared for: Rijksinstituut voor Kust en Zee /RIKZ.

Kleinhans, M.G., 2002, *Sediment dynamics on the upper continental shelf and foreshore–review*, Utrecht University, Institute for Marine and Atmospheric research, EC MAST Project No. MAS3-CT97-0086.

Knaapen, M.A.F. and S.J.M.H. Hulscher, 2002, 'Regeneration of sand waves after dredging', *Coastal Engineering 46*, 277-289.

Komarova, N.L. and A.C. Newell, 2000, 'Nonlinear dynamics of sandbanks and sand waves', *J. Fluid Mech., vol. 415*, pp. 285-321.

Koninklijke Marine, 2001, *Waterstanden, Stromen – Langs de Nederlandse kust en aangrenzend gebied (HP 33)*, Dienst der Hydrografie (in Dutch).

Laban, C. and R.T.E. Schüttenhelm, 1981, 'Some new evidence on the origin of the Zeeland ridges', *Spec. Publs int. Ass. Sediment 5* , 239-245.

Lanckneus, J., V. Van Lancker, G. Moerkerke, D. Van den Eynde, M. Fettweis, M. De Batist and P. Jacobs, 2001, *Investigation of the natural sand transport on the Belgian continental shelf* (BUDGET). Final report. Federal Office for Scientific, Technical and Cultural Affairs (OSTC), 104 p. + 87 p. Annex.

Morelissen, R., S.J.M.H. Hulscher, M.A.F. Knaapen, A.A. Németh, R. Bijker, 2003, 'Mathematical modelling of sand wave migration and the interaction with pipelines', *Coastal Engineering 48*, 197-209.

Open University, 1999, Waves, tides, and shallow-water processes, Oceanography Course Team, Butterworth-Heinemann, Oxford, Second edition.

Pattiaratchi, C.B. and P.T. Harris, 2002, 'Hydrodynamics and sand-transport controls on en echelon sandbank formation: an example from Moreton Bay, eastern Australia', *Marine and Freshwater Research, 53*, 1101-1113.

Peters, B.G.T.M., 2000. *Large-scale sand extraction offshore: The modeling of Large-scale Sand extraction pits*, Master thesis, University of Twente, The Netherlands.

Rijksinstituut voor Kust en Zee/RIKZ, 2003, *Kustlijnkaarten 2003*, RS Drukkerij BV, Rijswijk (in Dutch).

Rijkswaterstaat, 1998, *Informatie op maat – Een vijfstappenplan met het doel te weten wat te meten,* Ministerie van Verkeer en Waterstaat, Rijksinstituut voor Kust en Zee/RIKZ (in Dutch).

Rijkswaterstaat, 2003a, *(Deel)projectplan K2005*Algemeen, Einddoel 5*, Ministerie van Verkeer en Waterstaat, Rijksinstituut voor Kust en Zee/RIKZ, intern document (in Dutch).

Rijkswaterstaat, 2003b, *(Deel)projectplan K2005*Zeebodem, Einddoel 4*, Ministerie van Verkeer en Waterstaat, Rijksinstituut voor Kust en Zee/RIKZ, intern document (in Dutch).

Rijkswaterstaat, 2003c, *Getijtafels voor Nederland*, Ministerie van Verkeer en Waterstaat, Rijksinstituut voor Kust en Zee/RIKZ.

Rijkswaterstaat, 2004, *Regionaal Ontgrondingenplan Noordzee 2 (RON2)*, Directie Noordzee (in Dutch).

Roos, P.C., S.J.M.H. Hulscher, B.G.T.M. Peters and A.A. Németh, 2001, *A simple morphodynamic model for sandbanks and large-scale sand pits subject to asymmetrical tides*, in Proc. RCEM symposium 2001, IAHR, Hokkaido, Japan, 91-100.

Roos, P.C. and S.J.M.H. Hulscher, 2003, 'Large-scale seabed dynamics in offshore morphology: modeling human intervention', *Review of Geophysics*, 41(2), 1010, doi:10.1029/2002RG00012.

Soulsby, R., 2003, Sandpit scenario testing for extractions from pits and sandbanks, Draft Version 4 (from Website Sandpit, 2003).

Stolk, A., 2003, *Regelgeving en milieuaspecten bij de winning van mineralen in de Noordzee*, in: Congres Syllabus, 4^{e} Nationaal Slibcongres 2003 (in Dutch).

Svasek, 2001, *PUTMOR, field measurements at a temporary sand pit, Part 3: Final report*, prepared for: the National Institute for Coastal and Marine Management (RIKZ) and the Directorate North Sea (DNZ) of the Directorate-General for Public Works and Water Management (RWS), the Netherlands.

Technische Adviescommissie voor de Waterkeringen (TAW), 2002, *Leidraad Zandige Kust* (in Dutch).

Terpstra, T., 2004, *In a Bar under the Sea - Functions and values on the Zeeland ridges and the relative risks of large scale sand extractions*, Master thesis, University of Twente, Rijksinstituut voor Kust en Zee/RIKZ, to appear.

Van Alphen, J.S.L.J. and M.A. Damoiseaux, 1989, 'A geomorphological map of the Dutch shoreface and adjacent part of the continental shelf', *Geologie en Mijnbouw*, 68: 433-443.

Van den Eynde, 2003, *Het numerieke model mu-SEDIM voor de bepaling van het totale sedimenttransport in de Belgische Kustwateren*, Beheerseenheid van het Mathematische Model Noordzee (BMM), MOMO/1/DVDE/200309/NL/TR/1, Draft version (in Dutch).

Van de Meene, J., 1994, *The shoreface-connected ridges along the central Dutch coast*, Ph.D. thesis, Univ. Utrecht, The Netherlands, Nederlandse geografische studies, KNAG, Utrecht.

Van de Meene, J. and L.C. Van Rijn, 2000, 'The shoreface-connected ridges along the central Dutch coast – part 2: morphological modelling', *Continental Shelf Research 20*, 2325-2345.

Van Koningsveld, M., 2003, *Matching specialist knowledge with end user needs*, Ph.D. thesis, University of Twente, the Netherlands.

Van Rijn, L.C., 1986a, 'Mathematical modelling of suspended sediment in non-uniform flows', *Journal of Hydraulic Engineering*, vol. 112, no. 6.

Van Rijn, L.C., 1986b, 'Sedimentation of dredged channels by currents and waves', *Journal of Waterway, Port and Ocean Engineering*, vol. 112, no. 5.

Van Rijn, L.C., 1993, *Handbook of Sediment Transport by Currents and Waves*, Delft hydraul., Delft, Netherlands.

Van Rijn, L.C. and D.J.R. Walstra, 2002, *Morphology of Pits, Channels and Trenches*, Part I: Literature review and Study Approach, prepared for: DG Rijkswaterstaat, Rijksinstituut voor Kust en Zee-RIKZ.

Van Woerden, J.A., 2002, *Syntheserapport Grootschalig Diep Zandwinnen, Gebaseerd op TNO DIS-RTP-010024 en DIS-RTP-010026*, TNO-rapport, DIS-RTP-010127, prepared for: Rijkswaterstaat, Directie Noordzee (in Dutch).

Vincent, C.E., A. Stolk and C.F.C. Porter, 1998, 'Sand suspension and transport on the Middelkerke Bank (southern North Sea) by storms and tidal currents', *Marine Geology 150*, 113-129.

Walgreen, M., D. Calvete and H.E. de Swart, 2002, 'Growth of large-scale bed forms due to storm-driven and tidal currents: a model approach', *Continental Shelf Research 22*, 2777-2793.

Walgreen, M., 2003, *Dynamics of sand ridges in coastal seas: the effect of storms, tides and grain sorting*, Ph.D. thesis, Univ. Utrecht, The Netherlands, IMAU, Utrecht.

Walstra, D.J.R., L.C. Van Rijn and G. De Boer, 2002, *Morphology of Pits, Channels and Trenches, Part III: Investigation of the longshore and cross-shore impact of various pit designs*, WL I Delft Hydraulics, prepared for: RIKZ, DNZ, RWS.

Walstra, D.J.R., L.C. Van Rijn, S.E. Hoogewoning and S.G.J. Aarninkhof, 1999, 'Morphodynamic modelling of dredged trenches and channels', *Coastal Sediments 1999*, 2355-2370.

Walstra, D.J.R., L.C. van Rijn, M. Boers and J.A. Roelvink, 2003, 'Offshore sand pits: verification and application of hydrodynamic and morphodynamic models', WL|Delft Hydraulics, RWS, RIKZ, In: *Proceedings of the International Conference on Coastal Sediments 03*, may 18-23, Florida (2003)

Websites

Website Directie Noordzee, December 2003, http://www.noordzee.org/rws/dnz/Levende_zee/economisch_gebruik/visserij.htm

Website EUMARSAND, December 2003, http://www.azti.es/eumarsand/EUMARSAND.htm

Website MUMM, December 2003, www.mumm.ac.be

Website Nederlandse Vissersbond, December 2003, www.vissersbond.nl

Website Noordzee Atlas, December 2003, www.noordzeeatlas.nl

Website Noordzeeloket, December 2003, www.noordzeeloket.nl

Website Sandpit, September 2003,
http://sandpit.wldelft.nl/mainpage/mainpage.htm
http://sandpit.wldelft.nl/reportpage/reportpage.htm

Website Stichting De Noordzee, October 2003, http://www.noordzee.nl

Website Telemac, December 2003, http://www.telemacsystem.com

Website WL Delft Hydraulics, October 2003,
www.wldelft.nl
http://www.wldelft.nl/soft/d3d/index.html
http://www.wldelft.nl/soft/chess/sutrench/index.html

Appendices

Appendix A : Geomorphology of the Zeeland ridges

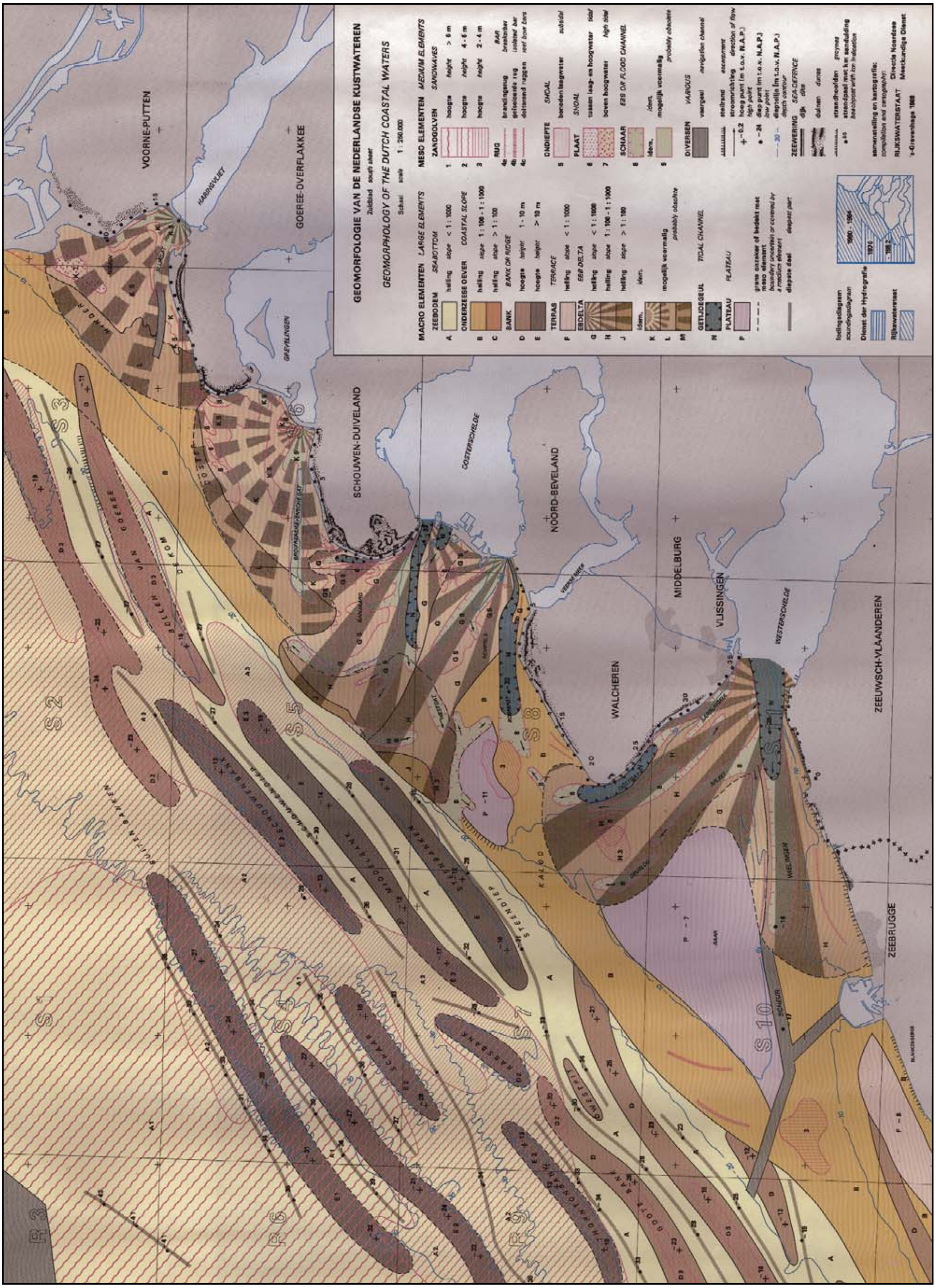


Figure 0.1: Geomorphological map Zeeland ridges (Van Alphen & Damoiseaux, 1989)

Appendix B : Origin of the Zeeland ridges

Baak (1936; in Houbolt, 1968) compared the position of the so-called Old Dunes in western Holland – ill-defined barriers with dunes on top – with that of the Zeeland ridges. He considered the Zeeland ridges as drowned extensions of the barrier chain (Figure B.1). Houbolt (1968) concluded from sparker records and shallow cores that the Zeeland ridges were in part erosional forms and were not formed by submarine or subaerial sand accumulation only. One of his arguments was the absence of flat-based ridges, indicative for lateral movement of these ridges. Instead, on a schematised cross-section he showed markers rising from below within the ridges. Furthermore, on one section over the Middelbank cores were taken. In the profiles from the Middelbank yellowish-brown upper sands, directly overlie bluish-grey sediments. Van Straaten (1954) (in Houbolt, 1968) studied such colourations in the Waddenzee. He distinguished in three zones, the colouring of which was due to different stages of authigenic iron: the hydroxide zone (L), the monosulphiric zone (M) and the bisulphuric or pyrite zone (P). The succession in which the zones are given is the normal sequence encountered in many bottom profiles according to Van Straaten. On the Middelbank no intermediate (M) stage was observed. This is an indication that the contact between the yellowish-brown sands and the underlying bluish-grey sediments is erosional, hence that the bluish-grey sands are fossil. Which is a second indication that the Zeeland ridges are at least part erosion forms.

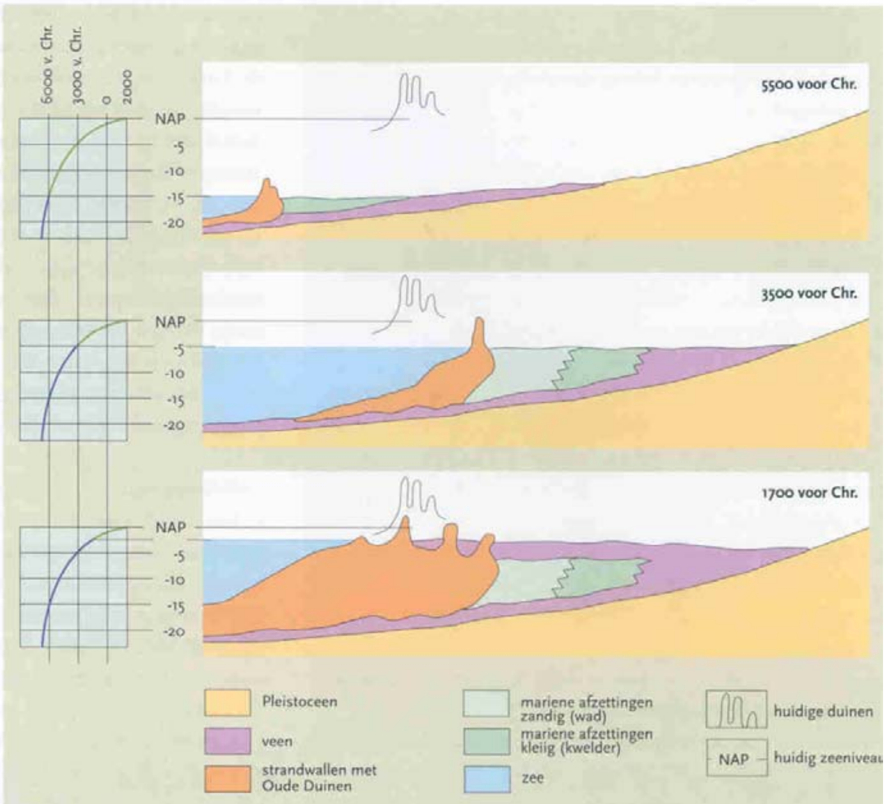


Figure B.1: Sea level rise and the building up of the coastal zone in the years 5500, 3500 and 1700 before Chr. (ICID, 2003)
blue = sea
orange = barrier chain with Old Dunes
dark green = marine clay deposits
pale green = marine sand deposits
yellow = Pleistocene and other high grounds
NAP = present sea level
= present dunes

Moreover, in some places, amongst others on the Thorntonbank, the truncation of reflectors rising from below was observed at about the same depth as a break and a change in the mollusc content. Though not a prove, the above is a third argument in favour of the view that at least part of the relief of the Zeeland ridges is due to erosion of older deposits. A fourth argument to support the view of Houbolt (1968) can be found in the truncation of the Zeeland ridges by those of the Hinder Group, which suggests that the Zeeland ridges are older than those of the Hinder Group. Considering the above four arguments it is very likely that at least the lower parts of the Zeeland ridges consist of older sediments. The upper parts are most probably recent sediments. Houbolt (1968) draws the conclusion that the Zeeland ridges are nearly stationary, because if they had moved more than their width, the lower, fossil, part would have been reworked. There are indeed no data on record that point to a significant displacement of the Zeeland ridges (Van Veen 1936 in: Houbolt, 1968).

According to Laban and Schüttenhelm (1981) the Zeeland ridges and the nearby sandwave field essentially consist of Angulus pygmaeus sands. They concluded that several of the Zeeland ridges are built on top of or are leaning against a core consisting of older deposits at least in part of (early) Atlantic age. These older deposits, provisionally named 'initial ridges', appear to be elongated in shape. Some of the Zeeland ridges seem to lack an older core, however, the Zeeland ridges pre-date leeside deposits that are up to 2000 years old. As regards the processes that caused the inferred transport of large amounts of sand into the southeastern Southern Bight, one can merely speculate. Laban and Schüttenhelm (1981) favour transport mechanisms induced by asymmetrical tidal flow. Perhaps part of the water brought from the south into the Southern Bight by tidal current spilled at lower sea-level stands over the drowned form land bridge between Norfolk and the Dutch island of Texel and did not flow back to the south. This land bridge submerged when the sea level rose to about -30 meter below the present level, i.e. around 8300 years ago (Jansen et al., 1979 in: Laban & Schüttenhelm, 1981). In Figure B.3, the cross-sections over some of the Zeeland ridges are shown. The locations of the cross-sections are indicated on Figure B.2. Finally, we are not aware of any research on the Zeeland ridges after the research of Laban and Schüttenhelm in 1981. In Figure B.4, the thickness of the Holocene (0-10.000 years before present time) layers in the area of the Zeeland ridges is shown. The black lines indicate the locations of the Zeeland ridges. The x-axis and y-axis correspond to eastern longitude and north latitude respectively. As one can see, a large part of the ridges consists of Holocene material.

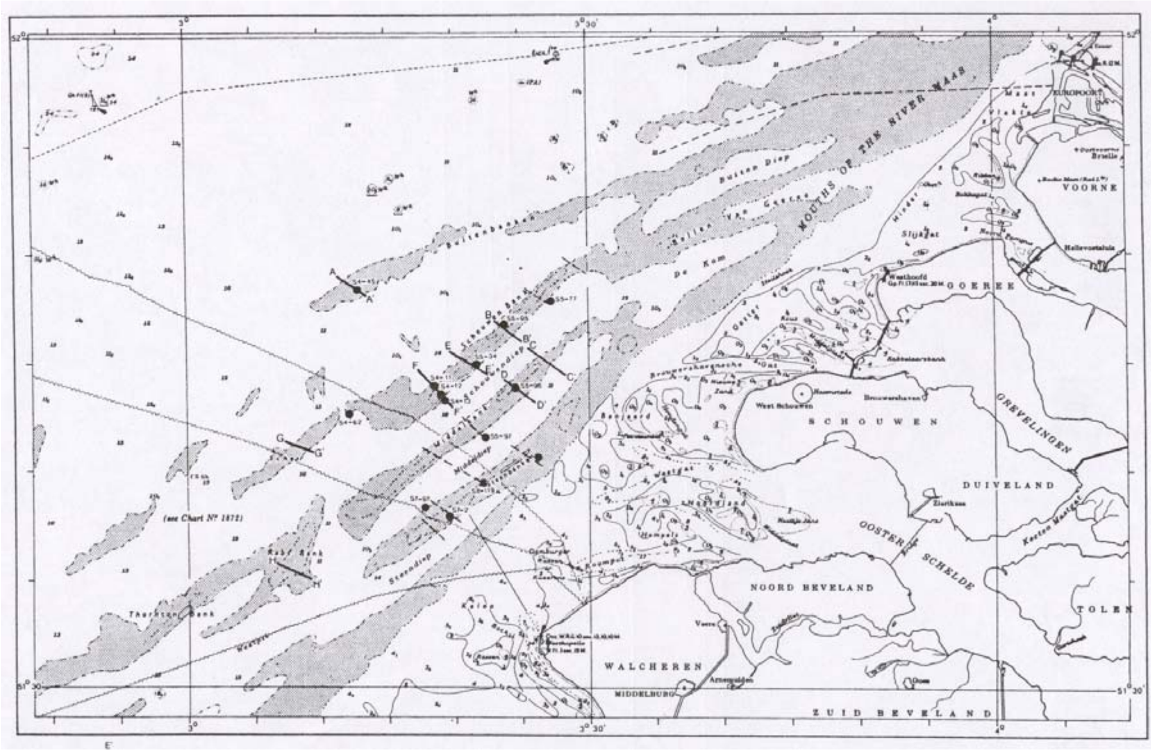


Figure B.2: The Zeeland ridges off the southwestern Dutch coast. Depths are in fathoms (and feet) below LLWS. Areas with water depths between 5 and 10 fathoms (between 9,1 and 18,2 meters) are shaded. Positions of the cross-sections over the Zeeland ridges are indicated by thick black lines (Laban & Schüttenhelm , 1981)

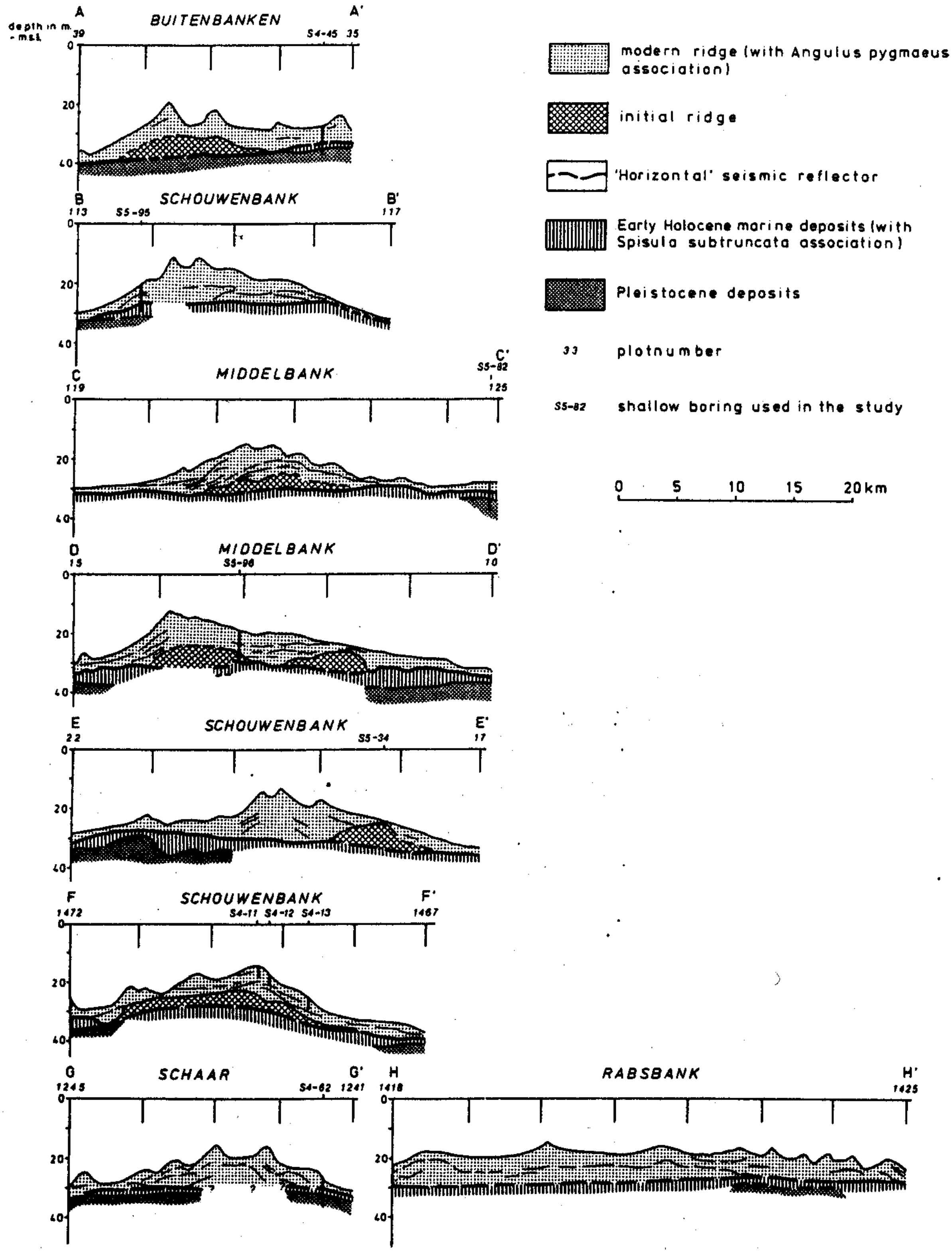


Figure B.3: Cross-sections Zeeland ridges (Laban & Schüttenhelm , 1981)

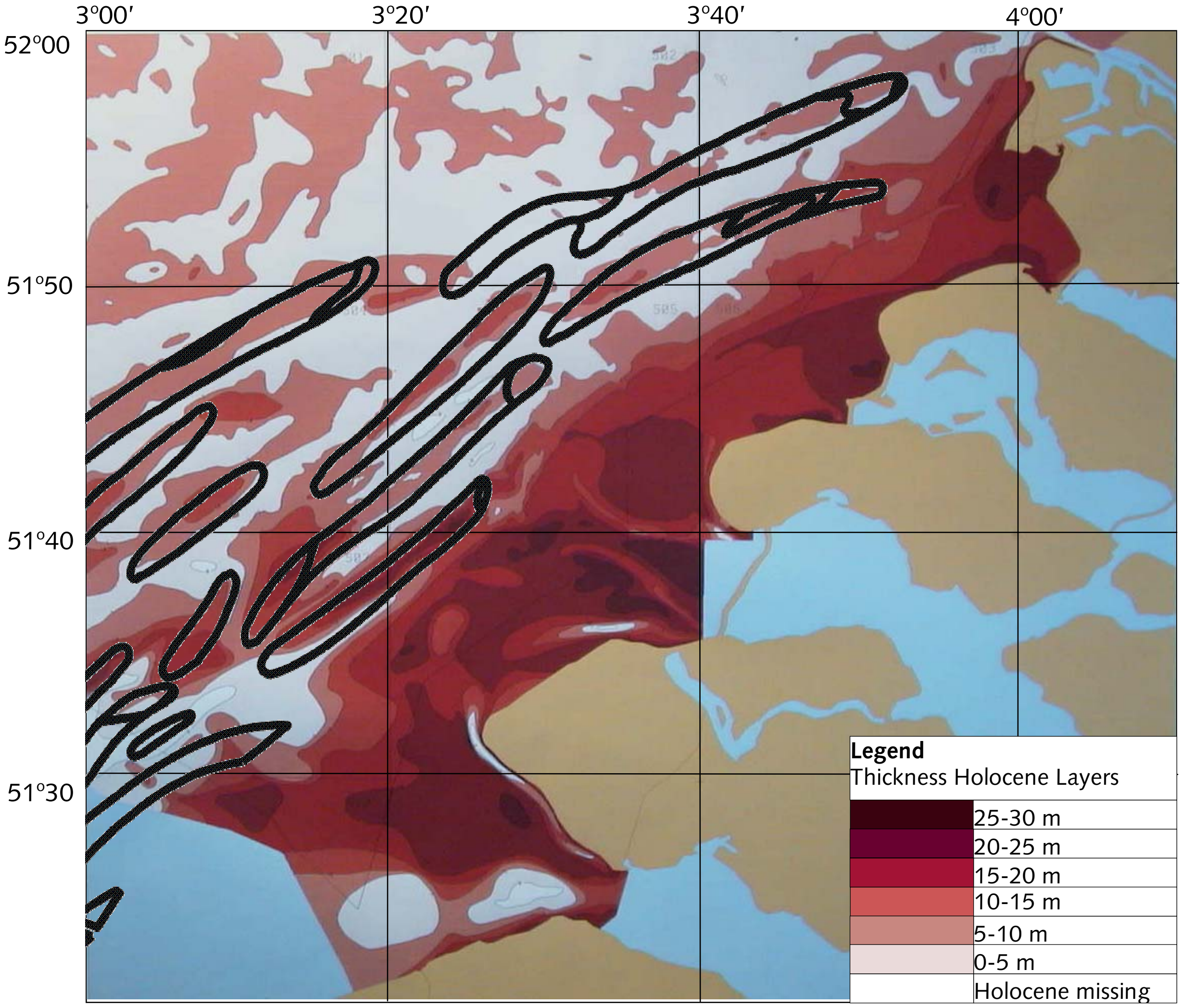


Figure B.4: Thickness Holocene Layers (map from TNO-NITG, 2003)

Appendix C : Grain sizes Zeeland ridges

The black lines in Figure C.1 indicate the location of the Zeeland ridges and the x- and y-coordinates correspond to eastern longitude and north latitude respectively.

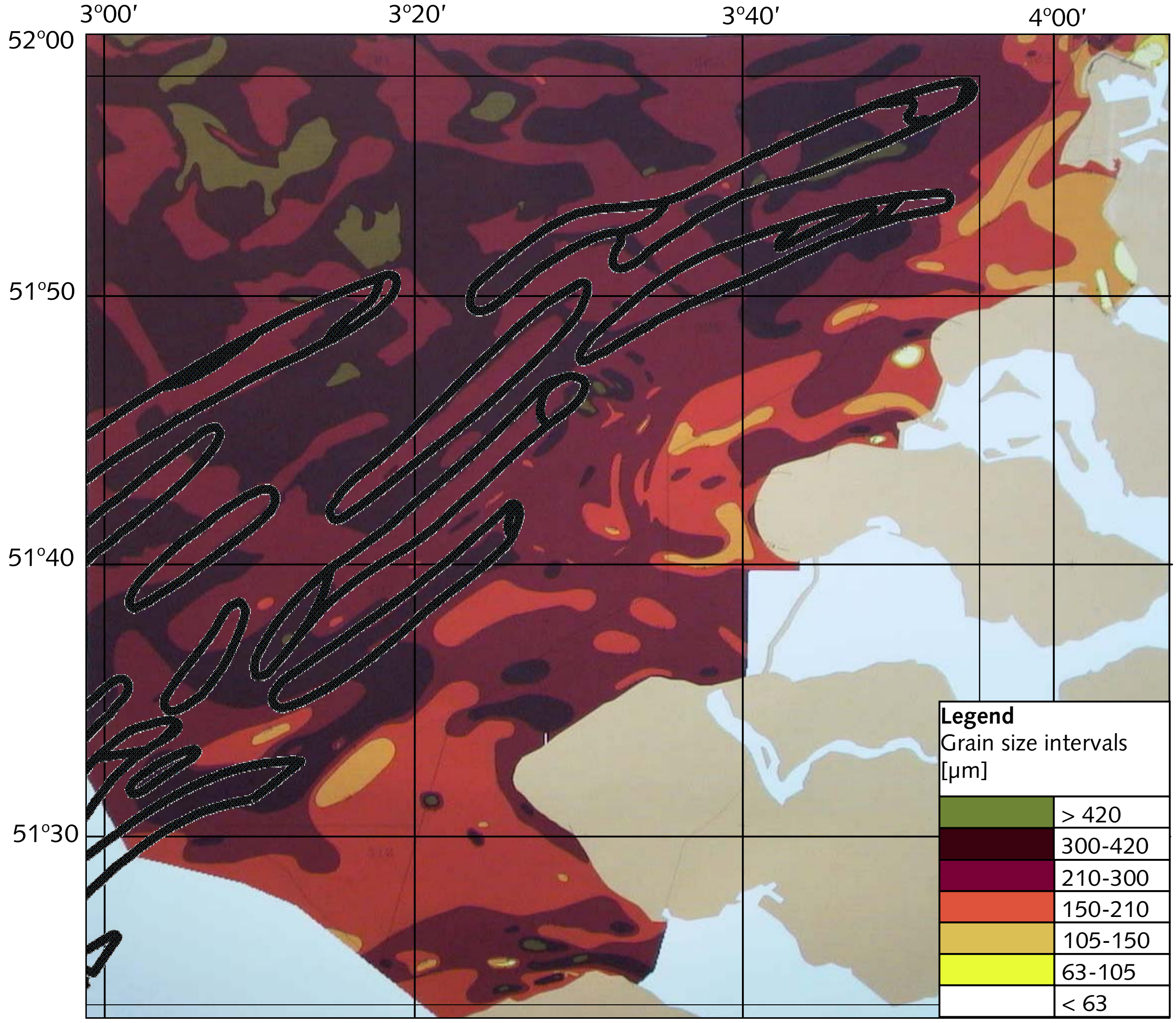


Figure C.1: Grain size first meter (map from TNO-NITG, 2003)

Appendix D : Tidal current system North Sea

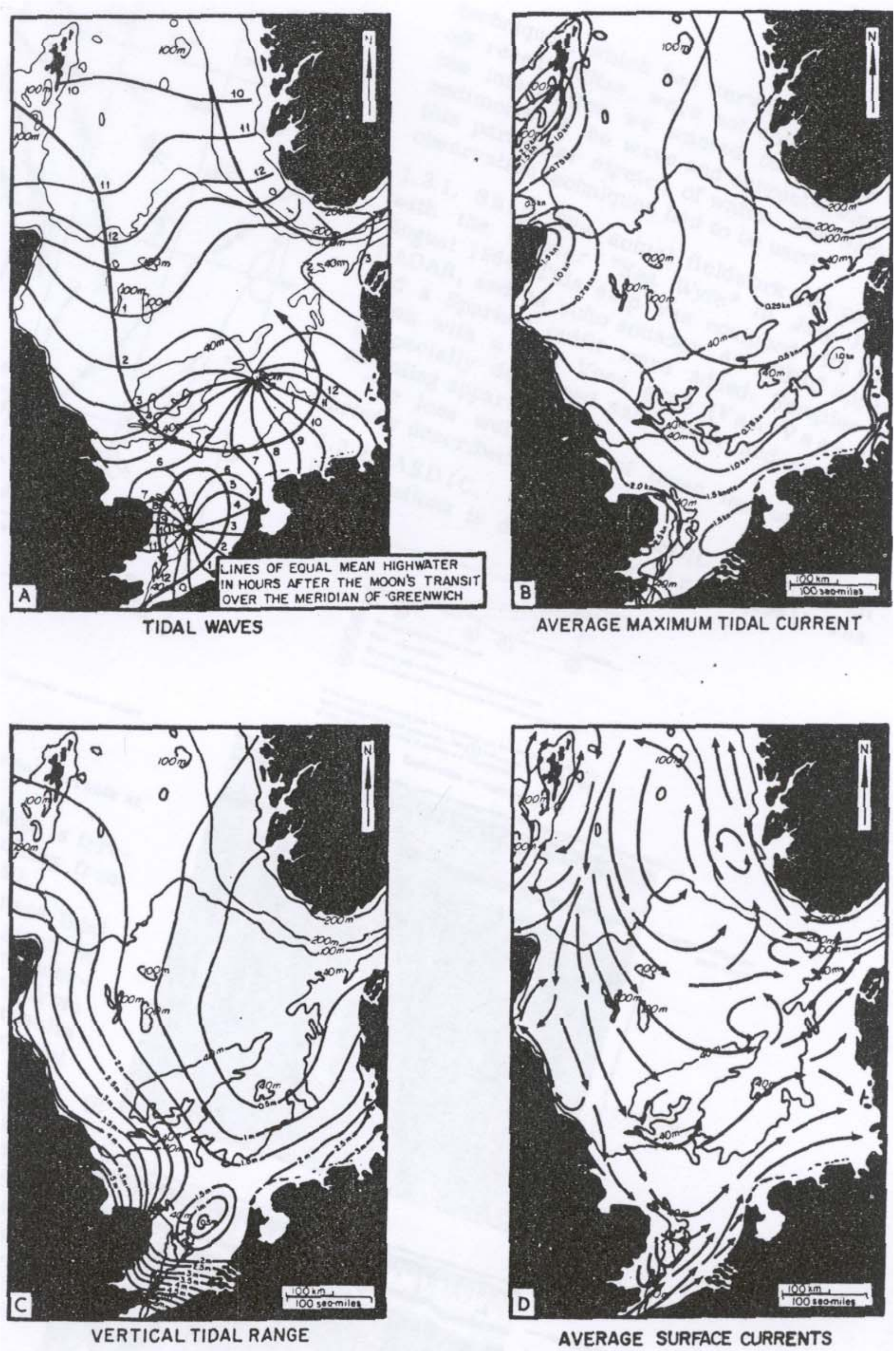


Figure D.1: Generalities of the tidal current system in the North Sea (Houbolt, 1968)

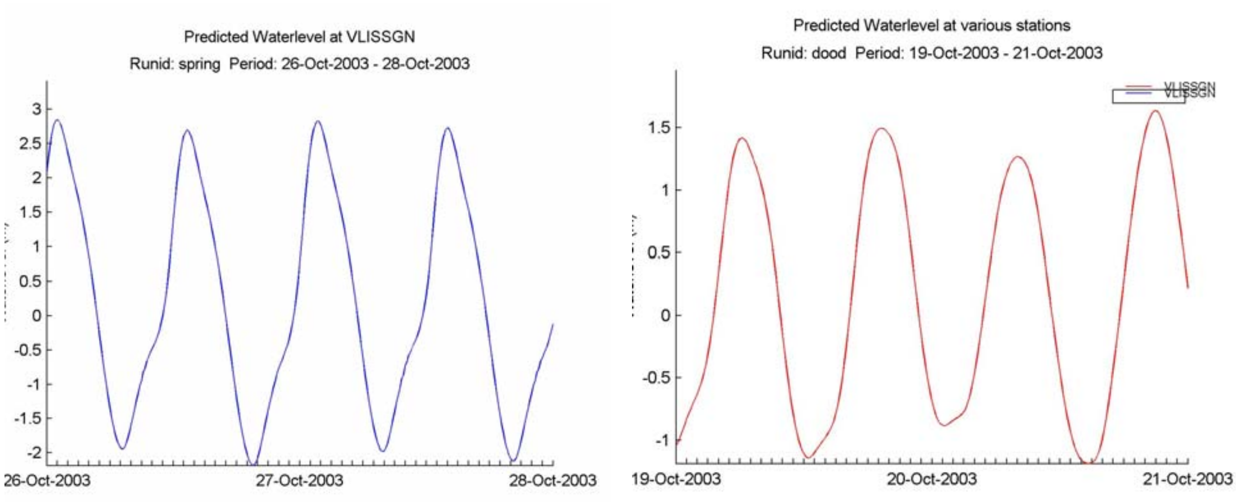


Figure D.2: Water levels (m+NAP) at Vlissingen, spring tide (left); neap tide (right) (from Kustzuid model, 2003)

Appendix E : User functions Netherlands Continental Shelf

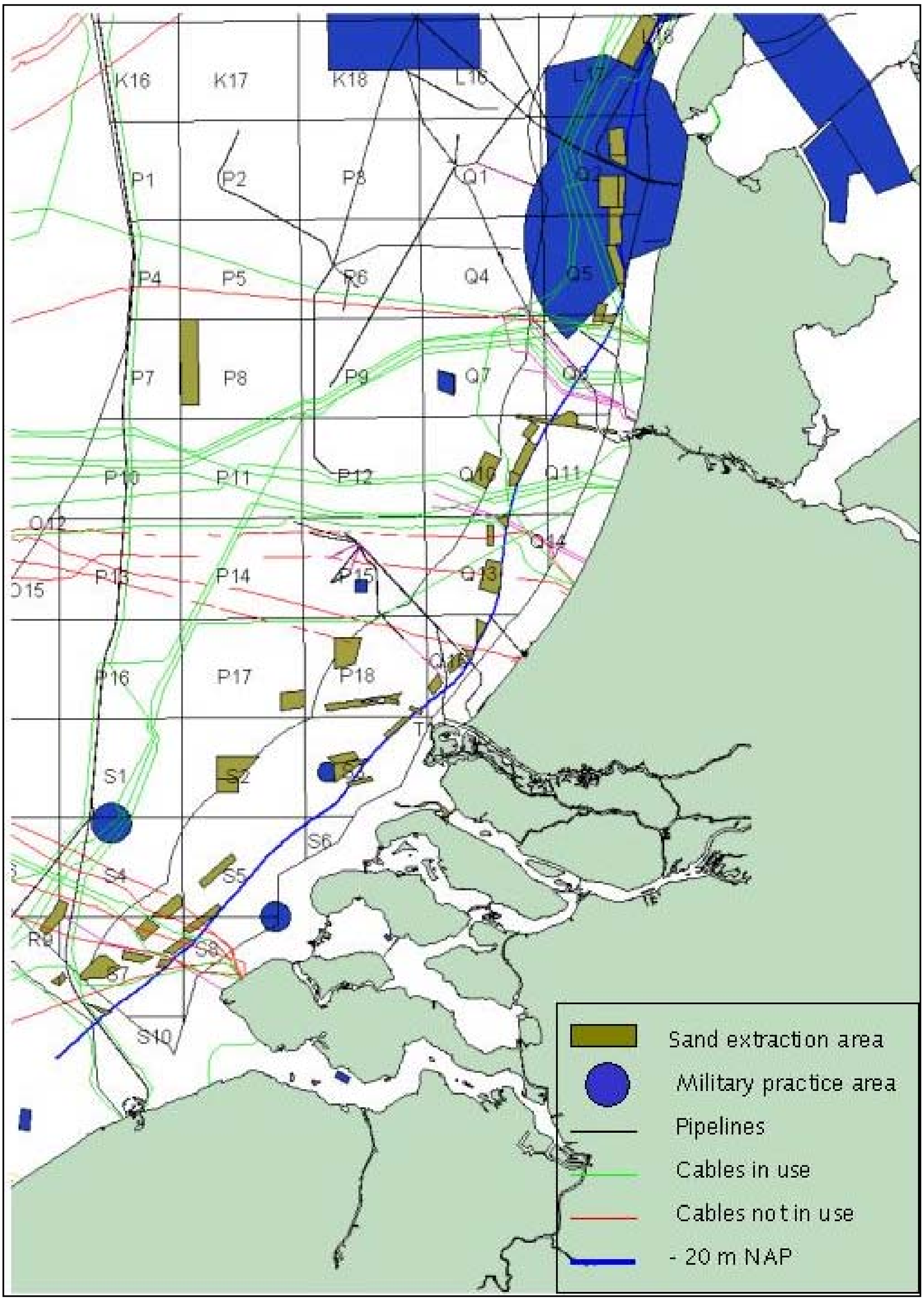


Figure E.1: User functions on the Netherlands Continental Shelf (map from RWS, DNZ, 2003)

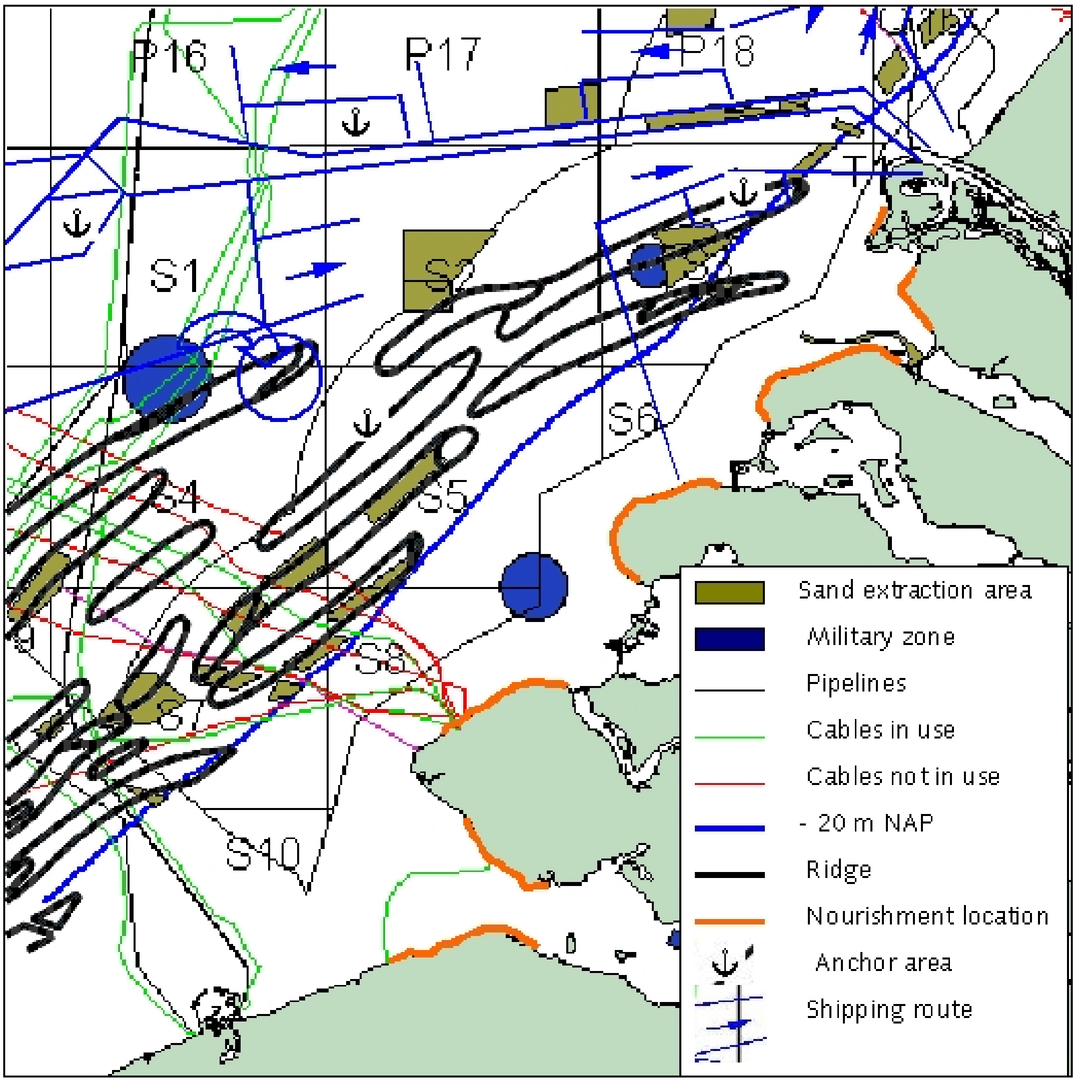


Figure E.2: User functions in the area of the Zeeland ridges (map from RWS, DNZ, 2003)

Appendix F : Concepts of morphodynamic modelling

The essential elements in morphodynamic modelling are found in the morphological loop (Figure F.1), which is explained here for the case of a tidally dominated offshore environment.

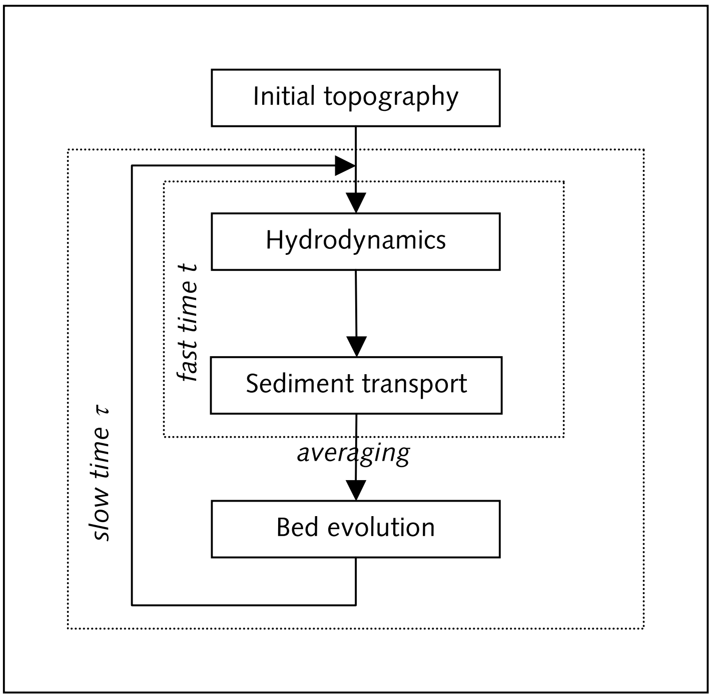


Figure F.1: Morphological loop (Roos & Hulscher, 2003)

Important is the separation in two time scales, with a fast time t for the hydrodynamics and sediment transport within the tidal cycle (half a day) and a slow time τ for the seabed evolution (decades to centuries). After specifying an initial topography, the next step is to solve the hydrodynamics, i.e. to determine currents, tides and waves. For large-scale computations in a shallow water domain, a depth-averaged approach is usually suitable and the Coriolis force and bottom friction should be included. Depending on flow conditions and sediment characteristics, non-cohesive sediment can be transported as bed load or as suspended load. The bed changes, caused by this sediment transport, are so slow that only the tidal average of the transport matters. We end up with an updated topography at a new level in morphodynamic time (Roos & Hulscher, 2003).

Appendix G : Model equations Twente model

Non-dimensional variables (Roos & Hulscher, 2003):

$$\bar{u} = \frac{u^*}{U^*}, \qquad t = \sigma^* t^*, \qquad \vec{x} = \frac{\sigma^*}{U^*}\vec{x}^*, \qquad z_b = \frac{z_b^*}{H^*},$$

$$z_s = \frac{g^* z_s^*}{U^{*2}}, \qquad \vec{S} = \frac{\vec{S}^*}{\alpha_b^* U^{*\beta_b}}, \qquad c = \frac{\gamma^* H^* c^*}{\alpha_s^* U^{*\beta_s}} \tag{G.1}$$

Asterisks denote dimensional quantities.

Scaled morphodynamic model (Roos & Hulscher, 2003):

$$\nabla z_s + \frac{\partial \vec{u}}{\partial t} + \vec{u}\cdot\nabla\vec{u} + f\vec{e}_z \times \vec{u} + \frac{r\vec{u}}{1 - z_b} = 0 \tag{G.2}$$

$$\nabla\cdot\left[(1 - z_b)\vec{u}\right] = 0 \tag{G.3}$$

$$\vec{S} = |\vec{u}|^{\beta_b}\left\{\frac{\vec{u}}{|\vec{u}|} - \lambda\vec{\nabla} z_b\right\} \tag{G.4}$$

$$A\left[\frac{\partial c}{\partial t} + \vec{u}\cdot\nabla c\right] = \frac{|\vec{u}|^{\beta_s}}{1 - z_b} - c \tag{G.5}$$

$$\frac{\partial z_b}{\partial \tau} + \hat{\alpha}_b \vec{\nabla}\cdot\left\langle \vec{S}\right\rangle + \frac{\hat{\alpha}_s}{A}\left\langle |\vec{u}|^{\beta_s} - (1 - z_b)c\right\rangle = 0 \tag{G.6}$$

U*	= maximum velocity tidal wave
u*= (u*,v*)	= velocity components in the directions of the horizontal coordinates (x*,y*)
σ*	= tidal frequency
∇*	= (∂/∂x*,∂/∂y*)
e_z	= unit vector (0,0,1)
z_s*	= free surface evolution
z_b*	= bed level with respect to H^*
H*	= undisturbed water depth
g*	= gravitational acceleration
f*	= Coriolis parameter
t*	= time
r*	= linearised friction parameter
α_b*	= bed load sediment transport parameter
α_s*	= suspended load sediment transport parameter
β_b	= power of bed load transport
β_s	= power of suspended load transport
λ*	= bed slope parameter
γ*	= deposition factor
t	= fast hydrodynamic timescale
τ = μt	= slow morphodynamic timescale
μ	= max(α_b, α_s)
<…>	= averaging over a tidal cycle

Basic state and linearisation (Roos & Hulscher, 2003):

$$\phi = \left(\vec{u}, z_b, \nabla z_s, \vec{S}, c\right) \tag{G.7}$$

$$\phi_0 = \left(\vec{u}_0, 0, (\nabla z_s)_0, \vec{S}_0, c_0\right) \tag{G.8}$$

Tidal flow (Roos et al., 2001):

$$u_0(t) = u_r + \in_u \cos t + \mu_u \cos(2t - \varphi_u) \quad \text{(G.9)}$$

$$v_0(t) = v_r + \in_v \sin t + \mu_v \sin(2t - \varphi_v) \quad \text{(G.10)}$$

u_r, v_r = residual current (M_0-component)
$\in_v / \in_u$ = tidal eccentricity
μ_u, μ_v = M_4 amplitude in x and y direction
φ_u, φ_v = M_4 phase in x and y direction

Linear stability analysis (Roos et al., 2001):

$$h(x, y, \tau) = \gamma A(\tau) e^{-i\vec{k}\cdot\vec{x}} + c.c. \quad \text{(G.11)}$$

$$\phi = \phi_0 + \gamma\phi_1 + O(\gamma^2) \quad \text{(G.12)}$$

$$\frac{dA(\tau)}{d\tau} = \omega A(\tau) \quad \text{(G.13)}$$

$$h_1 = e^{\omega_r \tau} e^{-i|\vec{k}|(e_k \cdot x - c\tau)} + c.c. \quad \text{(G.14)}$$

γ = small parameter
$A(\tau)$ = function of order one
k = (k,l) = wave vector
c.c. = complex conjugate of a complex number
$\varpi = \varpi_r + i\varpi_I$ = growth rate

Sand pit (Roos et al., 2001):

$$h\big|_{\tau=0} = \gamma h_{pit} \quad \text{(G.15)}$$

$$h_{pit}(x) = -\exp\left[-\frac{\pi}{L^2}(x^2 + y^2)\right] \quad \text{(G.16)}$$

$$\tilde{h}_1(\vec{k}, \tau) = \tilde{h}_{pit}(\vec{k}) e^{\omega(\vec{k})\tau} \quad \text{(G.17)}$$

h_{pit} = pit shape parameter, is of order one
L = pit diameter
$\tilde{h}_{pit}$ = Fourier transform of the initial pit shape

Appendix H : Input parameters and results Twente model

Input parameters

Input parameter	Standard value	Unit
Physical parameters:		
- Coriolis force (f)	0.83[a]	-
- Friction parameter (r)	0.6[b]	-
- Transport exponent (b)	3[a]	-
- Gravity parameter (λ)	0.0084[a]	-
Basic state:		
- M2-parameter for x-direction	1.0[c]	-
- Tide eccentricity ($\in$)		-
- Residual current (u_{res})		m/s
- Residual current (v_{res})		m/s
- M4-amplitude (μ_u)		m
- M4-amplitude (μ_v)		m
- M4-phase (φ_u)		degrees
- M4-phase (φ_v)		degrees
Initial profile:		
- Initial profile (Ip);	3/4	
• 0 = no pit		-
• 1 = vertical pit		-
• 2 = slope pit		-
• 3 = gaussian pit		-
• 4 = ellips		-
• 5 = uniform		-
- Initial profile length scale (L_{ip})		-
- Initial profile second length scale (L_{iq})		-
- Initial profile angle (L_{ia})		degrees

Table H.1: Input parameters Twente model
[a] *after Roos & Hulscher (2003)*
[b] *after Roos et al. (2001)*
[c] *after Kustzuidmodel (2003)*

Description	Scenario
Influence of Coriolis force	1-2
Influence of M_4- tide	3
Influence of residual current (M_0)	4-5
Different shapes of the pit:	6 (L = 2xB) 7 (L = 4xB)
Pit (L=2xB) under different angles	8-12

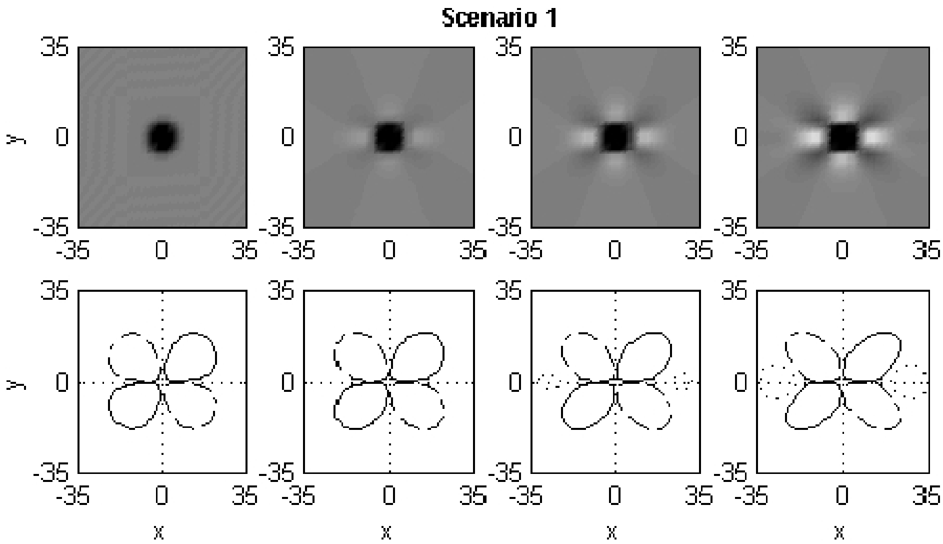
Table H.2: Scenarios Twente model

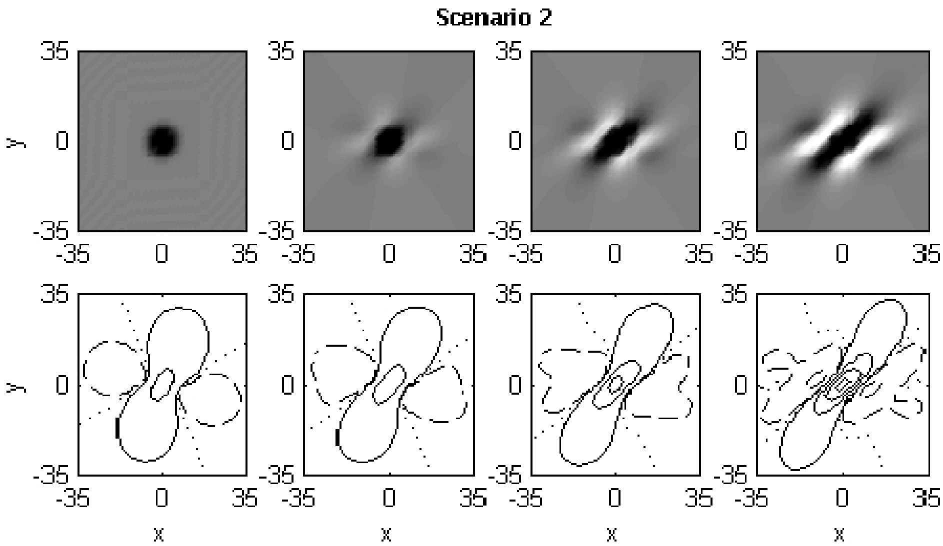
	Physical parameters				Basic state					Initial profile			
Input parameter	f	r	b	λ	M_2	$\in$	u_{res}	μ_u	φ_u	Ip	L_{ip}	L_{iq}	L_{ia}
Scenario 1	0	0.6	3	0.0084	1.0	0	0	0	0	3	1.199	1.199	0
Scenario 2	0.83	0.6	3	0.0084	1.0	0	0	0	0	3	1.199	1.199	0
Scenario 3	0.83	0.6	3	0.0084	1.0	0	0	0.13[a]	120[a]	3	1.199	1.199	0
Scenario 4	0.83	0.6	3	0.0084	1.0	0	0.1	0.13[a]	120[a]	3	1.199	1.199	0
Scenario 5	0.83	0.6	3	0.0084	1.0	0	0.05	0.13[a]	120[a]	3	1.199	1.199	0
Scenario 6	0.83	0.6	3	0.0084	1.0	0	0	0	0	4	1.696	0.848	0
Scenario 7	0.83	0.6	3	0.0084	1.0	0	0	0	0	4	2.399	0.600	0
Scenario 8	0.83	0.6	3	0.0084	1.0	0	0	0	0	3	1.696	0.848	30
Scenario 9	0.83	0.6	3	0.0084	1.0	0	0	0	0	3	1.696	0.848	60
Scenario 10	0.83	0.6	3	0.0084	1.0	0	0	0	0	3	1.696	0.848	90
Scenario 11	0.83	0.6	3	0.0084	1.0	0	0	0	0	3	1.696	0.848	-30
Scenario 12	0.83	0.6	3	0.0084	1.0	0	0	0	0	3	1.696	0.848	-60

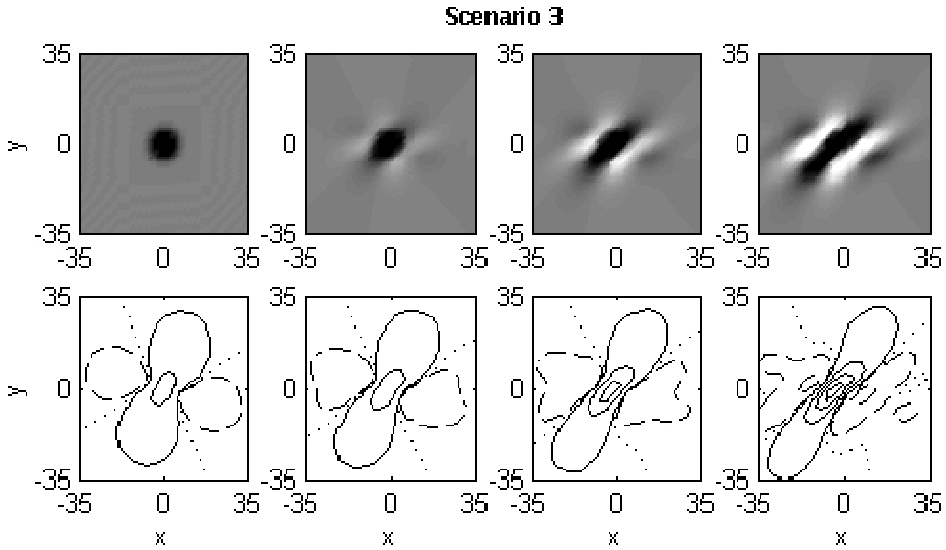
Table H.3: Input parameters scenarios Twente model
[a] at Vlissingen, after Rijkswaterstaat (2003c)

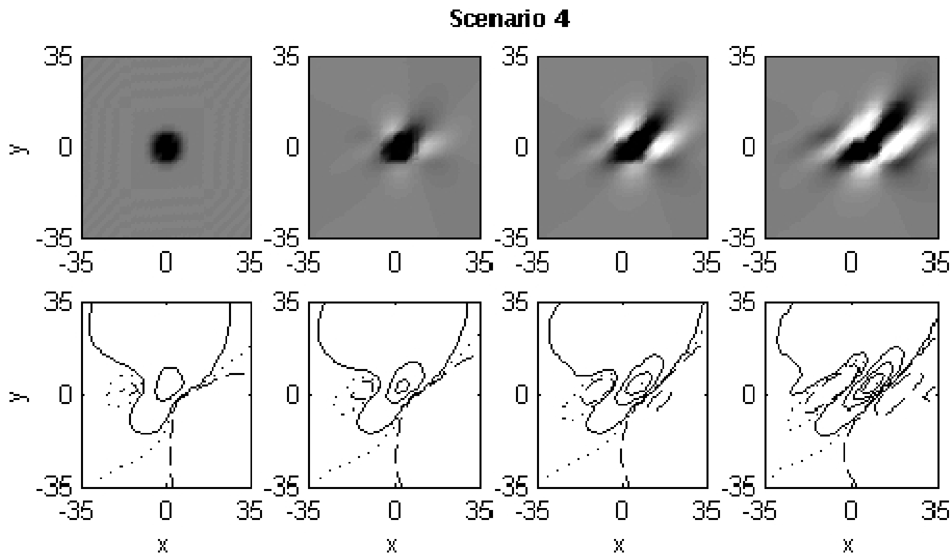
Scenario plots

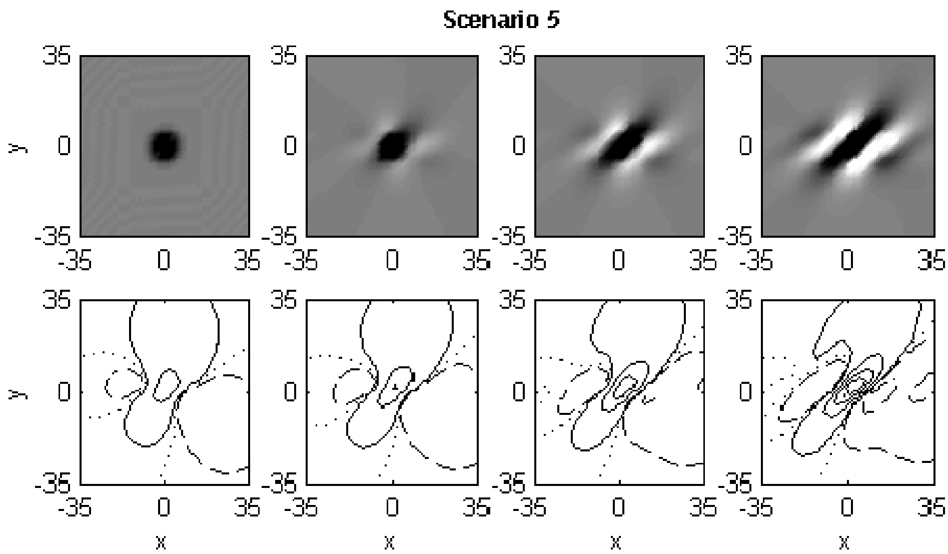
In the top row of each scenario plot the bed evolution is shown. Troughs are black, crests white and undisturbed seabed grey. In the bottom rows, the residual currents are shown. Solid streamlines correspond to anticlockwise rotation, whereas dashed ones correspond to clockwise rotation. The evolution times, which are given from left to right are τ=0, τ=1, τ=2, and τ=3. The distances on the x- and y-axis are given in km.


Scenario 1
35
0
-35
-35
0
35
y
x

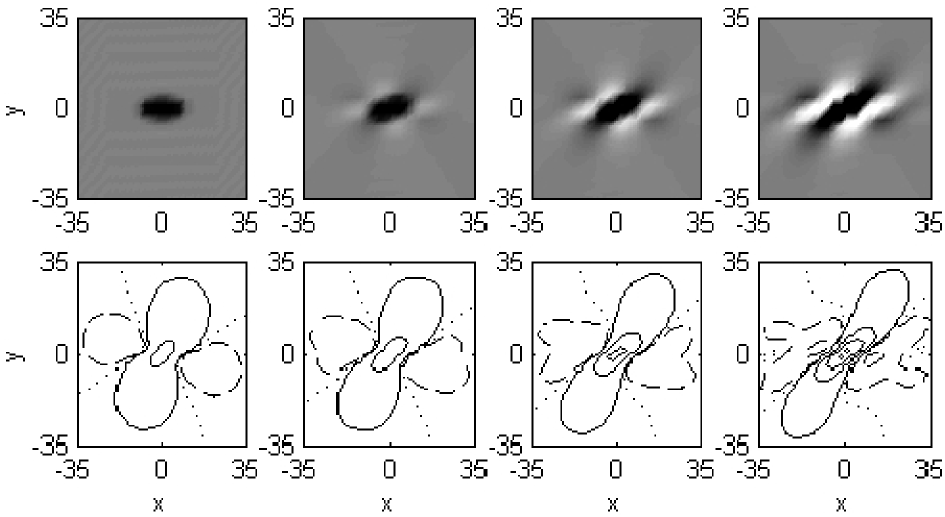

Scenario 2
35
0
-35
-35
0
35
y
x


Scenario 3
35
0
-35
-35
0
35
y
x

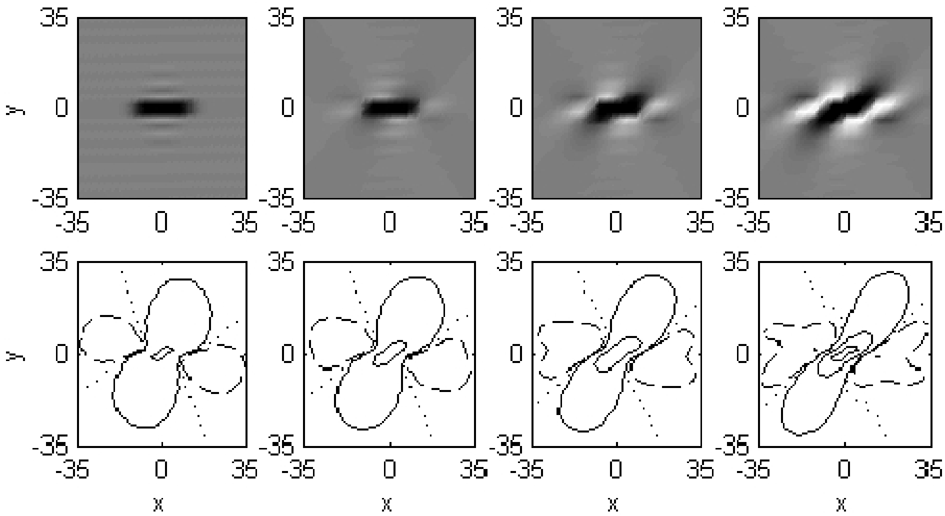

Scenario 4
35
0
-35
-35
0
35
y
x

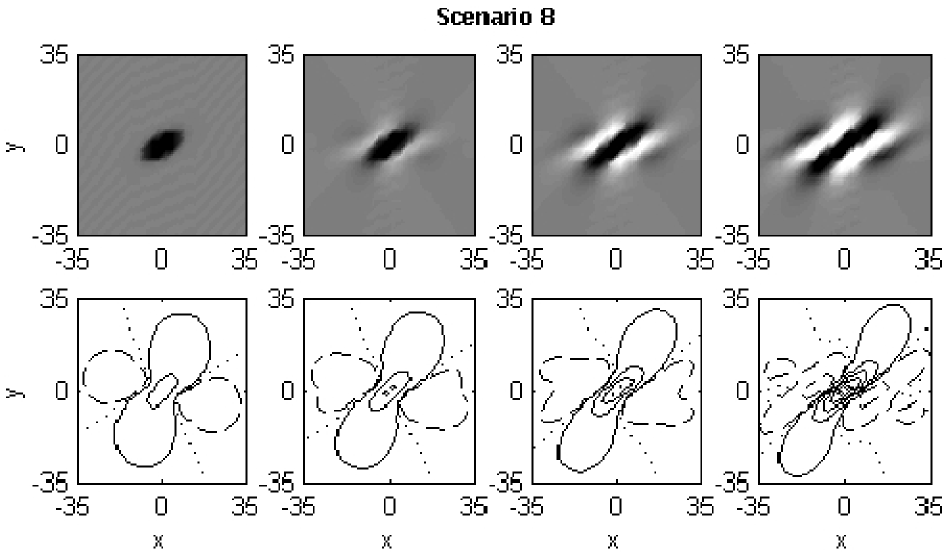

Scenario 5
35
0
-35
-35
0
35
y
x

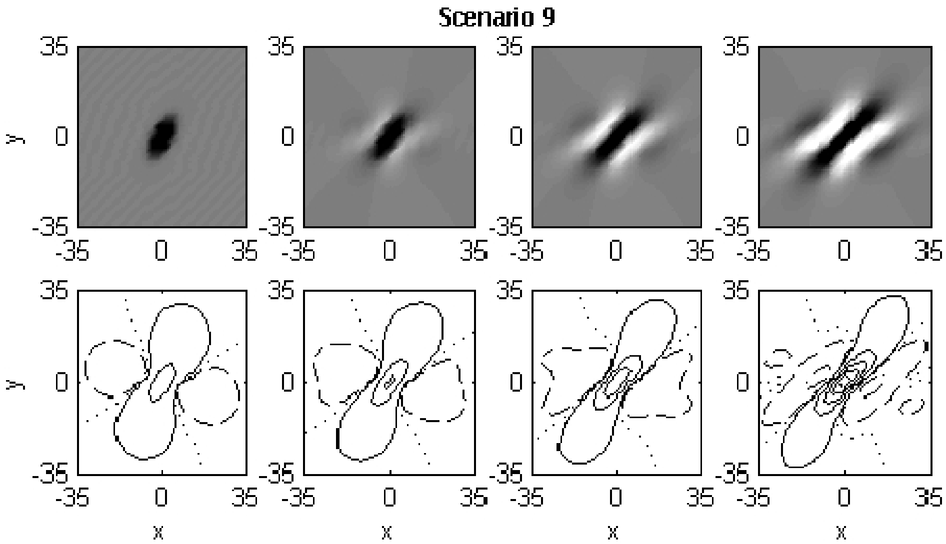
Scenario 6

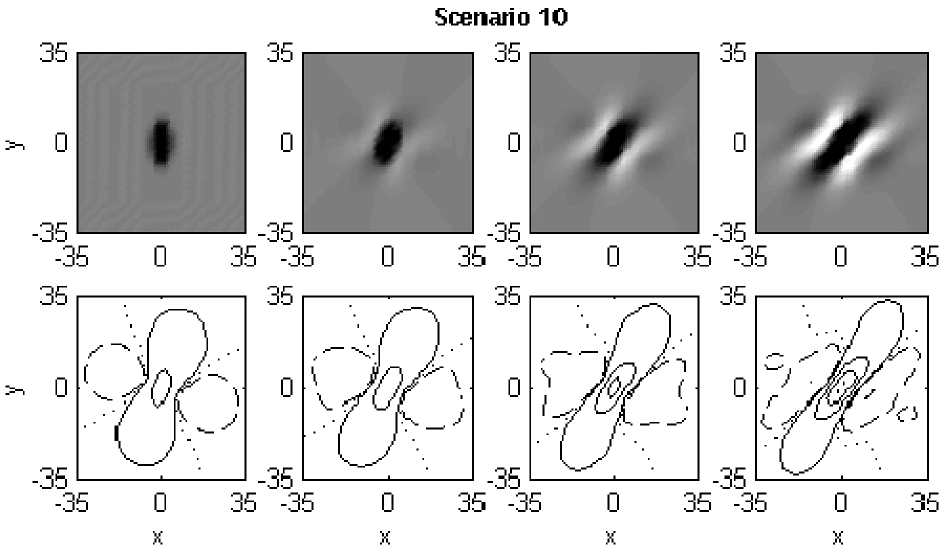


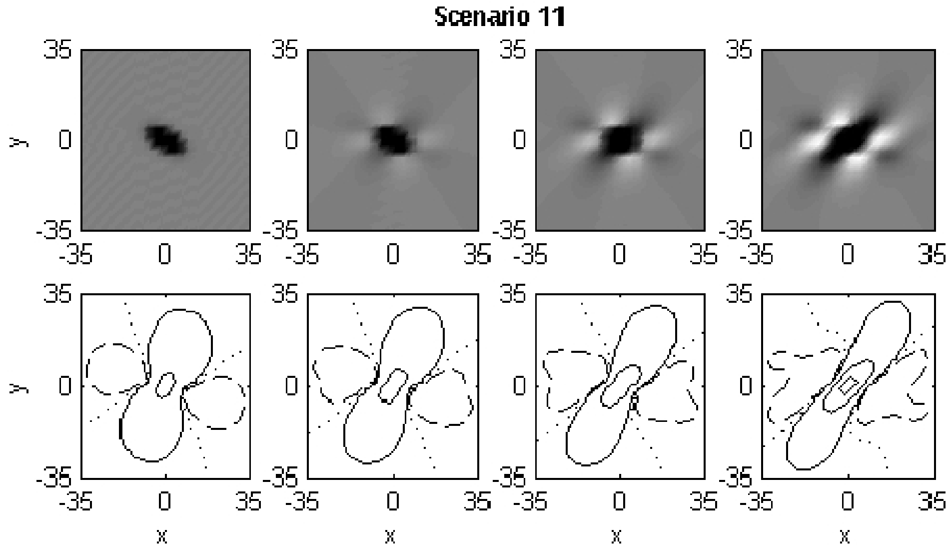
Scenario 7

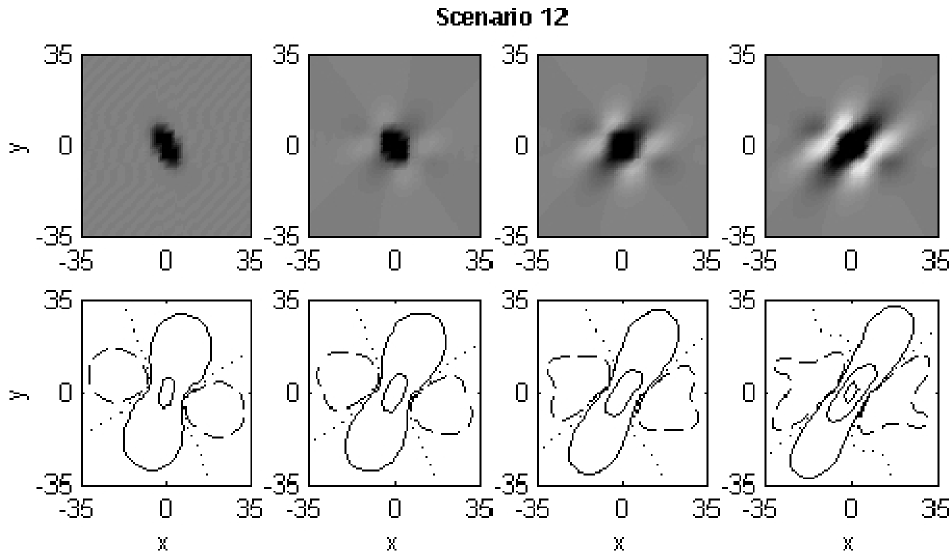



Scenario 8
y
x
35
0
-35


Scenario 9
y
x
35
0
-35


Scenario 10
y
x
35
0
-35


Scenario 11
35
0
-35
-35
0
35
y
x


Scenario 12
35
0
-35
-35
0
35
y
x

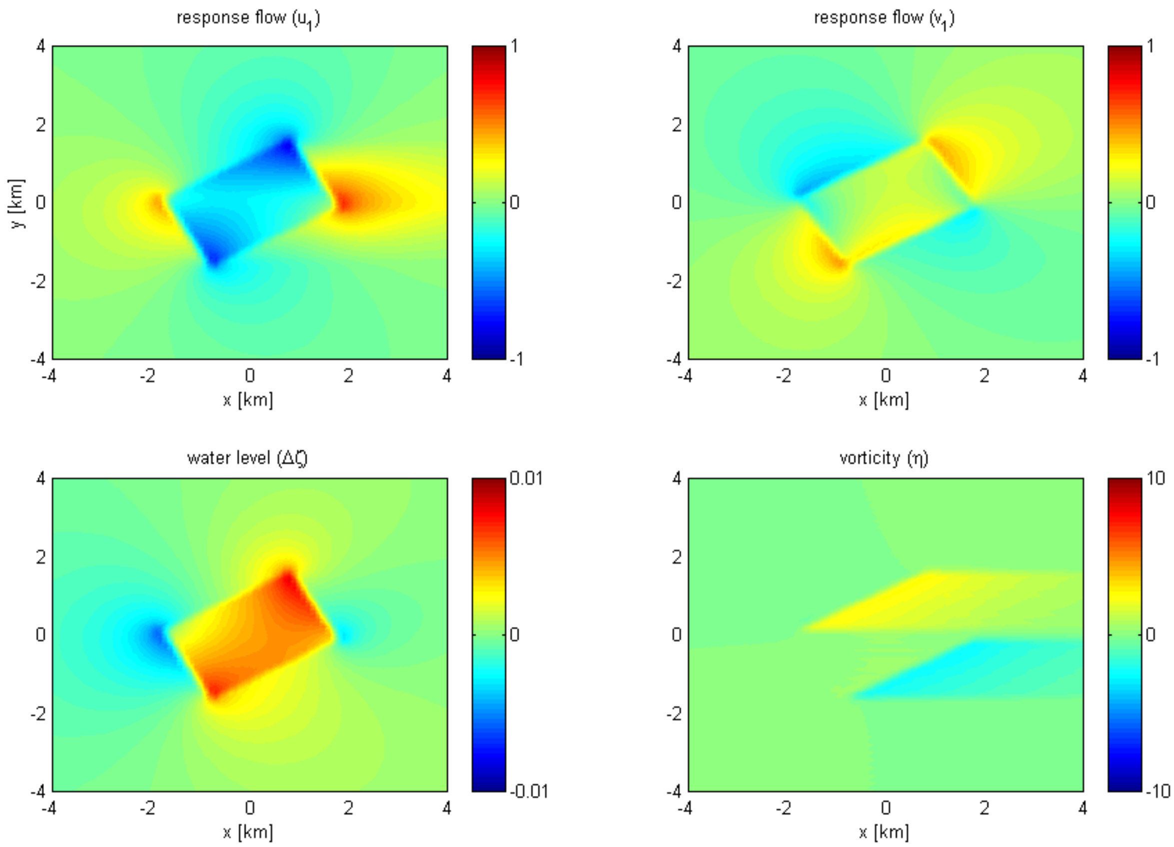


Figure H.1: Hydrodynamic results (Hommes, 2004)
u_{res} = 1 m/s; L = 3 km; B = 2 km; θ = 30°

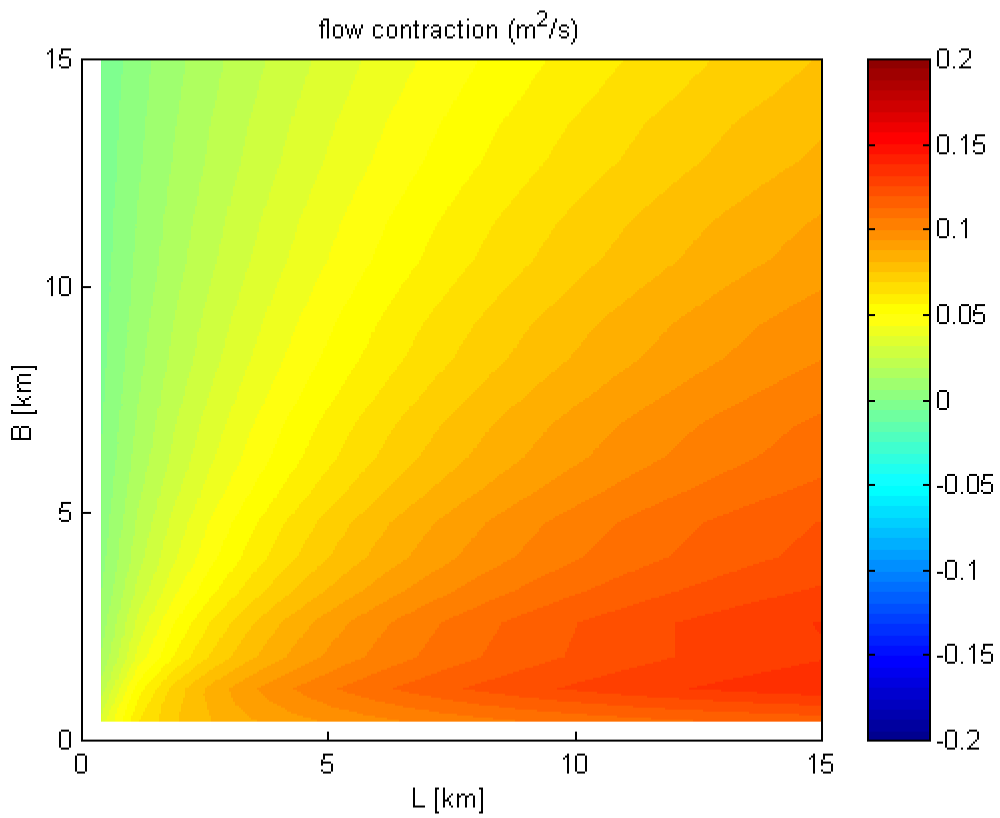


Figure H.2: Flow contraction of a pit (Hommes, 2004)

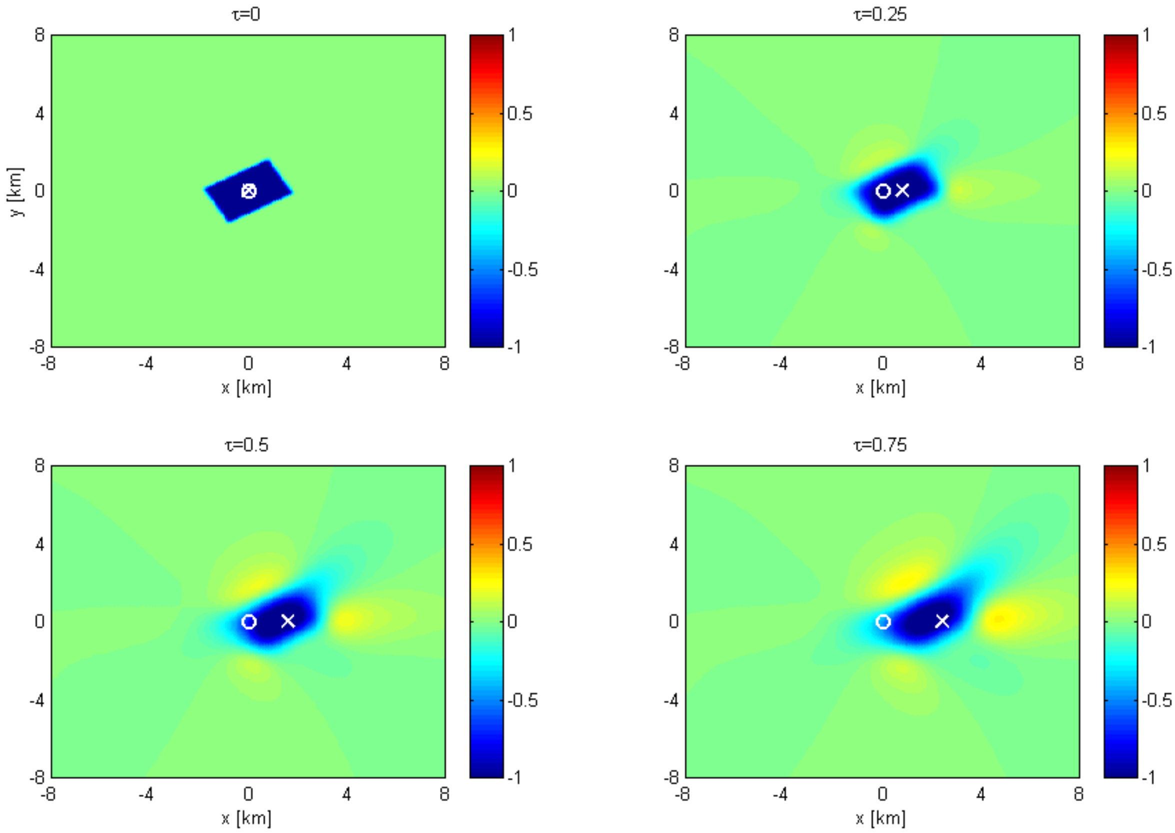


Figure H.3: Pit migration (Hommes, 2004)
u_{res} = 0.1m/s; M_2 = 1 m/s; L = 3km; B = 2km; $\theta = 30^o$

Appendix I : eQwin model

On the horizontal axis in Figure I.1 and Figure I.2 the cross-shore position of the ridge (x) is scaled with the wavelength of the ridge (L) and on the vertical axis (z) the water depth (H) is scaled with the average water depth (H_0 = 30 m). The upper plots in Figure I.1 and Figure I.2 show the original equilibrium profile (red dotted line); before sand extraction and the profile direct after sand extraction (blue line). The blue line in the bottom plots in Figure I.1 and Figure I.2 shows the difference between the two lines in the upper plots; the extraction pit itself.

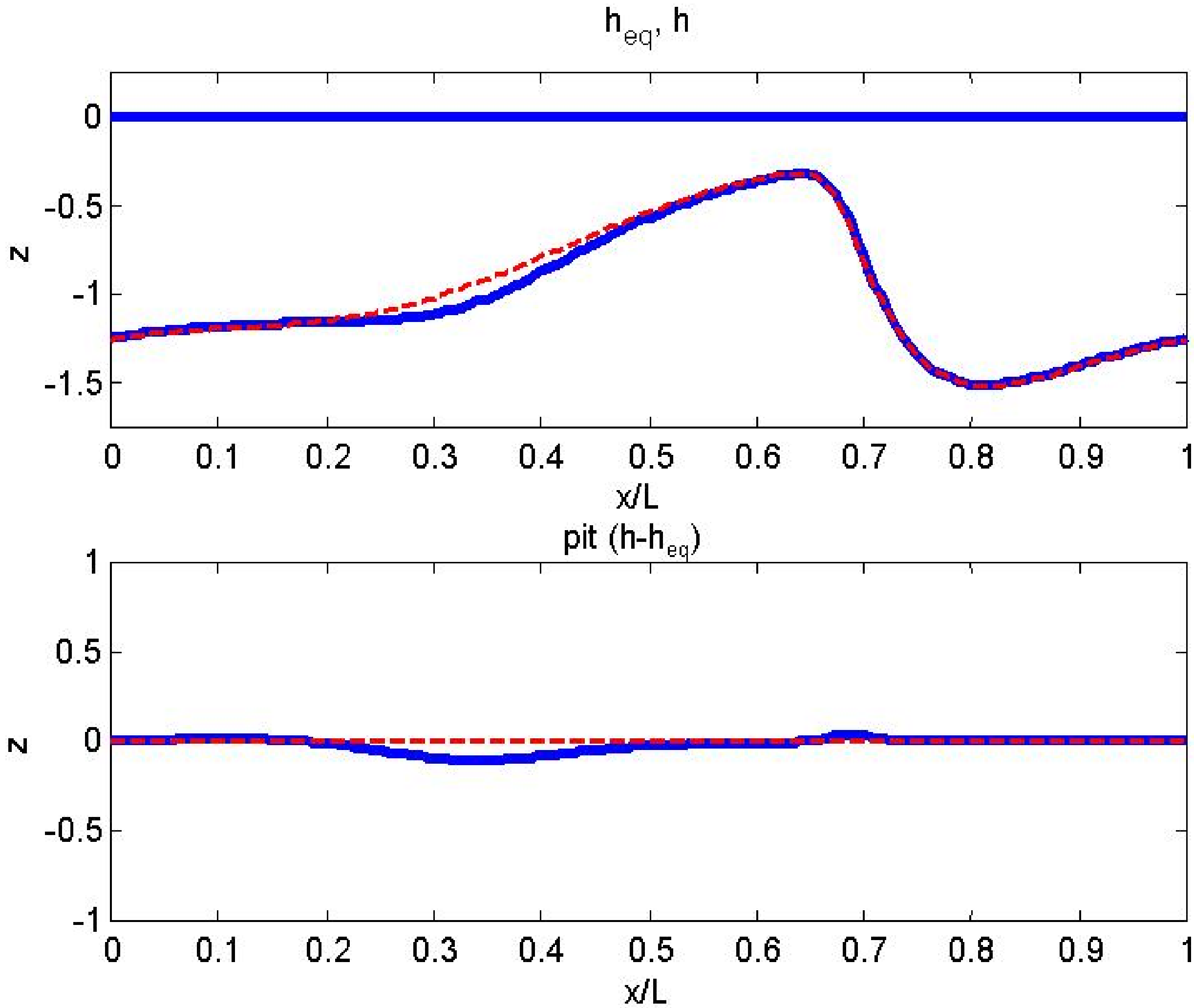


Figure I.1: Wide pit on the flank of an asymmetric migrating ridge (Roos, UT, 2003)

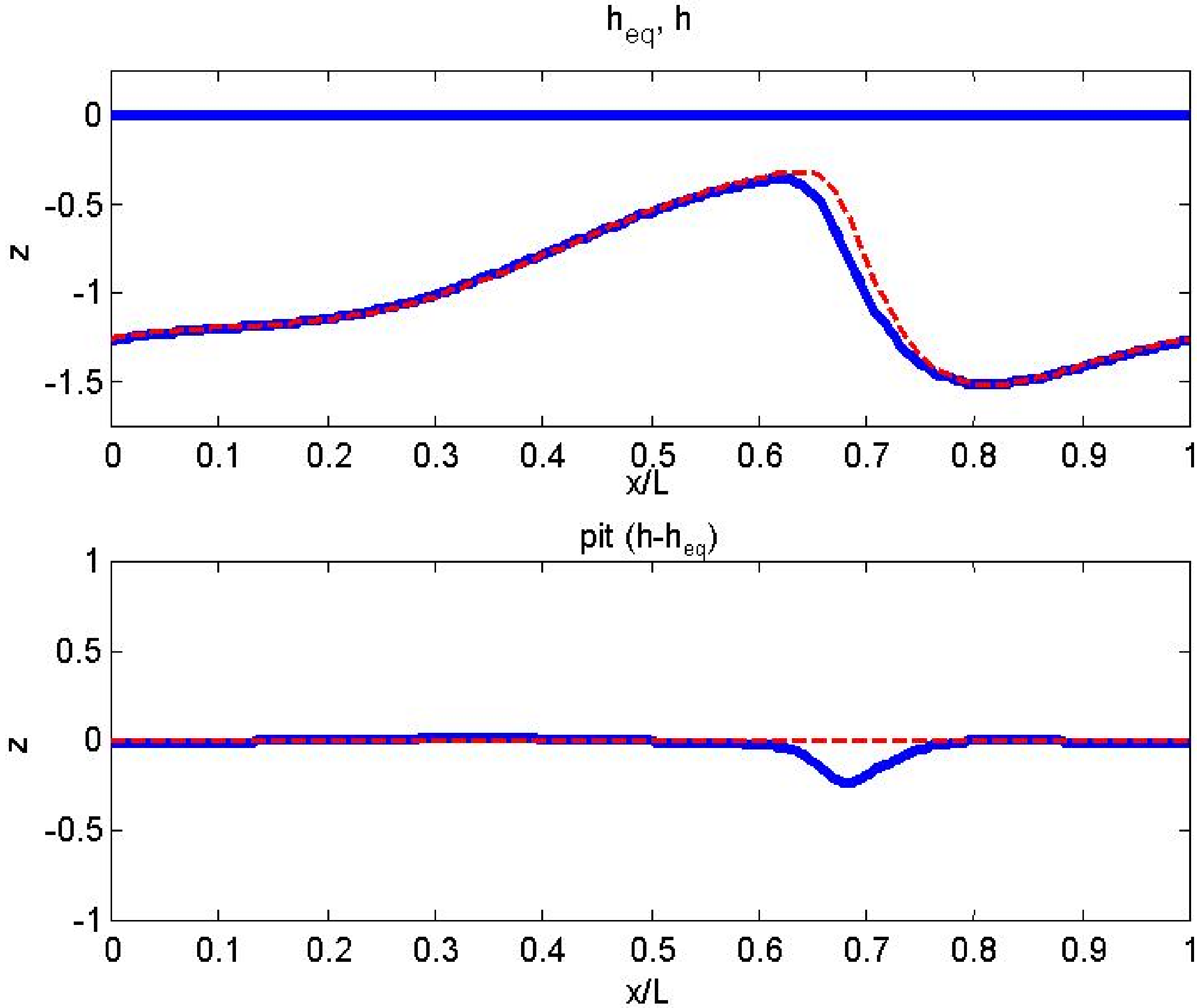


Figure I.2: Deep pit on the crest of an asymmetric migrating ridge (Roos, UT, 2003)

Appendix J : Model equations Amplitude-evolution model

Landau equation (Knaapen & Hulscher, 2002):

$$\frac{\partial A}{\partial \hat{t}} = A - \hat{\alpha}\left|A\right|^2 A \tag{J.1}$$

$$\hat{t} = \frac{t}{\alpha_0 T} \tag{J.2}$$

$$\hat{\alpha} = \frac{\alpha_1}{\alpha_0} \tag{J.3}$$

$$h(x,t) = A(\tau)\cos kx + h.o.t. \tag{J.4}$$

Maximum amplitude (Knaapen & Hulscher, 2002):

$$A(t=\infty) = \sqrt{\frac{\alpha_0}{\alpha_1}} \rightarrow \alpha_1 = \frac{\alpha_0}{A^2} \tag{J.5}$$

A = amplitude of the bed form = h(x,t)
$\hat{t}$ = morphological timescale
α_0 = linear grow velocity
α_1 = model parameter
t = real time
T = time parameter defining the morphological timescale
k = wave number of the perturbation
h.o.t. = higher order terms, representing asymmetry

Appendix K : Input and Results Amplitude-evolution model

Input parameter	Unit
Amplitude after dredging (A_0)	m
Linear grow velocity (α_0)	s^{-1}
Parameter α_1	$s^{-1}m^{-2}$
Long timescale (T)	years
Time step (dt)	years
Output time (time)	years

Table K.1: Input parameters Amplitude-evolution model

Description scenario	**Scenario numbers**
Different amplitudes	1-3
Sensitivity to α (and τ)	4-6

Table K.2: Scenarios Amplitude-evolution model

Input parameter	A_{before}	A_0	α_0	α_1	T	dt	time
Scenario 1	7.5	6.5	0.37[a]	0.0066	70 [a]	1/12	linspace (0, 600, 1000)
Scenario 2	7.5	5	0.37[a]	0.0066	70 [a]	1/12	linspace (0, 600, 1000)
Scenario 3	7.5	3	0.37[a]	0.0066	70 [a]	1/12	linspace (0, 600, 1000)
Scenario 4	7.5	5	0.185	0.0033	70 [a]	1/12	linspace (0, 1000, 2000)
Scenario 5	7.5	5	0.37[a]	0.0066	70 [a]	1/12	linspace (0, 1000, 2000)
Scenario 6	7.5	5	0.74	0.0132	70 [a]	1/12	linspace (0, 1000, 2000)

Table K.3: Input parameters scenarios Amplitude-evolution model
[a] after Hulscher (1996)

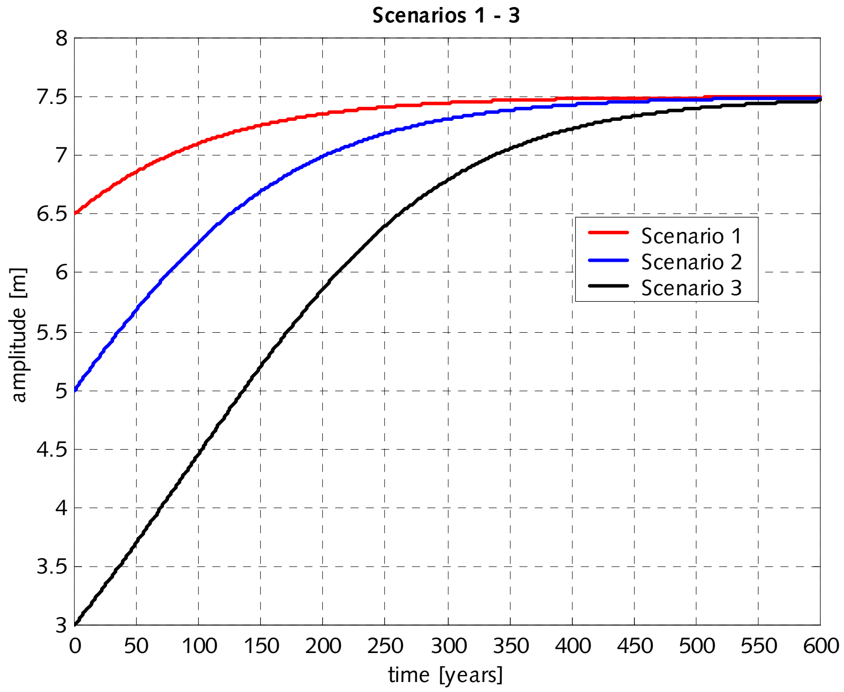


Figure K.1: Results scenario 1, 2 and 3

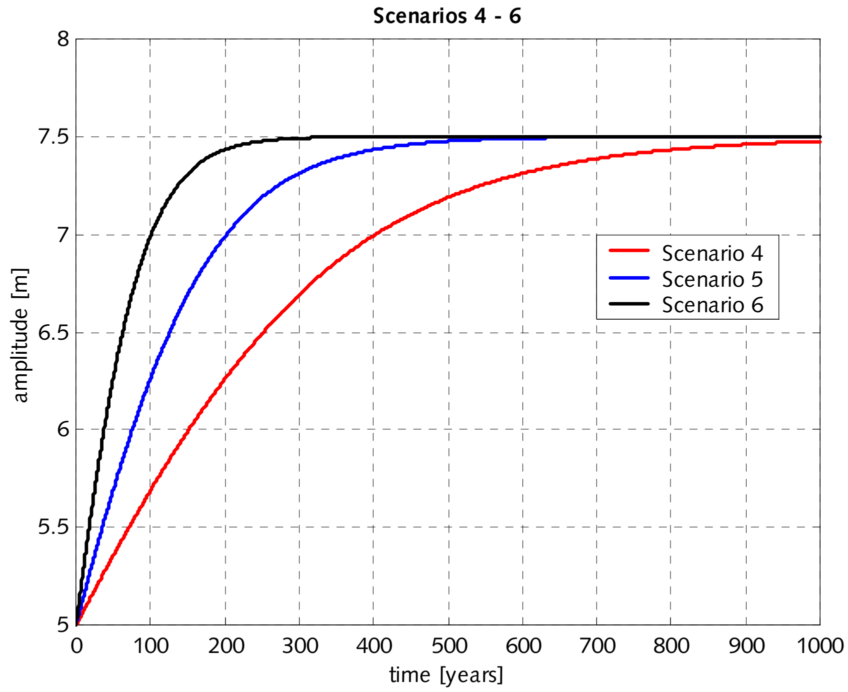


Figure K.2: Results scenario 4, 5 and 6

Appendix L : Model equations Utrecht model

Dimensional momentum equation (Walgreen et al., 2002):

$$\frac{\partial \vec{v}}{\partial t} + \left(\vec{v} \cdot \vec{\nabla}\right)\vec{v} + \vec{f} \times \vec{v} = -g\vec{\nabla} z_s - \frac{gD}{2\rho}\vec{\nabla}\rho + \frac{\vec{\tau}_s - \vec{\tau}_b}{\rho D} \quad \text{(L.1)}$$

Mass conservation equation (Walgreen et al., 2002):

$$\frac{\partial D}{\partial t} + \vec{\nabla} \cdot \left[D\vec{v}\right] = 0 \quad \text{(L.2)}$$

$\vec{v}$ = depth-averaged velocity
D = local water depth = z_s - z_b
z_s = free surface elavation
z_b = bottom depth = -H + h
H = undisturbed water depth
h = perturbations due to the presence of undulations on the bottom
$\vec{\nabla}\rho$ = constant horizontal density gradient
$\vec{\tau}_b$ = bed shear stress = $\rho r \vec{v}$
r = friction parameter
τ_s = wind-stress

Sediment flux (Walgreen et al., 2002):

$$(1-p)\frac{\partial h}{\partial t} + \vec{\nabla} \cdot \left\langle q_b + q_s \right\rangle = 0 \quad \text{(L.3)}$$

$\vec{q}_b$ = volumetric transport per unit width of sediment as bed load
$\vec{q}_s$ = suspended sediment transport
p = porosity of the bed
<…> = average over a wave period

Bed load transport (Bailard, 1981 in: Walgreen et al., 2002):

$$\left\langle \vec{q}_b \right\rangle = v_b \left[\left\langle \left|\vec{u}\right|^2 \vec{u} \right\rangle - \lambda_b \left\langle \left|\vec{u}\right|^3 \right\rangle \vec{\nabla} z_b \right] \quad \text{(L.4)}$$

Suspended load transport (Bailard, 1981 in: Walgreen et al., 2002):

$$\left\langle \vec{q}_s \right\rangle = v_s \left[\left\langle \left|\vec{u}\right|^3 \vec{u} \right\rangle - \lambda_s \left\langle \left|\vec{u}\right|^5 \right\rangle \vec{\nabla} z_b \right] \quad \text{(L.5)}$$

λ_b = bed slope parameter bed load transport
λ_s = bed slope parameter suspended load transport
v_b, v_s = sediment properties coefficients
$\vec{u}$ = depth-averaged velocity, consisting of a wave-averaged part $\vec{v}$ and a wave part $\vec{u}_w$

Basic state velocity (Walgreen et al., 2002):

$$V(x,t) = V_0(x) + V_{tide}(x,t) \quad \text{(L.6)}$$

$$V_0(x) = \frac{1}{r}\left(\frac{\tau_{sy}}{\rho} - gs_0 H(x) - \frac{g}{2\rho}\frac{\partial \rho}{\partial y} H^2(x)\right) \quad \text{(L.7)}$$

$$V_{tide}(x,t) = V_{M_2}(x)\sin\left(\sigma t + \varphi_{M_2}(x)\right) + V_{M_4}(x)\sin\left(2\sigma t + \varphi_{M_4}(x) + \theta\right) \quad \text{(L.8)}$$

$$V_{M_2}(x) = \frac{gs_1 H}{\sqrt{(\sigma H)^2 + r^2}} \quad \text{(L.9)}$$

$$\varphi_{M_2}(x) = \arctan\left(\frac{r}{\sigma H}\right) \tag{L.10}$$

$$V_{M_4}(x) = \frac{g s_2 H}{\sqrt{(2\sigma H)^2 + r^2}} \tag{L.11}$$

$$\varphi_{M_4}(x) = \arctan\left(\frac{r}{2\sigma H}\right) \tag{L.12}$$

σ = radian frequency of M_2 tide
s_0 = amplitude of sea surface elevation (steady component)
s_1 , s_2 = amplitude of sea surface elevation (oscillating components)
θ = phase between M_2 and M_4 sea surface gradient (constant)

Appendix M : Results Utrecht model

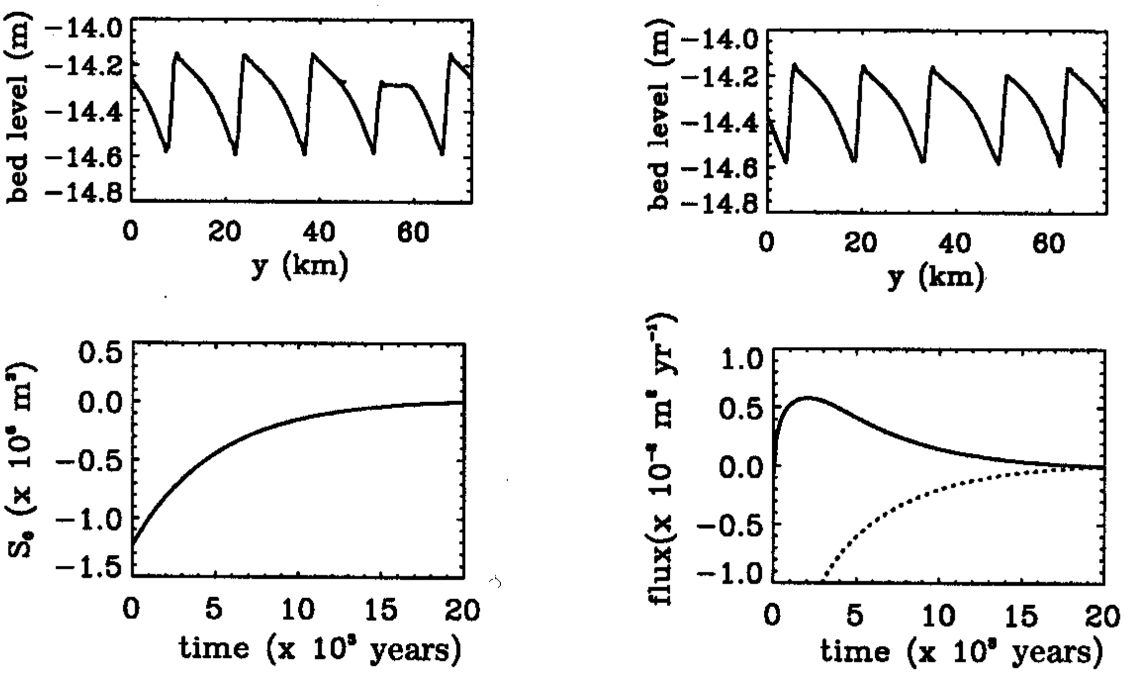


Figure M.1: *Top; Along-shelf transect of the bed level at x= 3 km (centre of the inner shelf), immediately after sand extraction (left) and after 1000 years (right). Bottom left; net sand volume S_0 stored in the inner shelf versus time Bottom right; net cross-shelf component of the sediment flux induced by the sand extraction at the transition line x = 0 between inner shelf and nearshore zone (solid line) and at the transition x = L_s between inner and outer shelf (dashed line) (De Swart & Calvete, 2003)*

Appendix N : PUTMOR project

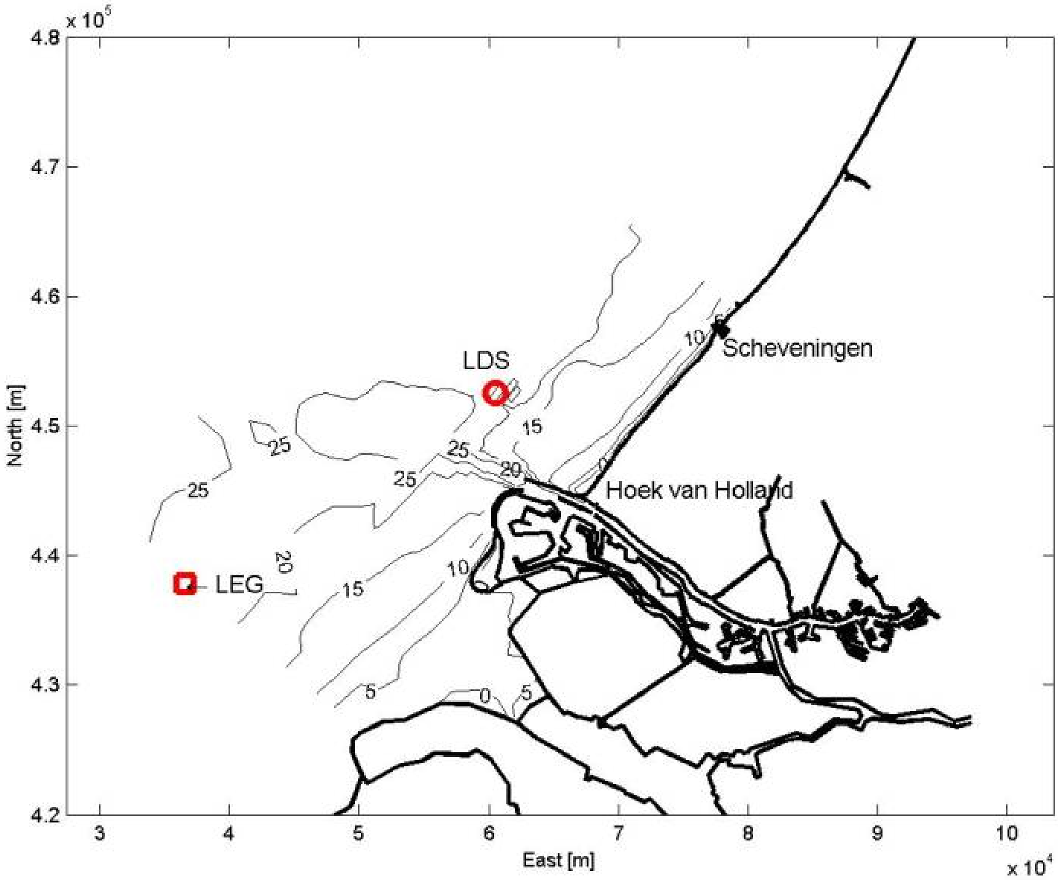


Figure N.1: Location of PUTMOR pit (LDS) and Wave station (LEG) (Hommes, 2004)

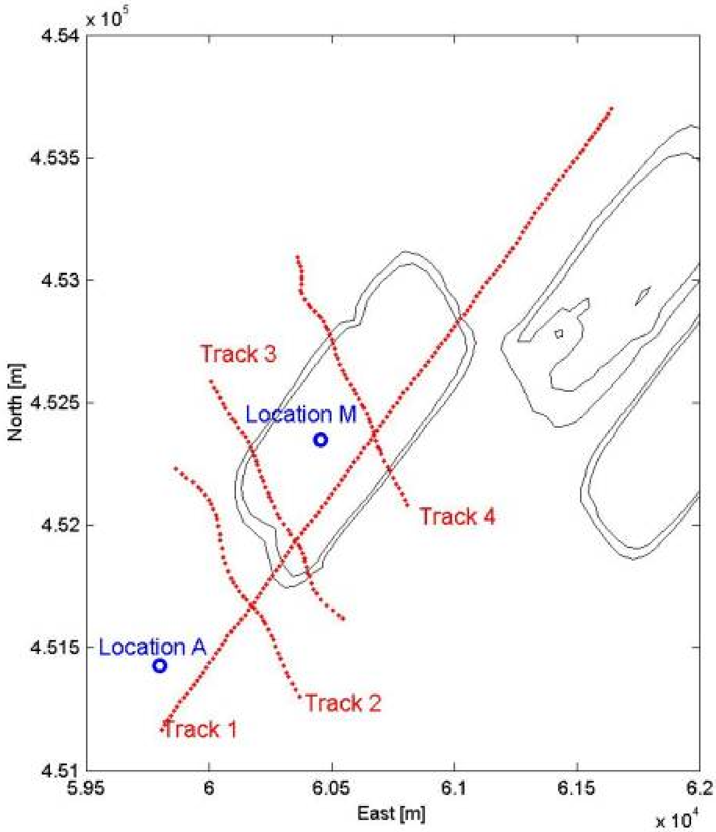


Figure N.2: Locations measurements (Hommes, 2004)

Appendix O : Results Delft3D

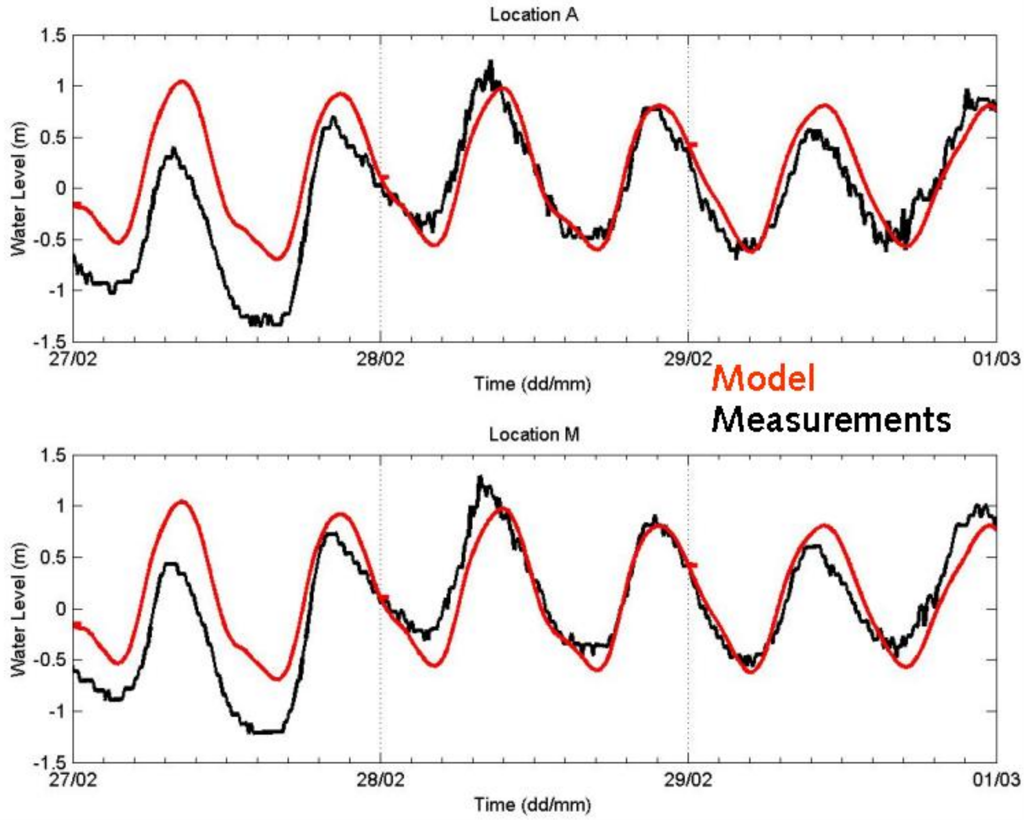


Figure O.1: Comparison of water levels (Hommes, 2004)

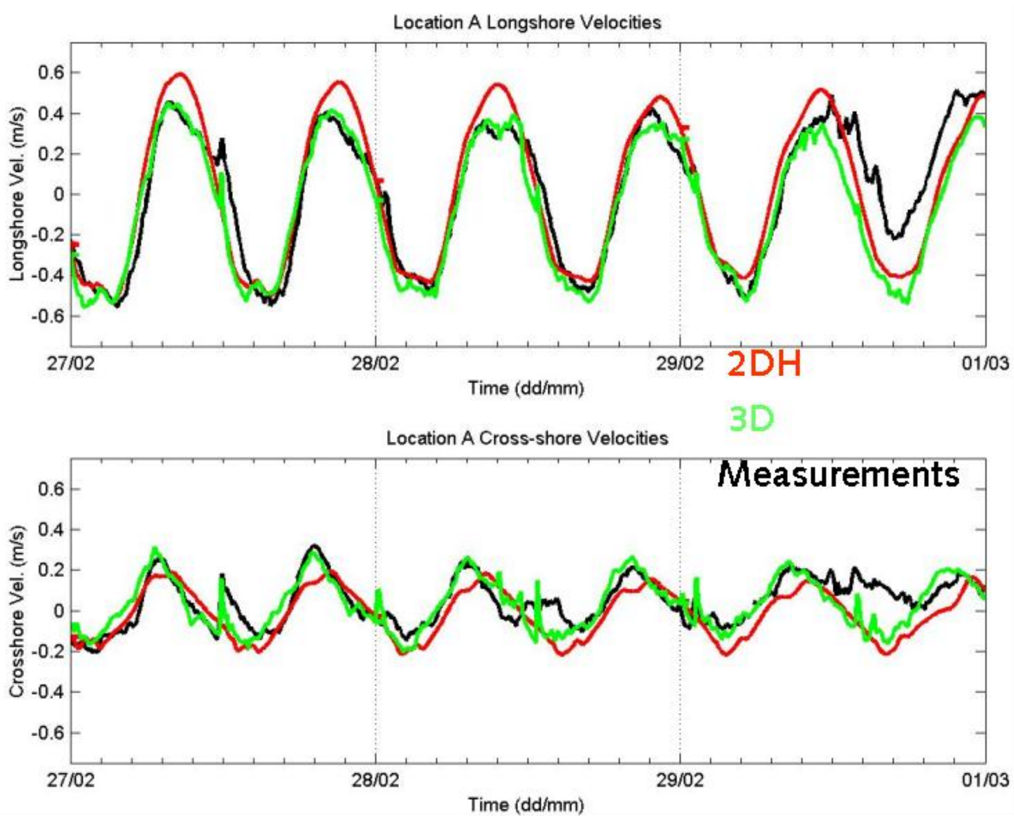


Figure O.2: Comparison of depth-averaged longshore and cross-shore velocities at location A (Hommes, 2004)

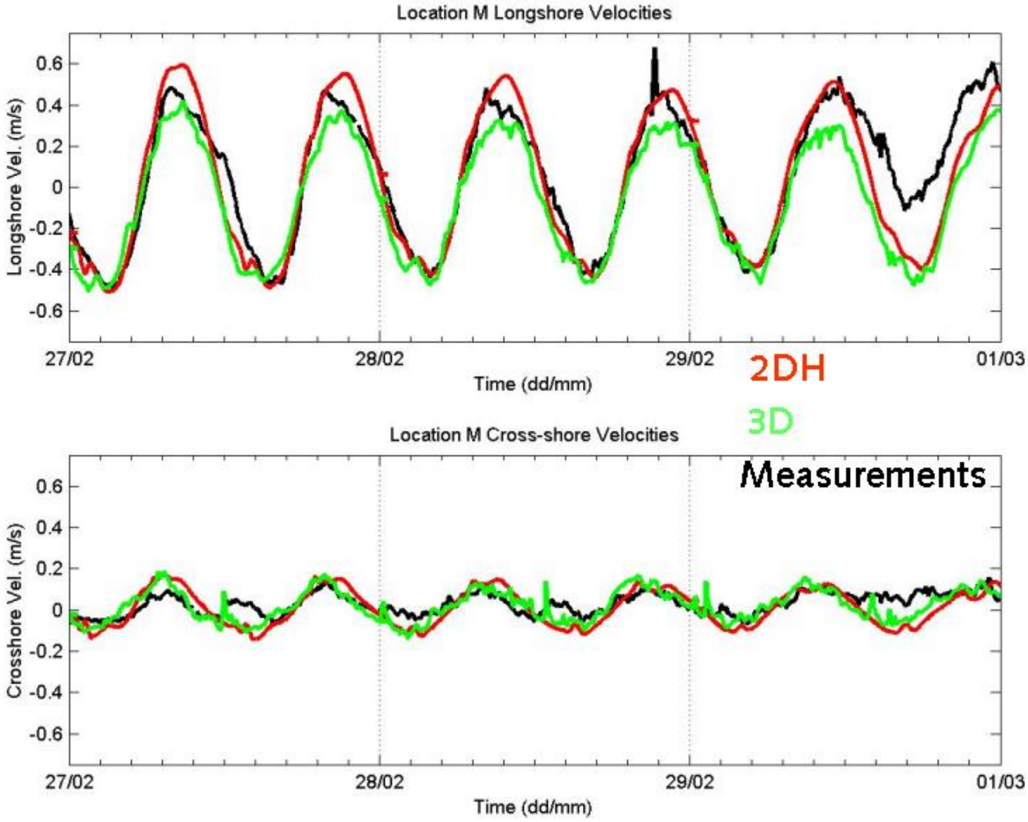


Figure O.3: Comparison of depth-averaged longshore and cross-shore velocities at location M (Hommes, 2004)

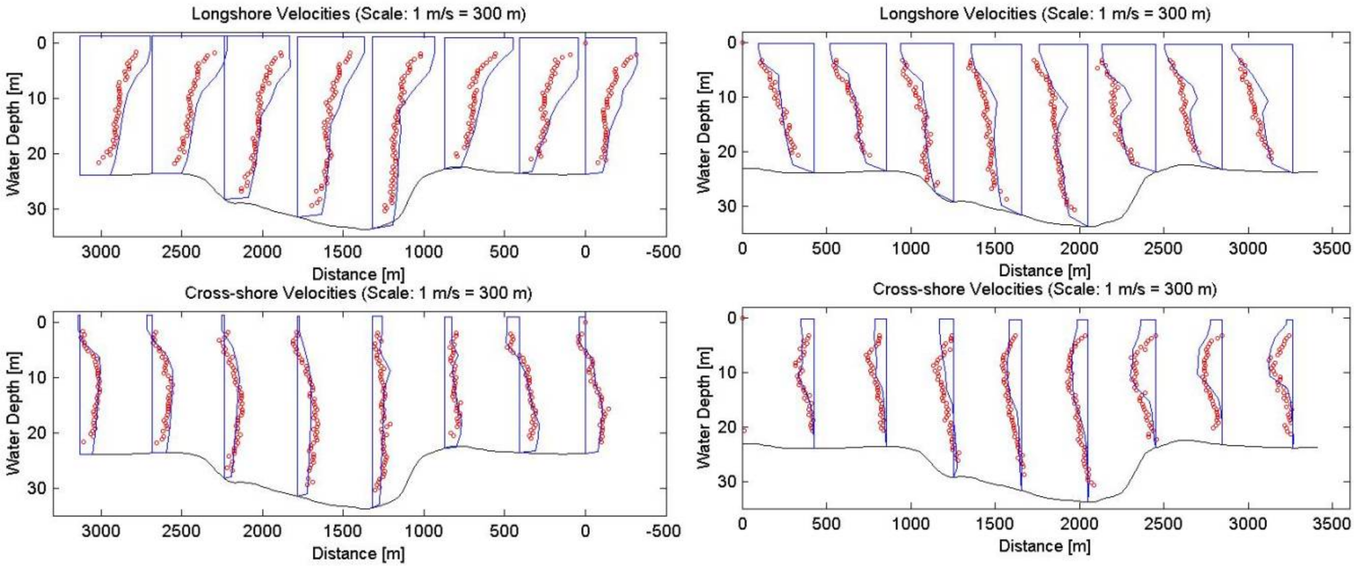


Figure O.4: Comparison of measured (circles) and calculated (solid) longshore (top) and cross-shore (bottom) velocity profiles at track 1 during maximum flood (left) and maximum ebb (right) (Hommes, 2004)

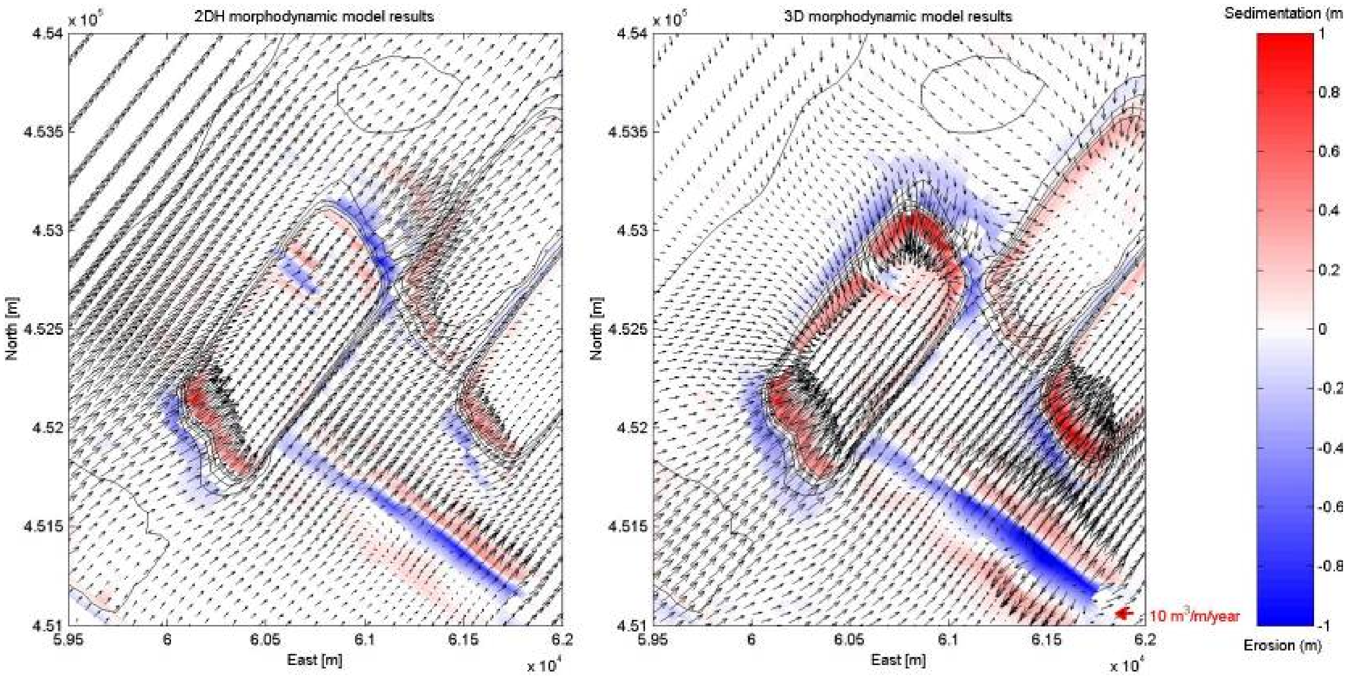


Figure O.5: Comparison of residual transports (left: 2DH; right: 3D) (Hommes, 2004)

Appendix P : Results SUTRENCH

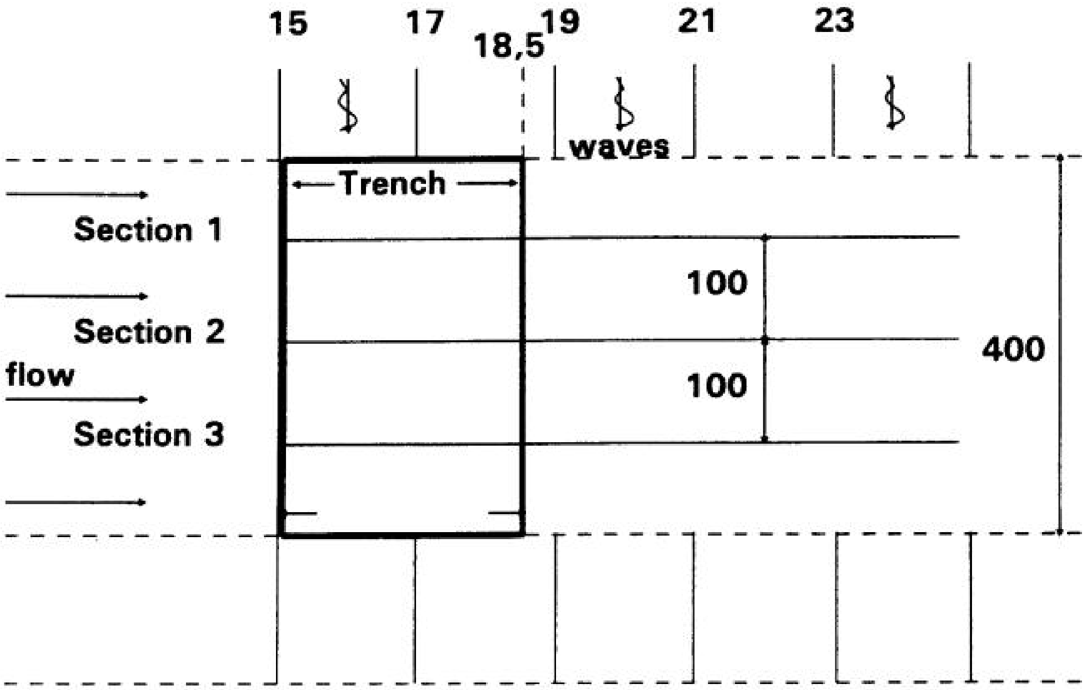


Figure P.1: Experimental set up (Walstra et al., 1999)

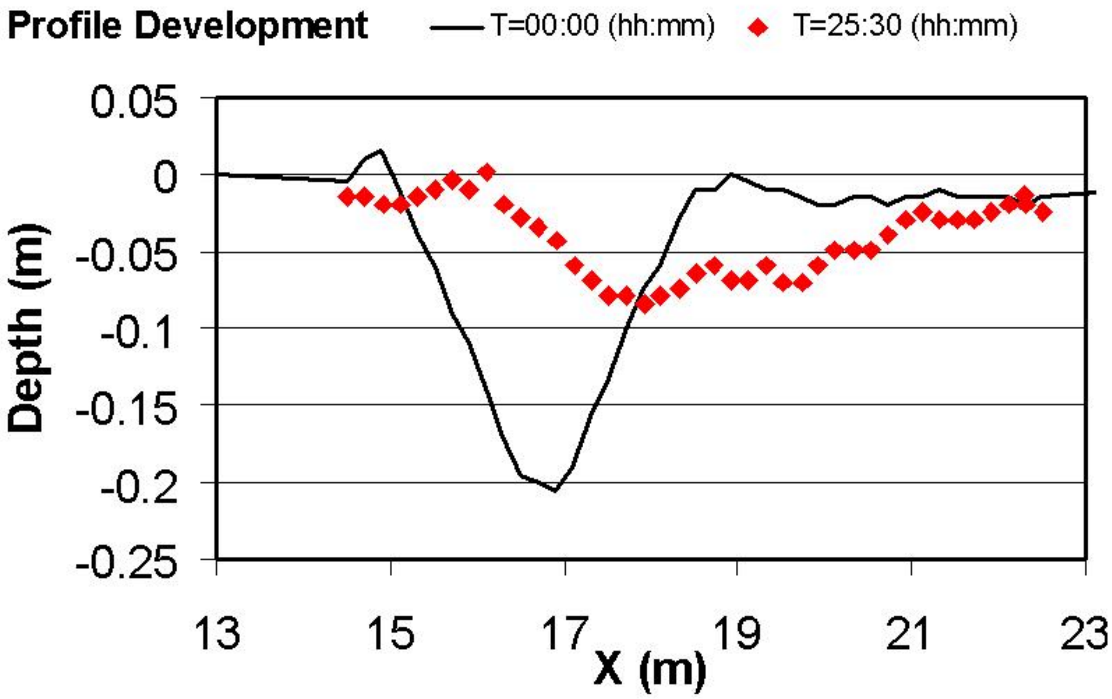


Figure P.2 :Results trench perpendicular to current and parallel to waves (Hommes, 2004)

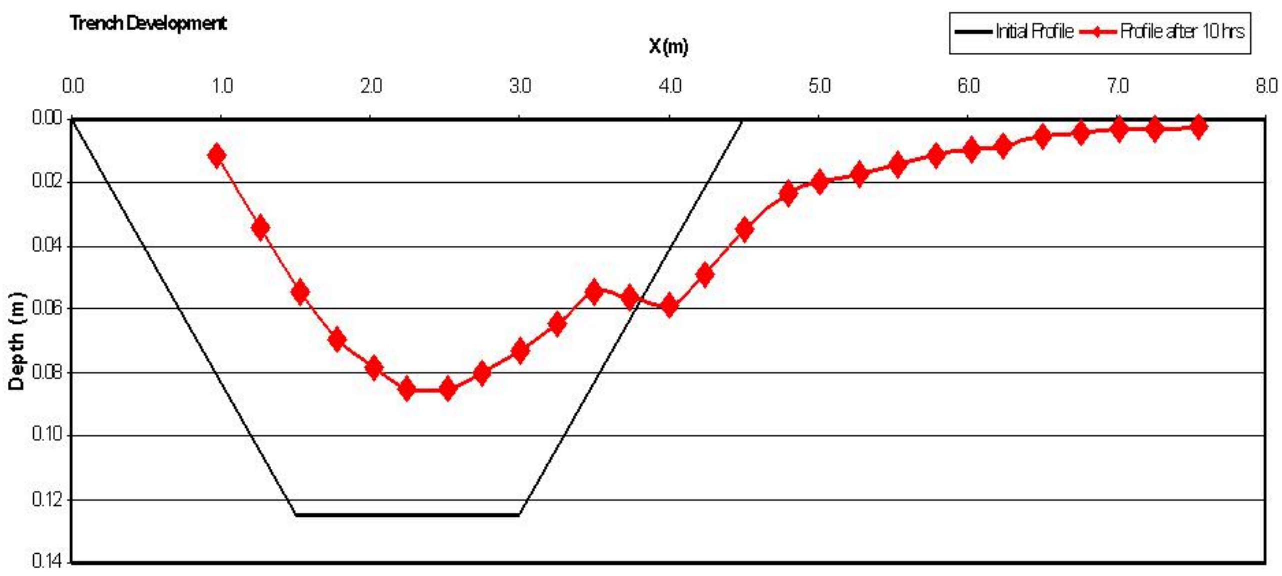


Figure P.3: Results trench perpendicular to current and waves (Hommes, 2004)

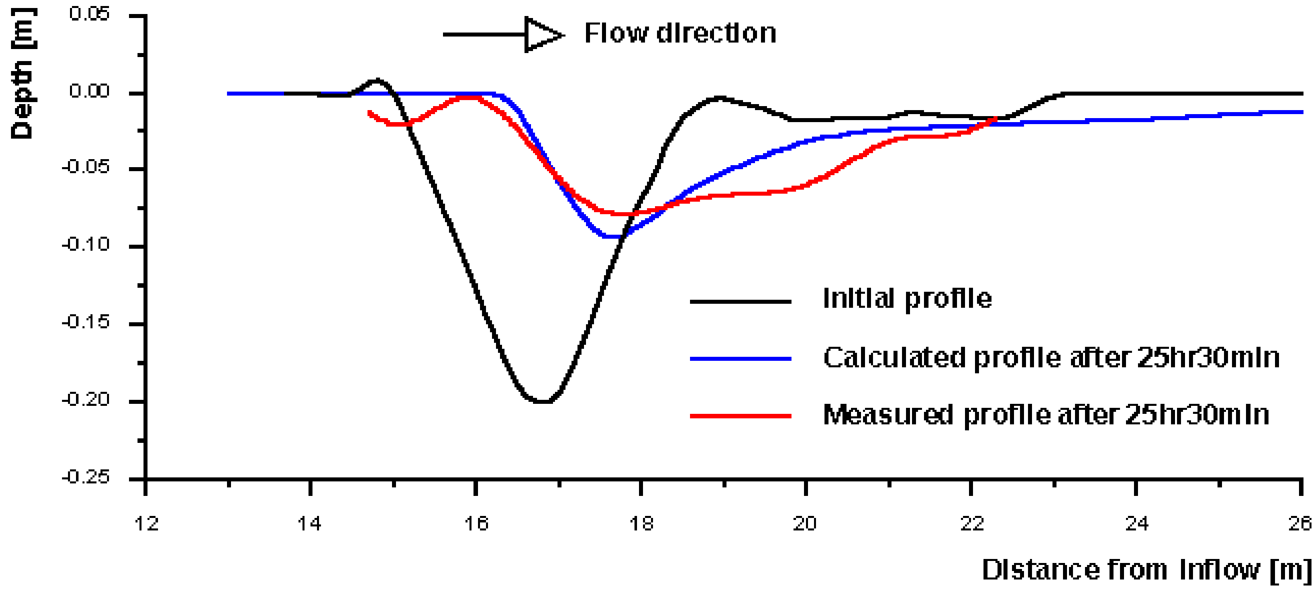


Figure P.4: Comparison of measured and calculated trench after 25hr30min (Website WL Delft Hydraulics, 2003)

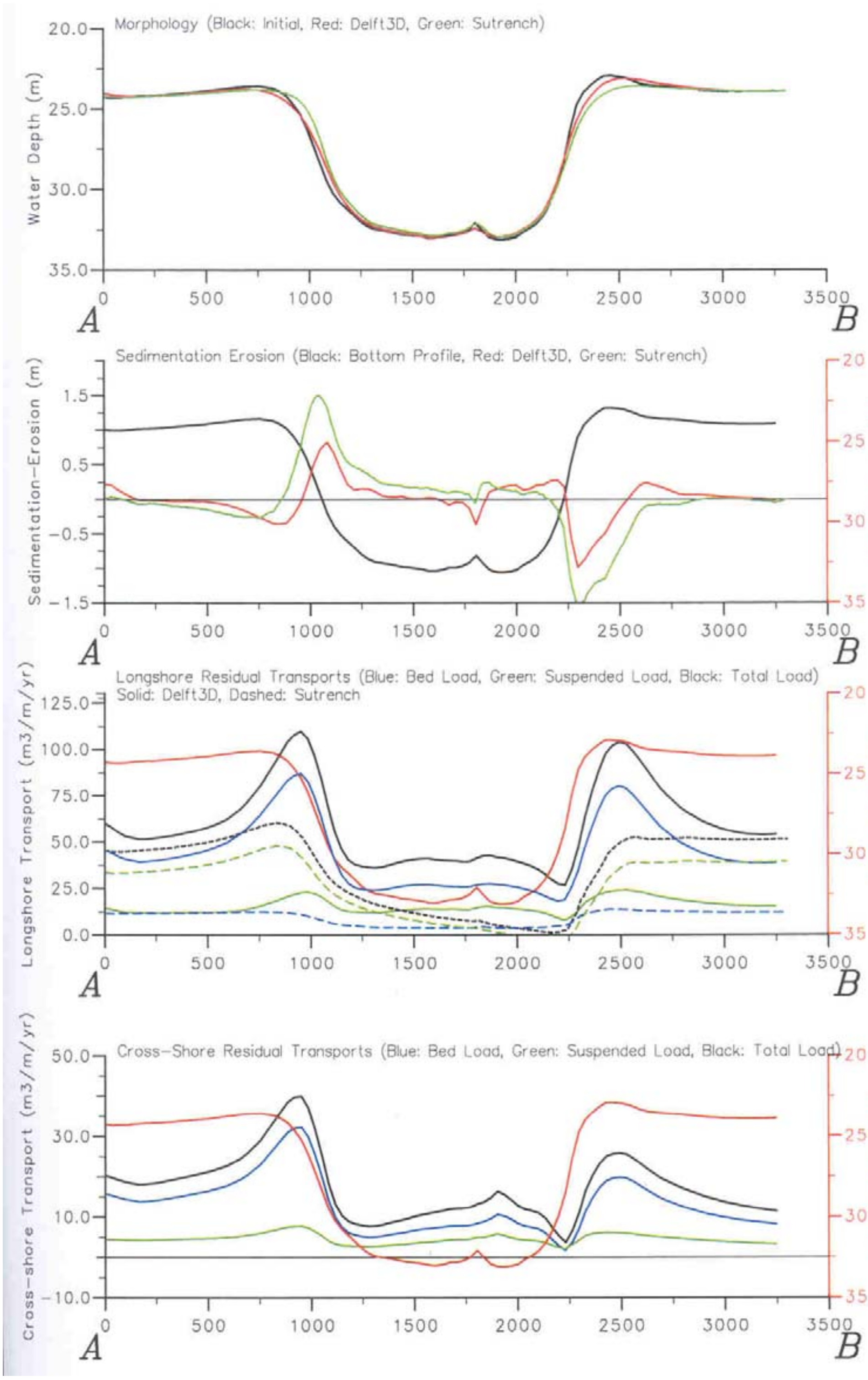


Figure P.5: Comparison between Delft3D and SUTRENCH (Walstra et al., 2002)

Appendix Q : Results Telemac

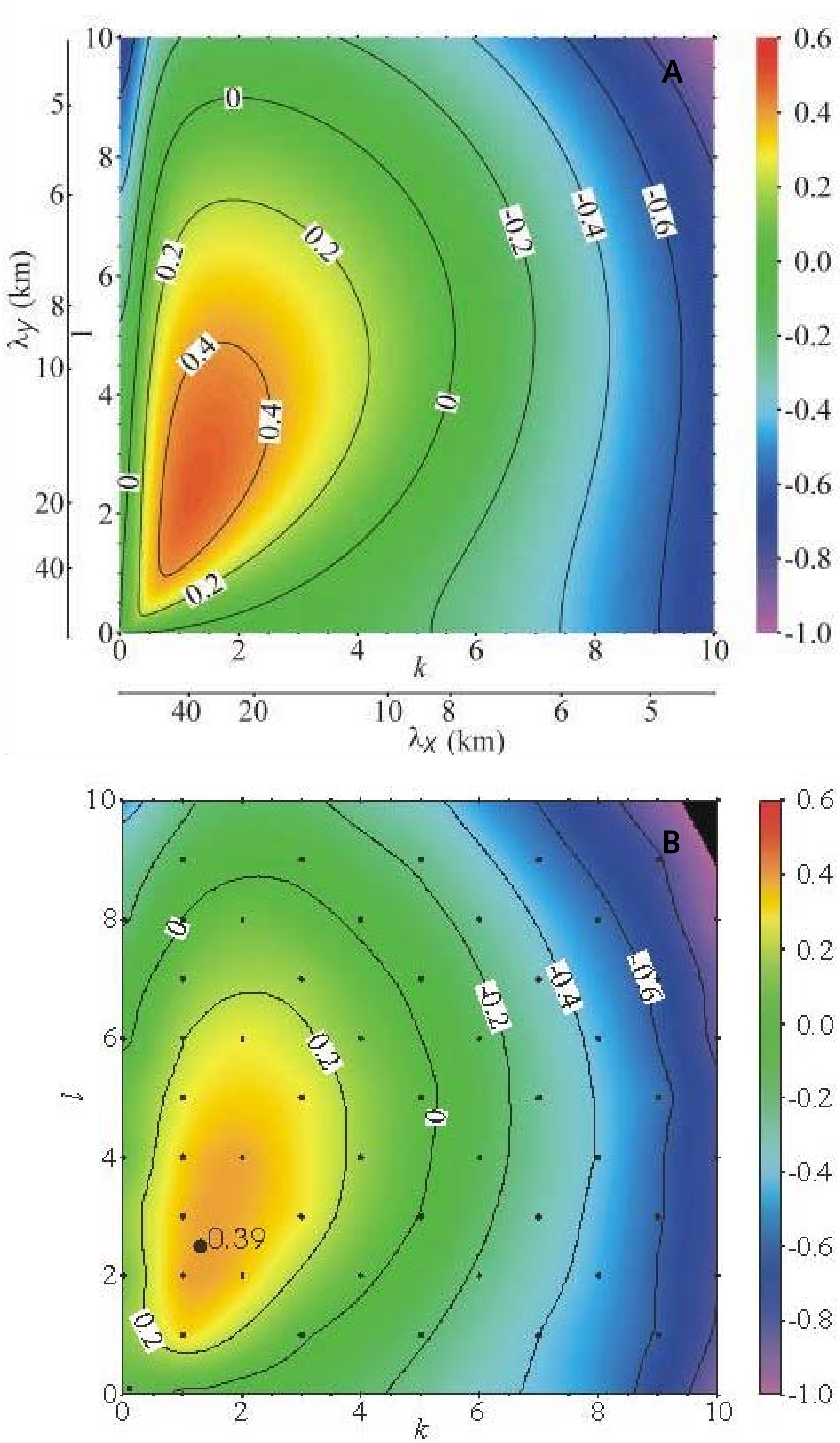


Figure Q.1: Dimensionless growth rate; (analytical) stability analysis (A); numerical result (B) (Hommes, 2004)

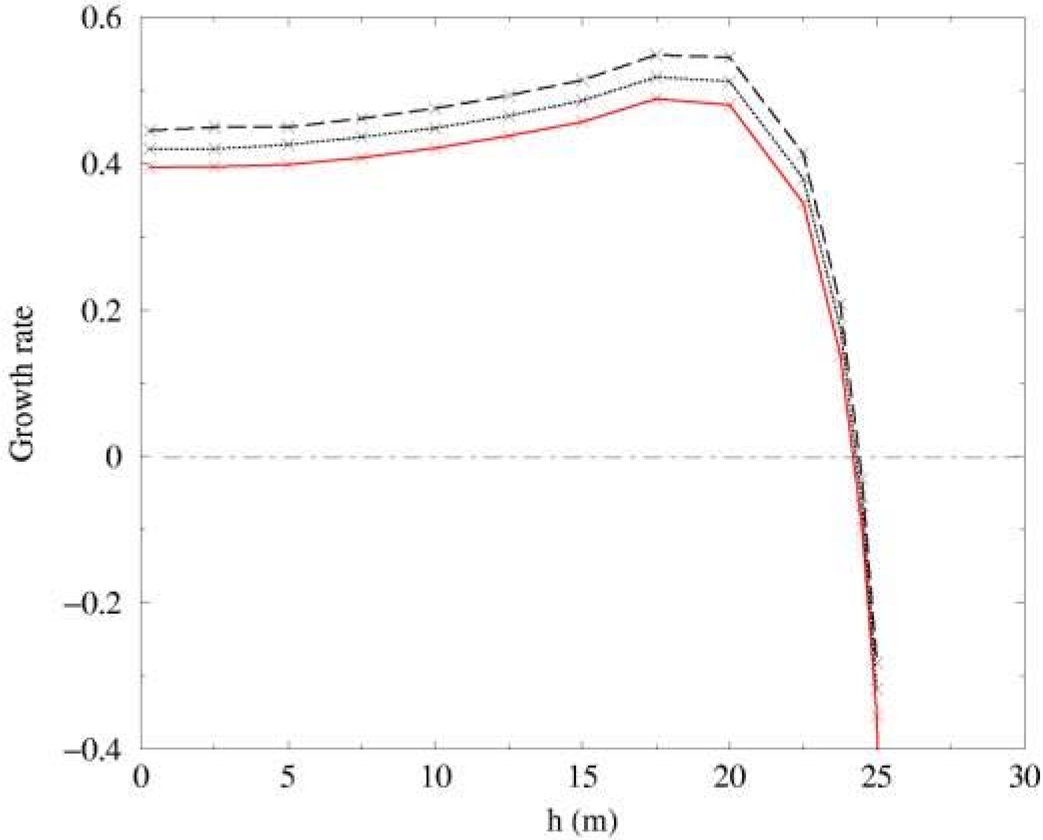


Figure Q.2: Finite amplitude dimensionless growth rate for different values of the bottom slope effect coefficient (λ); $\lambda = 7.27x10^{-3}$ (solid line); $\lambda = 3.64x10^{-3}$(dotted line); $\lambda = 0$ (dashed line) (Idier & Astruc, 2003)

Appendix R : Results mu-SEDIM

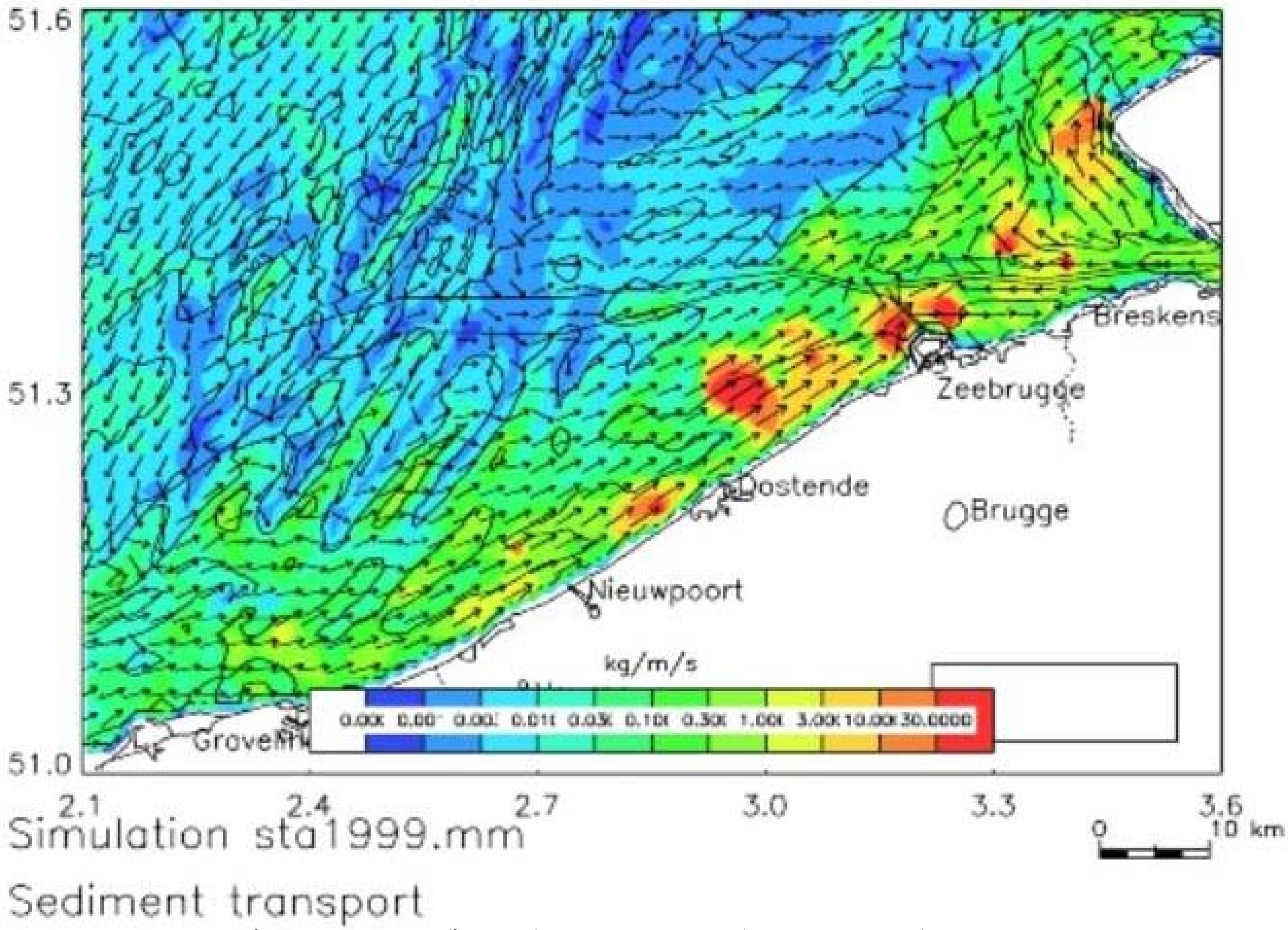


Figure R.1: Sediment transport (kg/m/s) on BCS in 1999 (Hommes, 2004)

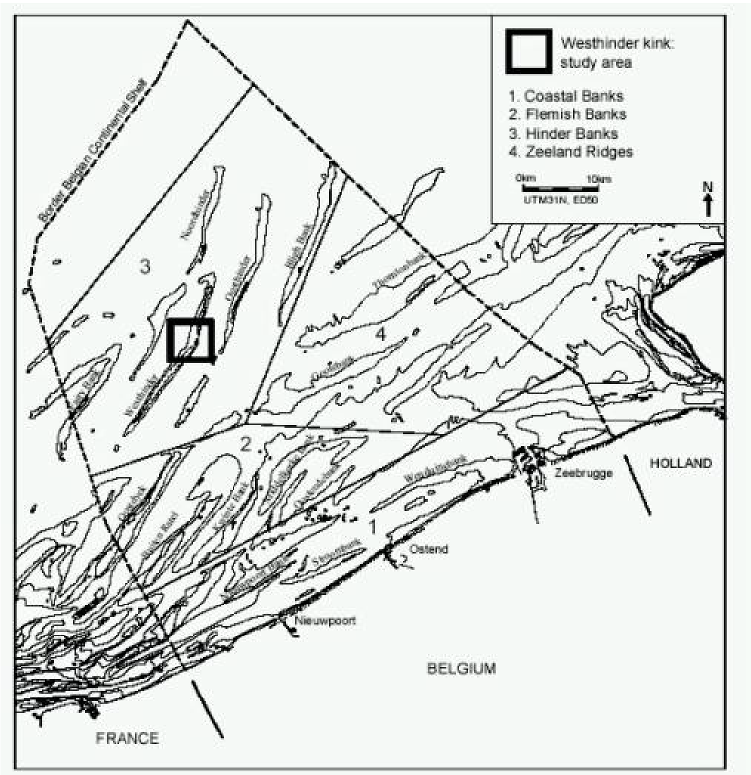


Figure R.2: Location Westhinderbank

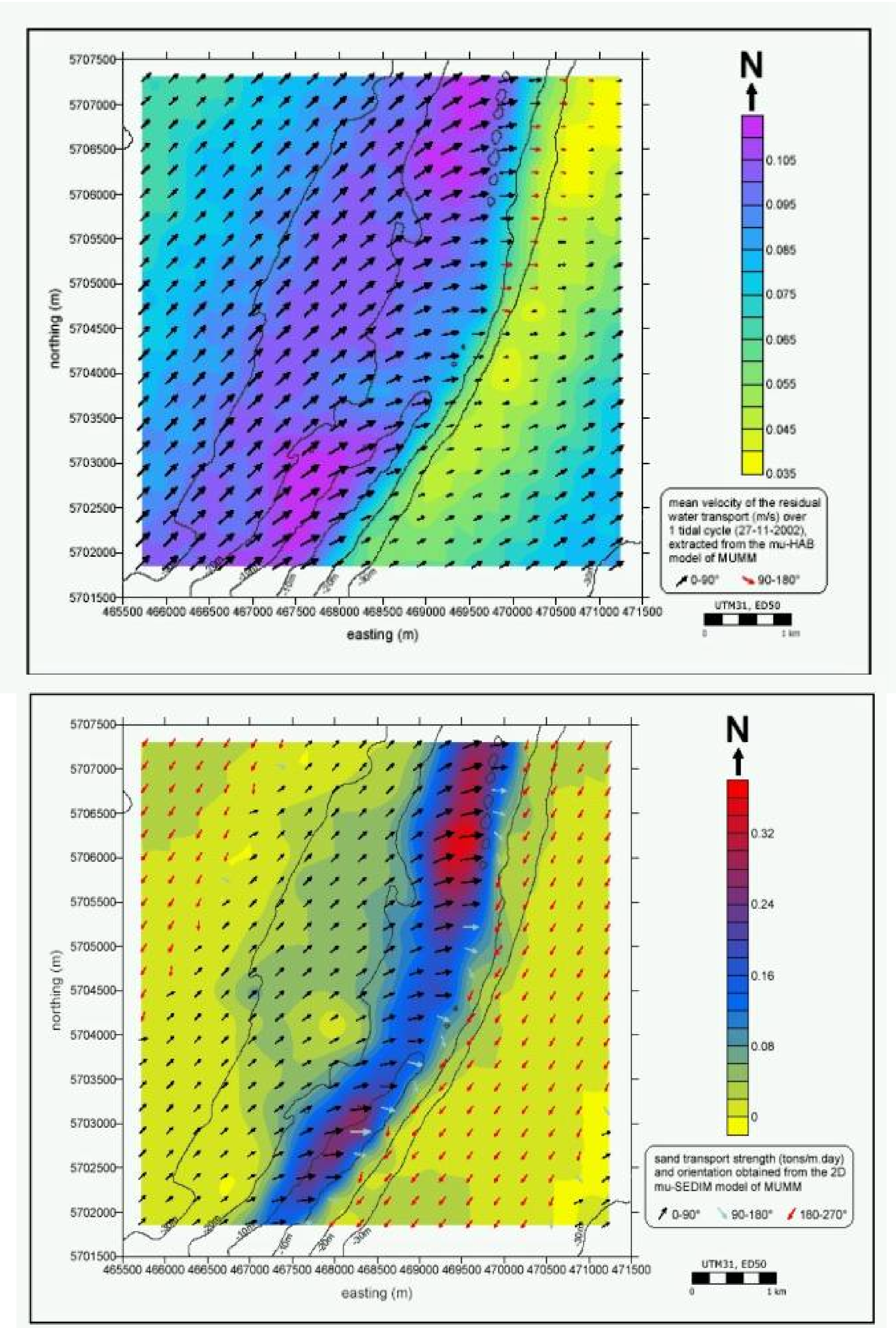


Figure R.3: Residual water transport (m/s) on Westhinderbank (top); sand transport strength (tons/m·day) on Westhinderbank (bottom) (Hommes, 2004)

Appendix S : RIKZ Workshop

On November 18th 2003, we organised a workshop for model developers at RIKZ in The Hague. In this appendix, the aim of the workshop is described and the list of participants is given. Furthermore, the programme of the workshop and the guidelines for the presentations are shown. Finally, we describe the discussion case and the results of the workshop.

Aim workshop

By organising this workshop for model developers, we want to gain knowledge on different instruments. The aim of this workshop is:

Get an objective judgement of the possibilities, limitations and accuracy of different instruments, now and in the future, regarding the modelling of sand extraction on the Zeeland ridges.

Participants

Chairman:	Jan Mulder (RIKZ)
Organizer:	Saskia Hommes (RIKZ, student UT)

Marien Boers	RIKZ
Job Dronkers	RIKZ (only morning programme)
Dries van den Eynde	MUMM (Brussel, Belgium)
Suzanne Hulscher	University of Twente
Déborah Idier	University of Twente
Michiel Knaapen	University of Twente
Sonja Ouwerkerk	TU Delft (PhD student, only morning programme)
Leo van Rijn	WL Delft Hydraulics
Pieter Roos	University of Twente
Teun Terpstra	RIKZ (student UT)
Pieter Koen Tonnon	WL Delft Hydraulics (student TUD)
Henriët van der Veen	University of Twente
Dirk-Jan Walstra	WL Delft Hydraulics

Programme

9:30-10:00	Arrive at RIKZ
10:00-10:20	Introduction by Saskia Hommes
10:20-10:50	Presentation ‘Public concerns and predictive models’ by Marien Boers
10:50-11:20	Presentation by Pieter Roos
11:20-11:40	Presentation by Job Dronkers
11:40-12:10	Presentation Amplitude-evolution model by Michiel Knaapen
12:10-13:00	Lunch break
13:00-13:30	Presentation Telemac by Déborah Idier
13:30-14:00	Presentation mu-SEDIM by Dries van den Eynde
14:00-14:45	Presentation SUTRENCH and Delft3D by Dirk-Jan Walstra
14:45-15:15	Break
15:15-15:35	Introduction discussion by Teun Terpstra
15:35-16:45	Discussion
16:45-17:00	Conclusions on the day

Presentations

The maximum duration of each presentation is 20 minutes, after which there is some time for questions. To stimulate a similar representation of each model, we formulated a few guidelines for the presentations. The guidelines are the following:

- Short model description, e.g.;
    - Input and output parameters
    - Accuracy and validation of the model
- Focus on modelling of long term (up to 100 years) effects of large-scale sand extraction;
    - Impact on coastal user functions:
        - Coastal safety and maintenance
        - Offshore infrastructure
        - Navigation
- Focus on area of the Zeeland ridges;
- Current possibilities, limitations and accuracy of the model;
- Future possibilities of the model.

Case: 'Large-scale sand extraction on the Schouwenbank'

Teun Terpsta introduced the discussion by a presentation on the different user functions in the area of the Zeeland ridges, the value of the ridges and the availability of sand in the research area. This is the topic of his Master thesis (Terpstra, 2004). After this introduction, we held a discussion on the case of a large-scale sand extraction on the Schouwenbank and how the long-term physical effects, caused by such an extraction, can/should be modelled now and in the future. We tried to focus on the research questions and Coastal State Indicators (CSI's).

Case description

- 1 pit
- Cables, pipelines, and existing concession areas are avoided (this is in line with policy and legislation)
- Pit dimensions comparable to Project Mainport Rotterdam;
    - External need = 145×10^6 m^3 filling sand
    - Pit depth = 10 m
    - Surface area = 14×10^6 m^2 (=14 km^2)
- Location: Schouwenbank (Figure S.1)

Overall questions

We formulated some overall questions:

- Can the existing models predict the CSI's?
- What is the accuracy of the predictions?
- What are the uncertainties in the predictions?
- How can we decrease these uncertainties?
    - What information is missing?
    - What knowledge is missing?

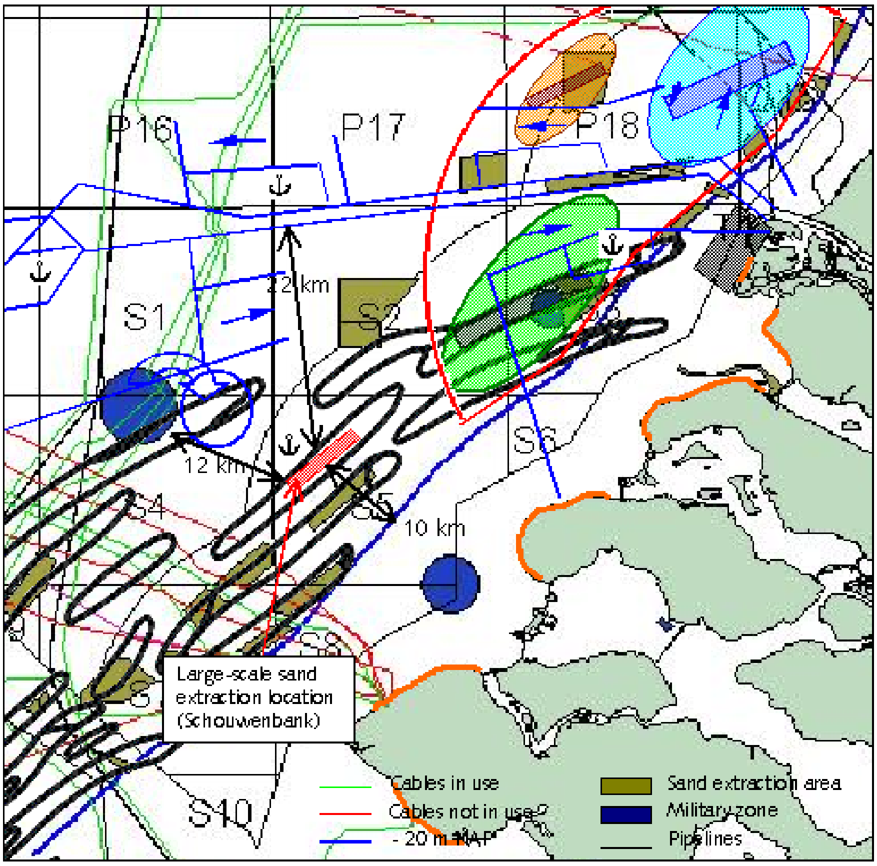


Figure S.1: Location large-scale extraction on Schouwenbank (map from RWS, DNZ, 2003)

Results

Starting point of a model

According to Ms. Hulscher it is very important that we can describe a realistic seabed, with patterns like sand ridges, with the models. Ms. Hulscher states that this should be the starting point of each model. The eQwin model can describe ridges in equilibrium position. Ms. Idier showed in her presentation, that Telemac 2D (+ Sisyphe) can also describe sand ridges. With Delft3D this has not yet been done, at this moment a relative approach is used. The evolution of a disturbed situation is compared with the evolution of the undisturbed situation. Mr. Walstra agrees however that one should tune the bed, like the water movement is tuned, before one starts modelling an intervention. If this is not done, we do not know if we are calculating the effect of the intervention or the natural behaviour (tuning) of the system. Mr. Roos adds that also for calculating the initial behaviour after an extraction, one must first model the long-term behaviour. This must be done, to determine the starting point (equilibrium ridge) of the model, assuming that the present state is in equilibrium.

Coupling models

From the discussion, it follows that for solving these kind of problems, we must couple different models (results). Mr. Walstra describes a case of 5-6 years ago for the Maasvlakte, in which process-based models and behaviour models (Delft3D, PONTOS, RAM, Asmita) were coupled successfully and predictions up to 300 years were made. This case shows that coupling of models is possible. First, the models can be coupled to describe the starting point of a model right. For example, a model like eQwin could form the starting point of a model like Telemac or Delft3D. Second, with a model like Delft3D it may be possible to find better estimations of parameters, for example the growth rate, which are used in stability models (PIT'R, eQwin, Amplitude-evolution model). The question remains, how the coupling of models can be achieved in a feasible way. This is a question for research managers (RIKZ) but also for model developers.

Hydrodynamic modelling

Mr. Boers states that on the short term we can predict CSI's, which focus on hydrodynamics. However, the discussion in the workshop focuses on the morphological effects of sand extraction, because the selected models are (mainly) morphological models. Other models (e.g. Nautilus and SWAN) could be used to predict the hydrodynamic effects of sand extraction. The difficulty is the morphological evolution. Ms. Idier agrees with Mr. Boers on this point and adds that we can also predict tidal currents by numerical modelling.

Information need decision-makers

Mr. De Ronde underlines, from a decision-makers perspective, it is not only necessary to make average predictions, but also to calculate the worst-case scenario and to indicate with what range of values we are dealing. Ms. Hulscher emphasises that we are dealing with a non-linear system, which means that the system could turn to another equilibrium after a large intervention. Therefore, we cannot use a linear approach to predict what will happen. Stability analysis models include these different equilibriums. Furthermore, Ms. Hulscher underlines that an obvious near field (in and round the pit) effect is that the pit will migrate. The difficulty lies in the fact that one does not know what far field effects a large-scale sand extraction will cause. For example: when the pit fills, this affects the sand transport in the vicinity of the pit. Also, a pit can cause the formation of bed patterns in the surrounding area. Moreover, Ms. Hulscher emphasises that some of the processes evolve exponential; this means that an initial small problem can cause a large problem on the longer term. According to Ms. Hulscher, to inspire the decision-makers with trust in the model predictions, it is important to determine which processes influence the pit the most and to look at the spatial scales. It is of major importance to make sure that processes, which take place on the same spatial scales, are represented correctly in the matter of magnitude order.

Test case

From the discussion, it follows that the most important information missing are measurements on sand transport and knowledge on the long-term (morphological) evolution of the sea bottom. Everyone agrees it would be very useful to run a test case. The Kwintebank in Belgium is a possibility for such a test case. From 1979 till 2003, $0.9\text{-}1.2{\cdot}10^6$ m^3/year of sand was extracted from this ridge. During this period the ridge was also monitored intensively, using black boxes, registering dredger activities; single-beam and later on (since November 1999) multi-beam echo sounders. Since February 2003, there is a temporary extraction closure for three years, because two depressed areas on the ridge exceeded the permitted extraction depth. Research has been carried out on the depressed area in the central part of the ridge. This area is 2500 m long, 400 m wide and has a maximum depth of 4.5 m. During the closure period monitoring (4 surveys/year) will take place to evaluate the natural potential of restoration of the ridge.

We conclude that it would be useful, to let a couple of persons do (parallel) calculations on the Kwintebank case, and to organise another discussion on this subject after some period. Then, also the coupling of models can be tried and the models can be validated with the Belgian measurements. It is a challenge for research managers and model developers, to respectively organise and run this test case. There is however already an ongoing European project (EUMARSAND) dealing with the impact of sand extraction on sandbanks and the study area is also the Kwintebank and its depression(s). Within this project, there should also be some morphodynamic modelling of this area, in collaboration between the University of Twente and MUMM. This project runs till 31 October 2005 (Website EUMARSAND, 2003).

Appendix T : Judgement instruments

Applicability

The applicability of an instrument shows for what purpose it can be used. We qualify the applicability by looking at the representation of processes, which are important to predict the CSI's. The scores on applicability are divided in four categories. An instrument scores 'not applicable' when it does not represent the processes. A 'qualitative' score stands for qualitative insight in a CSI and a 'moderate' score for quantitative insight in a CSI. Furthermore, an instrument that scores 'good' on a CSI directly supports the decision-making process. The difference between 'moderate' and 'good' is that 'moderate' results still have to be processed into the right format, whereas 'good' results give direct insight to decision-makers. Moreover, if a question mark is filled in, we do not know if an instrument is applicable to use for a CSI, due to lack of experience on this point. Finally, we place an 'F' if it is possible to use the instruments for a CSI in the near future (within approximately one year). In Table T.1 and Table T.2, the processes that influence the CSI's and an explanation for the scores on applicability of each model are given.

Reliability

The reliability of an instrument shows how reliable a prediction, on a CSI, with this instrument is. We qualify reliability on two points: spatial scale on which the predictions apply and representation of the situation (schematised or realistic). These two parameters together determine the scores on reliability. The scores for reliability are divided in four categories. An instruments scores 'not applicable' when it does not represent the processes, it scores 'not reliable' when it represents the processes but on schematised spatial scale (e.g. small spatial scale or large grid size) and with a schematised situation (e.g. flat sea bottom). Furthermore, a model scores 'moderate' when it represents the processes on a realistic spatial scale but with a schematised situation. Finally, an instrument scores 'good' when it represents the processes on a realistic spatial scale and in a realistic situation. Note that if an instrument is judged with an 'F' or a question mark to a CSI, obviously no score on reliability can be given. In Table T.3 and Table T.4, an explanation for the scores on reliability of each model is given.

CSI	Processes	Twente model		Amplitude-evolution model		Utrecht model	
MCL	- Sediment transport	1	Qualitative insight in sediment flux from nearshore zone	F	Sediment flux from nearshore zone can be included in near future	2	Quantitative insight in sediment flux from nearshore zone
Sand budget in nearshore zone	- Sediment transport	1	Qualitative insight in sediment flux from nearshore zone	F	Sediment flux from nearshore zone can be included in near future	2	Quantitative insight in sediment flux from nearshore zone
Erosion profile	- Wind/ Storms - Sediment transport	X	No wind/storms included	X	No wind/storms included	1	Qualitative insight in effects of storms on coast
Coverage cables & pipelines	- Sediment transport - Tide	2	Quantitative insight in bottom changes in pit area	F	Can be included after method of Morelissen et al. (2003)	X	No tide included
Distance pit to offshore infra-structure	- Sediment transport - Asymmetrical tide	2	Quantitative insight in pit migration	F	Can be included after method of Morelissen et al. (2003)	X	No tide included
Position ridge(s)	- Sediment transport - Tide	X	Not possible to include irregular positions of ridges	X	2DV model, not possible to include horizontal effects	X	Not possible to include irregular positions of ridges
Height ridge(s)	- Sediment transport - Tide/ Wind	F	eQwin model includes ridges	2	Quantitative insight in recovery period ridges	2	Quantitative insight in recovery period ridges
Tidal current	- Tide	1	Qualitative insight in changes in tidal currents	X	Not possible to predict hydrodynamic effects	X	No tidal currents included
Wave height	- Waves	X	No waves included	X	No waves included	F	Wave transformation model could be included
Water depth in area	- Sediment transport	1	Qualitative insight in changes in water depth	1	Qualitative insight in changes in water depth	1	Qualitative insight in changes in water depth
Depth and width shipping channel(s)	- Sediment transport - Asymmetrical tide	X	No shipping channel(s) included, starts from flat bottom	X	No shipping channel(s) included	X	No shipping channel(s) included
Distance pit to channel & anchor area	- Sediment transport - Asymmetrical tide	2	Quantitative insight in pit migration	F	Can be included after method of Morelissen et al. (2003)	X	No tide included

Table T.1: Applicability of instruments, part 1

X = not applicable; does not represent processes (red)
1= qualitative; qualitative insight (orange)
2 = moderate; quantitative insight (yellow)
3 = good; direct support decision-making process (green)
? = no experience (purple)
F = possible to apply in near future (purple)

CSI	Processes	Delft3D		Sutrench		Telemac		mu-SEDIM	
MCL	- Sediment transport	2	Quantitative insight in sediment flux from nearshore zone	X	Not possible to predict sediment flux from near-shore zone	2	Quantitative insight in sediment flux from nearshore zone	2	Quantitative insight in sediment flux from nearshore zone
Sand budget in nearshore zone	-Sediment transport	2	Quantitative insight in sediment flux from nearshore zone	X	Not possible to predict sediment flux from near-shore zone	2	Quantitative insight in sediment flux from nearshore zone	2	Quantitative insight in sediment flux from nearshore zone
Erosion profile	-Wind/Storms -Sediment transport	1	Qualitative insight in effects of storms on coast	X	Not possible to predict effects of storms on coast	1	Qualitative insight in effects of storms on coast	1	Qualitative insight in effects of storms on coast
Coverage cables & pipelines	- Sediment transport - Tide	2	Quantitative insight in bottom changes in pit area	2	Quantitative insight in bottom changes in pit area	2	Quantitative insight in bottom changes in pit area	2	Quantitative insight in bottom changes in pit area
Distance pit to offshore infra-structure	- Sediment transport - Asymmetrical tide	2	Quantitative insight in pit migration	2	Quantitative insight in trench migration	2	Quantitative insight in pit migration	2	Quantitative insight in pit migration
Position ridge(s)	-Sediment transport -Tide	?	No experience	X	2DV model, not possible to include horizontal effects	F	Idier and Astruc (2003) represented sand ridges with Telemac	?	No experience
Height ridge(s)	-Sediment transport -Tide/ Wind	?	No experience	F	After the method of Van de Meene & Van Rijn (2000)	F	Idier and Astruc (2003) represented sand ridges with Telemac	?	No experience
Tidal current	-Tide	1	Qualitative insight in changes in tidal currents	1	Qualitative insight in changes in tidal currents	F	Coupling between SISYPHE and Telemac-2D	F	Coupling between mu-SEDIM and mu-BCZ
		3	Direct support on short-term effects						
Wave height	-Waves	1	Qualitative insight in changes in wave height	1	Qualitative insight in changes in wave height	F	Coupling between SISYPHE and COWADIS	F	Coupling between mu-SEDIM and mu-WAVE
		3	Direct support on short-term effects						
Water depth in area	-Sediment transport	2	Quantitative insight in changes in water depth	2	Quantitative insight in changes in water depth	2	Quantitative insight in changes in water depth	2	Quantitative insight in changes in water depth
Depth and width shipping channel(s)	- Sediment transport - Asymmetrical tide	?	No experience	2	Quantitative insight in filling of a trench	?	No experience	?	No experience
Distance pit to channel & anchor area	-Sediment transport - Asymmetrical tide	2	Quantitative insight in pit migration	2	Quantitative insight in trench migration	2	Quantitative insight in pit migration	2	Quantitative insight in pit migration

Table T.2: Applicability of instruments, part 2

X = not applicable; does not represent processes (red)
1= qualitative; qualitative insight (orange)
2 = moderate; quantitative insight (yellow)
3 = good; direct support decision-making process (green)
? = no experience (purple)
F = possible to apply in near future (purple)

		Twente Model			Amplitude evolution model			Utrecht model		
CSI	**Spatial scale**	Spatial scale	Situation	Score	Spatial scale	Situation	Score	Spatial scale	Situation	Score
MCL	10-35 km	Realistic	Flat bottom	2			F	Realistic	Bottom slope = 15% of real value	2
Sand budget in nearshore zone	10-35 km	Realistic	Flat bottom	2			F	Realistic	Bottom slope = 15% of real value	2
Erosion profile	10-35 km			X			X	Realistic	Bottom slope = 15% of real value	2
Coverage cables & pipelines	≈ 10 km grid 500 m - 2 km	Realistic	Flat bottom	2			F			X
Distance pit to offshore infrastructure	≈ 20 km	Realistic	Flat bottom	2			F			X
Position ridge(s)	35 x 70 km grid 500 m - 2 km			X			X			X
Height ridge(s)	≈ 10 km grid 500 m - 2 km			F	Realistic	One ridge	2	Realistic	Bottom slope = 15% of real value	2
Tidal current	20-30 km	Realistic	Flat bottom	2			X			X
Wave height	20-30 km			X			X			F
Water depth in area	35 x 70 km grid 500 m - 2 km	Realistic	Flat bottom	2	Realistic	One ridge	2	Realistic	Bottom slope = 15% of real value	2
Depth and width shipping channel(s)	20-30 km			X			X			X
Distance pit to channel & anchor area	10-20 km	Realistic	Flat bottom	2			F			X

Table T.3: Reliability of instrument predictions, part 1

X = not applicable (red)
1 = not reliable; represents processes on schematised spatial scale with schematised situation (orange)
2 = moderate; represents processes on realistic spatial scale with schematised situation (yellow)
3 = good; represents processes on realistic spatial scale with realistic situation (green)
? = no experience (purple)
F = possible in near future (purple)

		Delft3D			Sutrench			Telemac			mu-SEDIM		
CSI	**Spatial scale (S)**	S	Situation	Score	S	Situation	Score	S	Situation	Score	S	Situation	Score
MCL	10-35 km	Realistic	Flat bottom	2			X	Realistic	Flat bottom	2	Realistic	Flat bottom	2
Sand budget in nearshore zone	10-35 km	Realistic	Flat bottom	2			X	Realistic	Flat bottom	2	Realistic	Flat bottom	2
Erosion profile	10-35 km	Realistic	Flat bottom	2			X	Realistic	Flat bottom	2	Realistic	Flat bottom	2
Coverage cables & pipelines	≈ 10 km grid 500 m - 2 km	Schema-tised	Flat bottom	1	Schema-tised	Flat bottom and small pit depth	1	Realistic	Flat bottom	2	Schema-tised	Flat bottom	1
Distance pit to offshore infra-structure	≈ 20 km	Realistic	Flat bottom	2	Schema-tised	Flat bottom and small pit depth	1	Realistic	Flat bottom	2	Realistic	Flat bottom	2
Position ridge(s)	35 x 70 km grid 500 m - 2 km			?			X			F			?
Height ridge(s)	≈ 10 km grid 500 m - 2 km			?			F			F			?
Tidal current	20-30 km	Realistic	Flat bottom	2	Schema-tised	Flat bottom and small pit depth	1			F			F
		Realistic	Bathymetry North Sea	3									
Wave height	20-30 km	Realistic	Flat bottom	2	Schema-tised	Flat bottom and small pit depth	1			F			F
		Realistic	Bathymetry North Sea	3									
Water depth in area	35 x 70 km grid 500 m - 2 km	Schema-tised	Flat bottom	1	Schema-tised	Flat bottom and small pit depth	1	Realistic	Flat bottom	2	Schema-tised	Flat bottom	1
Depth and width shipping channel(s)	20-30 km			?	Schema-tised	Flat bottom and small pit depth	1			?			?
Distance pit to channel & anchor area	10-20 km	Realistic	Flat bottom	2	Schema-tised	Flat bottom and small pit depth	1	Realistic	Flat bottom	2	Realistic	Flat bottom	2

Table T.4: Reliability of instrument predictions, part 2

X = not applicable (red)
1 = not reliable; represents processes on schematised spatial scale with schematised situation (orange)
2 = moderate; represents processes on realistic spatial scale with schematised situation (yellow)
3 = good; represents processes on realistic spatial scale with realistic situation (green)
? = no experience (purple)
F = possible in near future (purple)