Ministerie van Verkeer en Waterstaat
Rijkswaterstaat

Effects of a deep sand extraction pit

Final report of the PUTMOR measurements at the Lowered Dump Site

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Summary

Deep sand extraction on the Netherlands Continental Shelf (NCS)

In the “Nota Ruimte” (=National Spatial Strategy) the Dutch Government has announced to allow for deep sand extraction on the NCS, where former legislation only allowed for extraction till a depth of 2 m below the initial seabed. This new legislation has been worked out in the “Regionaal Ontgrondingenplan Noordzee 2” (= Regional Extraction Plan North Sea 2). It prescribes that for sand extractions with an extraction volume exceeding 10 million m^3 or an extraction area exceeding 500 hectares an environmental impact assessment is required, and that an ecological study is required when the intended extraction depth exceeds 2 m below the initial seabed.

It appears that there is little experience with the effects of deep sand extraction pits on existing values and user functions, due to the legislation prior to 2004. Since it is the responsibility of the Dutch Government to develop legislation on sand extraction, and to judge the proposals for sand extraction before granting an extraction license, Rijkswaterstaat, North Sea Directorate has asked Rijkswaterstaat, The National Institute of Coast and Sea/RIKZ to study the hydraulic and morphological responses of a deep sand pit and the risks of oxygen depletion and deposition of fines inside such a pit.

The general conclusion is that there are no indications that a deep sand extraction pit with a final water depth of 40 meter necessarily leads to unacceptable effects on existing values and user functions, and therefore it is expected that deep sand extraction will be an interesting alternative for shallow sand pits with a volume of more than 10 million m^3. For the environmental impact assessment of a proposed deep sand extraction pit, numerical models are available for useful predictions of the hydraulic and morphological response of such a pit.

The PUTMOR measuring campaign

From autumn 1999 till summer 2000 there was an opportunity to carry out measurements at a temporary deep sand pit (referred to as the PUTMOR pit) of the Lowered Dump Site (LDS) near Hook of Holland [Figures 1.1 and 1.3]. The PUTMOR pit was located at an initial water depth of 23 m and was left open for a period of 10 months, after which it was refilled with dredged material from the Port of Rotterdam. The pit had a content of about 4.5 million m^3, a length of 1300 m, a width of 500 m and an extraction depth varying between 5 and 12 m. Within a period of 10 months, Rijkswaterstaat gathered data about the hydraulic conditions, the water quality and the morphological changes.

The impact of a deep sand extraction pit on values and user functions

There are two major concerns related to deep sand extraction. The first concern is that benthic communities cannot re-establish on the bottom of a deep sand pit due to oxygen depletion and deposition of fines. The second concern is that a deep sand pit will harm existing cables, pipelines and offshore constructions, and the coastal defence system. To address these concerns, we have formulated the following questions:

- What effects has a deep sand pit on the flow conditions, stratification, oxygen depletion deposition of fines and bottom changes?
- Can the original benthic communities recover on the sand pit bottom?
- Is there a risk of damage to cables, pipelines and offshore structures?
- What is the effect on the sand budget of the coastal system?
- Is it possible to judge a sand pit design with an extraction depth of more than 2 metres below the initial seabed using hydraulic and morphodynamic models?

With the help of the PUTMOR measurements, which was made up with other measuring data from the NCS, we came to the following conclusions:

- The PUTMOR measurements showed an increase of the flow rate (discharge per meter width) inside the pit with one-third, but the flow velocity near the bottom of the pit has a decrease of one-third compared to the measured flow velocities outside the pit.
- The PUTMOR measurements did not show stratification and oxygen depletion inside the pit, below the initial seabed. In the upper ten metres of the water column, the usual haline stratification was measured, resulting from the fresh water discharge from the river Rhine. On the NCS, there are no records of oxygen depletion due to this haline stratification, which is probably the result of the temporal presence of a halocline during the tidal period and the upwelling of oxygen rich water from the offshore. Thermal stratification is not expected since the water depth inside the pit is less than 40 m, which is the minimum water depth for thermal stratification found at the NCS. Besides, the water inside the PUTMOR pit was refreshed four times a day due to the tide. In general, there is no chance on long-term haline or thermal stratification within a deep sand pit on the NCS with a final water depth less than 40 m pit, and we expect that the risk of oxygen depletion in such a pit is negligible.
- When there is a large deposition of fines, there may be a negative impact on the recovery of benthos communities. In the PUTMOR pit, we did not measure a large deposition if fines. However, the deposition of fines is very site-specific, depending on the local flow velocities, the suspended concentrations of fines and the characteristics of the sand extraction pit.
- We expect that recovery of benthic communities on the new seabed within a deep sand extraction pit is possible.
- The morphological changes of a large pit in deep water are very slow, although they depend on the local conditions. The backfilling of a deep sand pit at an initial water depth of more than 20 m is expected to take a period of centuries. The risks on offshore infrastructure and coast at a distance of more than half a kilometre away from the sand pit seem very small.
- There are numerical models available to judge the hydraulic and morphological responses of a deep sand pit. Calculations with the numerical model DELFT3D showed that flow velocities were predicted at a satisfactory level. This model also gives a good qualitative prediction of the backfilling/flattening and migration of a pit, a trench or a dump site under various environmental conditions, although the modelling of the magnitude of migration and backfilling or flattening in time should be further improved.

1 Sand extraction in a deep pit

1.1 Sand extraction on the Netherlands Continental Shelf

When there are initiatives for sand extraction on the Netherlands Continental Shelf (NCS) [Figure 1.1], it is necessary to minimize effects on existing values and user functions. The Dutch Government develops legislation on sand extraction and judges the proposals for sand extraction before granting a sand extraction license. This requires knowledge on the existing values and user functions, and the physical and ecological effects of the proposed sand extraction.

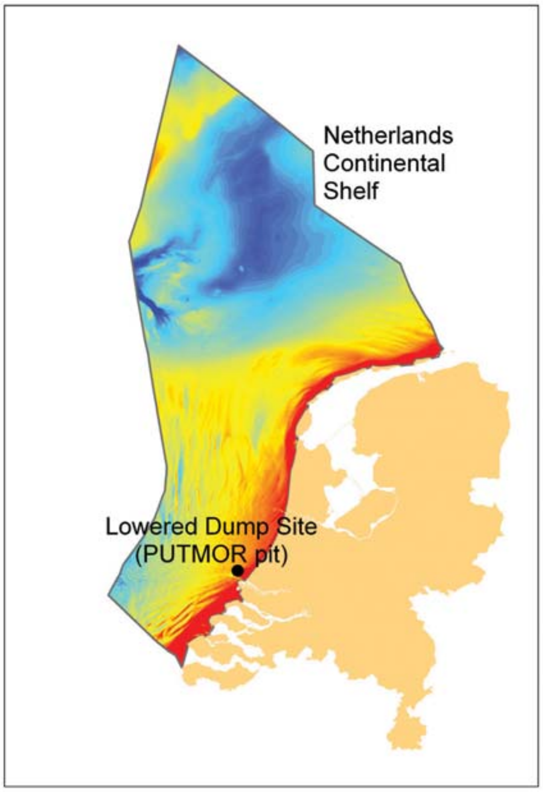


Figure 1.1
Netherlands Continental Shelf (NCS); the study area of this report

Initiatives for sand extraction

In The Netherlands, we have seen a large increase in the demand for sand from the North Sea, and we expect that this demand will increase during the coming years [Figure 1.2]. There are several reasons for this extra demand:

- There is a policy to maintain the sand budget of the nearshore zone, stretching to the straightened –20 m depth contour ["3e Kustnota" (=3rd National Coast Strategy), Ministerie van Verkeer en Waterstaat (2001)].

- There is an increasing scarcity for sand extraction locations on land. We expect that, under influence of the market, there will be an increased demand for sand from the North Sea. The Dutch government calls extraction of filling sand from the North Sea a national interest ["Nota Ruimte" (= National Spatial Strategy), Ministerie van Volkshuisvesting, Ruimtelijke Ordening en Milieubeheer *et al.* (2004)].
- There have been plans for land reclamation, like the Westerschelde Container Terminal near the Port of Vlissingen (Flushing) [DHV (2003)] and the second Maasvlakte near Rotterdam [Ministerie van Verkeer en Waterstaat *et al.* (2003)].

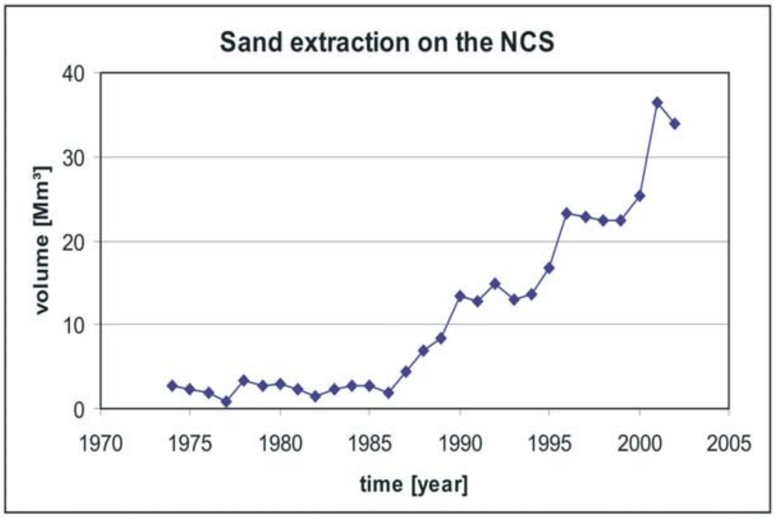


Figure 1.2
Annual sand extraction on the NCS

Developments in legislation

Until recently, sand extraction on the NCS was only allowed to a depth of 2 metres below the initial seabed. The "Nota Ruimte" allows deep sand extraction on the North Sea. Regulations for deep sand mining have been worked out in the "Regionaal Ontgrondingenplan Noordzee 2" (=Regional Extraction Plan North Sea) [Ministerie van Verkeer en Waterstaat (2004)]:

- Sand extraction is not permitted in the nearshore zone between the shoreline and the straightened –20 m depth contour, in order to protect coastal and ecological values.
- Sand extraction is neither permitted in a zone with a width of 500 m around offshore platforms, windmills, cables and pipelines.
- For sand extractions with an extraction volume exceeding 10 million m^3 or an extraction area exceeding 500 hectares an environmental impact assessment is required. An ecological study is required when the intended extraction depth exceeds 2 m. For both options knowledge of the physical and ecological response of the sand pits is needed to assess their environmental impact.

Deep sand extraction can be an attractive option to minimize the removal of benthos within a large area in case of large-scale sand extraction. Another reason for deep sand extraction is the mining of course sand for the construction industry, which can be found at a depth of several metres below the seafloor in the surrounding of the Euro-Maas Channel [Van Heijst (2004)].

Values on the NCS

We distinguish two categories of values on the NCS that need protection. Firstly, there are Landscape, Natural and Cultural values on the North Sea. Landscape values are hardly visible for the human eye. Natural values are represented by vulnerable ecosystems, which are protected by a number of laws, e.g., the European Bird and Habitat Directive. Archaeological remains, on the seabed mostly ship wreck, represent cultural values. Secondly, there are values related to the coast. We think of coastal protection during extreme storm surges, retreat of the coastline and loss of sand in the nearshore zone.

User functions on the NCS

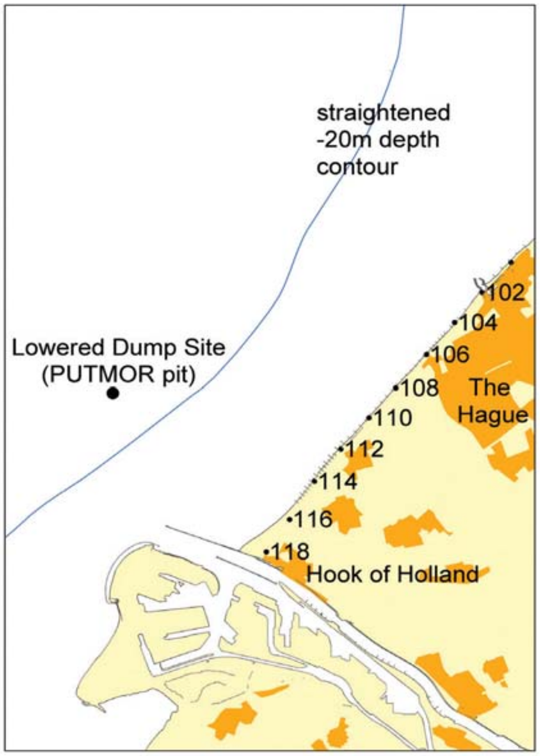
On the NCS, we have to deal with a number of user functions of the North Sea, which interests must be respected:
- Cables and pipelines
- Offshore platforms for the exploration of oil and gas
- Windmills
- Fisheries
- Shipping traffic
- Dump sites for harbour dredged material
- Military training grounds
- Sand extraction
- Shell extraction

1.2 Concerns related to deep sand extraction

Due to the legislation prior to 2004, the Dutch authorities have little experience with sand extraction deeper than 2 metres below the initial seabed. Therefore, there is an urgent need for information about the effects of deep sand extraction and the impacts on the existing values and user functions. Especially the following two concerns need to be considered:
- There is a concern that the conditions on the bottom of the new sand pit make a re-establishing of original benthos impossible.
- Due to the larger extraction depth, more sand can be extracted from a designated area. It is a concern that the morphological response of such a deep sand pit will negatively affect existing cables, pipelines and offshore structures, and on the sand budget of the nearshore zone.

In 1999 there was an opportunity to obtain more knowledge on sand pits with an extraction depth deeper than 2 metres. At that time, the first of six temporary sand pits forming the Lowered Dump Site (LDS) was dredged a little distance north of the Euro-Maas Channel, which is the entrance channel to the Port of Rotterdam [Figures 1.1 and 1.3]. The pit, which we call the PUTMOR pit, was located in a water depth of 23 m and was left open for a period of 10 months and then was refilled with dredged material from the Port of Rotterdam. The pit had a content of about 4.5 million m^3, a length of 1300 m, a width of 500 m and an extraction depth varying between 5 and 12 m.

Figure 1.3
Location of the Lowered Dump Site (LDS), including the PUTMOR pit



Rijkswaterstaat, North Sea Directorate asked Rijkswaterstaat, The National Institute of Coast and Sea/RIKZ to carry out the PUTMOR project, which includes physical measurements in and around the open pit within a period of 10 months. After the measuring campaign, the measuring data were analysed and used for the calibration and validation of hydrodynamic and morphodynamic models.

With all results of the PUTMOR project available, we aim to answer the following questions in this final report of the PUTMOR project:

- What effects has a deep sand pit on the flow conditions, stratification, oxygen depletion deposition of fines and bottom changes?
- Can the original benthic communities recover on the sand pit bottom?
- Is there a risk of damage to cables, pipelines and offshore structures?
- What is the effect on the sand budget of the coastal system?
- Is it possible to judge a sand pit design with an extraction depth of more than 2 metres below the initial seabed using hydraulic and morphodynamic models?

1.3 Answers from the PUTMOR project

With the help of the PUTMOR measurements, which was made up with other measuring data from the NCS, we came to the following conclusions:

- The PUTMOR measurements showed an increase of the flow rate (discharge per meter width) inside the pit with one-third, but the flow velocity near the bottom of the pit has a decrease of one-third compared to the measured flow velocities outside the pit.
- The PUTMOR measurements did not show stratification and oxygen depletion inside the pit, below the initial seabed. In the upper ten metres of the water column, the usual haline stratification was measured, resulting from the fresh water discharge from the river Rhine.

On the NCS, there are no records of oxygen depletion due to this haline stratification, which is probably the result of the temporal presence of a halocline during the tidal period and the upwelling of oxygen rich water from the offshore. Thermal stratification is not expected since the water depth inside the pit is less than 40 m, which is the minimum water depth for thermal stratification found at the NCS. Besides, the water inside the PUTMOR pit was refreshed four times a day due to the tide. In general, there is no chance on long-term haline or thermal stratification within a deep sand pit on the NCS with a final water depth less than 40 m pit, and we expect that the risk of oxygen depletion in such a pit is negligible.

- When there is a large deposition of fines, there may be a negative impact on the recovery of benthos communities. In the PUTMOR pit, we did not measure a large deposition if fines. However, the deposition of fines is very site-specific, depending on the local flow velocities, the suspended concentrations of fines and the characteristics of the sand extraction pit.
- The morphological changes of a large pit in deep water are very slow, although they depend on the local conditions. The backfilling of a deep sand pit at an initial water depth of more than 20 m is expected to take a period of centuries.
- We expect that recovery of benthic communities on the new seabed within a deep sand extraction pit is possible.
- The risks on offshore infrastructure and coast at a distance of more than half a kilometre away from the sand pit seem very small.
- There are numerical models available to judge the hydraulic and morphological responses of a deep sand pit. Calculations with the numerical model DELFT3D showed that flow velocities were predicted at a satisfactory level. This model also gives a good qualitative prediction of the backfilling/flattening and migration of a pit, a trench or a dump site under various environmental conditions, although the modelling of the magnitude of migration and backfilling or flattening in time should be further improved.

After considering the results of the PUTMOR project supplied with other data from the NCS, we did not found indications that a deep sand extraction with a final water depth less than 40 m will necessarily lead to unacceptable effects on existing values and user functions. This means that chances are high for a full recovery of benthic communities on the new seabed within a deep sand extraction pit. Furthermore, we expect that the morphological changes of a deep sand extraction pit are very slow, although they depend on the local conditions. As a result, we expect that the backfilling and migration of a deep sand pit will not affect offshore infrastructure and the coast at a distance of more than 500 m from the pit in the foreseeable future. Therefore we expect that a deep extraction pit will be an interesting alternative for shallow sand pits with a volume of more than 10 million m^3.

The conclusions and advices, described in this section, are based on analysis of the measurements and the simulation of deep sand pits with numerical models. This work is described in the remaining part of this report:

- Chapter 2 gives a description of the PUTMOR project concerning the measurements the analyses and the modelling work.
- Chapter 3 describes the hydraulic responses of a deep pit.
- Chapter 4 describes oxygen and stratification in a deep pit
- Chapter 5 describes the deposition of fines in a deep it.
- Chapter 6 describes the morphological responses of a deep pit.

In Chapter 7 we finish with conclusions and recommendations. Reports and measuring data are included on the enclosed DVD that is described in Appendix A.

2 Description of the PUTMOR Project

2.1 Introduction to the PUTMOR project

During the past ten years, much modelling work has been performed on the hydro- and morphodynamic behaviour of large sand pits and trenches [Hoogewoning and Boers (2002), Van Rijn and Walstra (2004)]. Although much progress has been made in the knowledge of the driving processes, there is still a big problem regarding model validation, due to the lack of field data. As a consequence, end users like Rijkswaterstaat are still rather reluctant to use model predictions to answer coastal management questions related to sand extraction. Therefore, lately, a lot of effort has been put in the collection of experimental data. A distinction is made between:

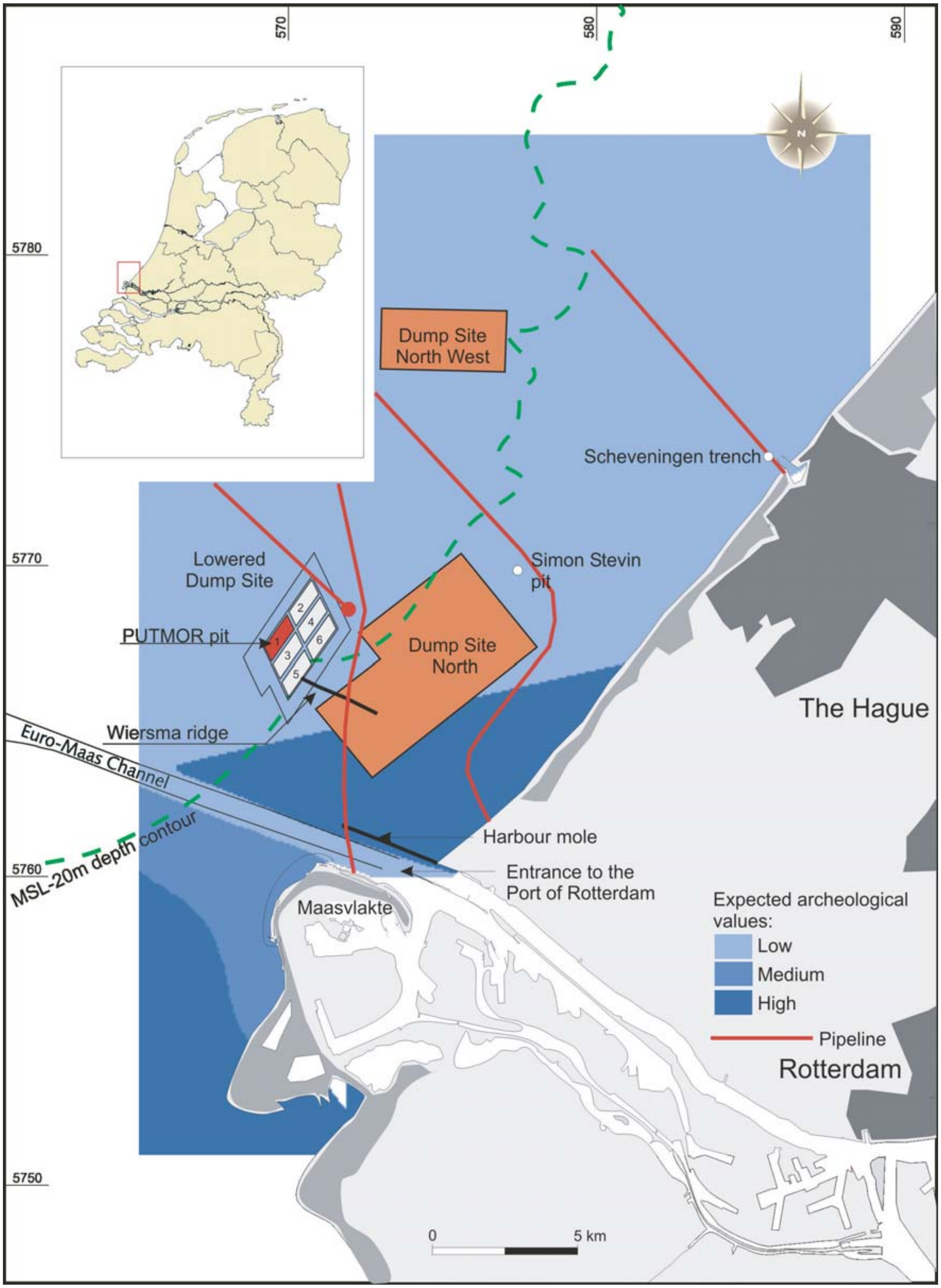
- **Investigation of historical field data**
  The morphological behaviour of a number of historical sand pits, trenches and dump sites on the NCS have been analysed and the data were collected in a database [Section 6.4]. Van Rijn and Walstra (2004) give an international overview of historical sand pits. As far as we know, there are no measurements of the hydrodynamic response of extraction or dump sites.
- **Investigation of historical laboratory data**
  There are a small number of (international) laboratory experiments concerning sand pits and trenches [Van Rijn and Walstra (2004)].
- **Execution of new field experiments**
  In this report, we describe the measurements carried out during the PUTMOR project.
- **Execution of new laboratory experiments**
  There have been plans for large-scale experiments in the Delta flume of WL|Delft Hydraulics, but they were not carried out yet.

In this chapter we give a description of the execution of the PUTMOR project, which was focussed on the first sand pit of the Lowered Dump Site (LDS) north of the entrance to the Port of Rotterdam. Measurements were started after completion of the pit in October 1999, and were finished in August 2000, after which the pit was refilled with dredged material from the Port of Rotterdam. The length of the pit was about 1300 m and the width about 500 m. The extraction depth varied between 5 and 12 meters and the total extracted volume of sand was about 4.5 million m^3. The slope of the pit varied between 1:10 and 1:25. Figure 2.1 shows a map of the coastal area where the LDS is located. The westernmost pit with Number 1 (red) is the pit where the measurements were carried out.

Description of the region surrounding the LDS

The LDS and the Dump Site North West are the successors of Dump Site North where dumping has been carried out since 1961. Dumping at Dump Site North faced too many problems because the water depth became too shallow for the dredging vessels. Besides, it was felt that too much dredged material returned to the entrance channel, which increased the dredging cost.

Figure 2.1
Map of the vicinity of the PUTMOR pit



Before the LDS and the Dump Site North West came into operation, an environmental impact assessment was carried out. One of the prerequisites for the license was the monitoring and evaluation of the behaviour of the harbour sediment after dumping. This has been fulfilled by Stutterheim (2002a), who reported the behaviour of the LDS, and by Stutterheim (2002b), who reported the behaviour of the Dump Site North West.

Furthermore, Figure 2.1 shows the Simon Stevin pit, extracted in 1982 northeast of the Dump Site North, which was an experimental pit that also served as a lowered dump site. Wiersma ridge, an artificial sandbank onshore of the PUTMOR pit, was built between 1982 and 1986 to prevent the return of dumped harbour material to the Port of Rotterdam [Redekker and Kollen (1983), Woudenberg (1996)]. North of the entrance to the Port of Rotterdam, we see a harbour mole, south we see the Maasvlakte, which was constructed between 1967 and 1972. A further extension with the Maasvlakte 2 is foreseen.

The expected archaeological values in the vicinity of the LDS, mostly wrecked ships, are limited. There are a number of pipelines, which can be damaged due to migration of the pits, when these were not refilled with harbour sediment. By policy, the straightened –20m depth contour [Figure 1.3], which is derived from the MSL –20m depth contour, is the landward boundary for sand extraction.

Description of the system surrounding the LDS

The hydraulic conditions in the vicinity of the PUTMOR pit are influenced by tide, wind and the outflow of the river Rhine. The Maasvlakte and the harbour mole result into flow contraction that increases the flow velocity at the LDS. The top layer of the seabed is part of the Bligh bank formation, consisting of fine sediment of marine origin. A few metres below the seafloor, the Kreftenheye layer is found, which includes courser sands of fluvial origin [Van Heijst (2004)]. The seabed is typically flat with a slope less than 1:1000, without morphological features like sand banks and sand waves [Van Alphen and Damoiseaux (1987)].

2.2 Preparations for the PUTMOR PROJECT

The preparations for the PUTMOR measurements were carried out by Rijkswaterstaat (The National Institute of Coast and Sea/RIKZ and the North Sea Directorate; Measurement Department) with the help of Hydrest Inc. The project plan was written by Hoogewoning (1999).

Hypotheses

In the project plan, Hoogewoning (1999) formulated five hypotheses concerning the effect of the PUTMOR sand pit on flow velocity, stratification, oxygen depletion, deposition of fines and morphological changes:

1. As the main direction of the longest dimension of the sand pit nearly coincides with the main direction of the tidal current and as the length / width ratio of the sand pit amounts about 2.5, an increase of the tidal flow through the sand pit is expected. The maximum depth-averaged tidal velocity in the sand pit is expected to be smaller than outside the sandpit due to the limited dimensions of the sand pit.
2. Due to the increased water depth, a reduction of the vertical mixing rate in the sand pit is expected. Consequently an increase of the present vertical stratification is expected in the sand pit.

3. Tidal velocities near the bottom in the sand pit are expected to be smaller than outside the sand pit. As a result of this, oxygen-concentrations in the lower part of the water column of the sand pit may be smaller than those outside the sand pit.
4. Given the expected behaviour of the water movement, sedimentation of fines is expected in the sand pit.
5. The expected morphological changes of the sand pit are characterised by flattening of the slopes and a backfilling of the sand pit. Largest changes are of course expected after storms.

Research questions

For the verification of these hypotheses, Hoogewoning (1999) formulated the following research questions, which should be answered within the PUTMOR project:

- What are the flow velocities inside the pit and how do they vary in time?
- How do the water levels interact with the varying flow velocities?
- What is the impact of wind on the flow velocities?
- What are the spatial variations of flow velocities inside and outside the pit?
- What are the vertical and temporal variations of temperature, salinity and density?
- Is there a correlation between Rhine discharge, wave activity and stratification?
- What are the magnitude and the temporal variation of oxygen concentration within the pit?
- Is there a correlation between flow velocity, stratification and oxygen concentration?
- What are the variations of the suspended sediment concentrations, fines and sand, near the bottom?
- Is there a correlation between flow velocities, waves and suspended sediment concentration?
- What are the morphological changes over a period of several months?
- What are the characteristics of sediment within the pit? Do they change during successive measurements?
- Is there deposition of fines in the pit?

Plan of operations

Based on the research questions, a plan of operations was submitted for frame-mounted measurements and ship-based measurements. The execution of this plan of operation is described in the following section.

2.3 PUTMOR measuring campaign

In this section we describe the circumstances during the PUTMOR measuring period. Furthermore, we describe the measurements inside and outside the sand pit, carried out using frames and vessels. Measurements using instrumented frames allow measuring physical parameters weeks to months, while ship-based measurements allow measuring physical parameters at different positions. We finish this section with an overview of the measured physical parameters.

Execution of the measurements

The PUTMOR measurements were carried out by the Measurement Department of Rijkswaterstaat, North Sea Directorate, using the following vessels:

- Mitra
- Octans
- Zirfaea

Circumstances during the PUTMOR measuring campaign

Following is a general description of the circumstances during the PUTMOR measuring campaign [Figure 2.2]:

- The water level at Hook of Holland, southeast of the PUTMOR pit, showed a maximum storm surge level of 2.4 m above Dutch Ordinance Level (NAP). The mean tidal difference was about 1.7 m.
- The wave period Tm02 at the Europlatform, about 50 km west southwest of the PUTMOR pit, showed a mean of 4.8 s and maximum of 7.9 s, while the spectral significant wave height Hm0 showed a mean of 1.55 m and a maximum of 5.08 m.

The wind speed at the Europlatform, southwest of the PUTMOR pit, had a mean of 9.0 m/s and a maximum of 21.7 m/s. The wind came from west to southwest most of the time.
The discharge of the river Rhine at Lobith, on the German – Dutch border, had a mean of 2,900 m^3/s and a maximum of 6,600 m^3/s.
The oxygen concentration slightly below the water surface at Noordwijk 10, northwest of the PUTMOR pit, had a mean value of 9.5 mg/l and a minimum value of 7.8 mg/l.

Frame-mounted measurements

Figure 2.3 gives an overview of the water depth below Mean Sea Level (MSL) and the positions of measuring instruments during the PUTMOR campaign. Frame-mounted measurements [Figure 2.4] were carried out at three different Locations A, M and B, aligned in the direction of the main tidal current:

- Location A is outside the pit at a depth of about 24 m below MSL. The frame at this location contained an ADCP for the vertical velocity profile and a Hydrolab, located 60 cm above the seabed for temperature, salinity, depth and turbidity.
- Location M is near the centre of the pit, at a depth of approximately 34 m below MSL. The frame at this location also contained an ADCP and a Hydrolab. In addition at Location M, an Aanderaa String measured temperature and salinity at 2, 7, 12, 22 and 28 m above the seabed.
- Location B is outside the pit, with a depth of approximately 24 m below MSL. The frame at this location contained a MORS, which measured the water pressure.

Figure 2.2
Circumstances during the PUTMOR measuring campaign

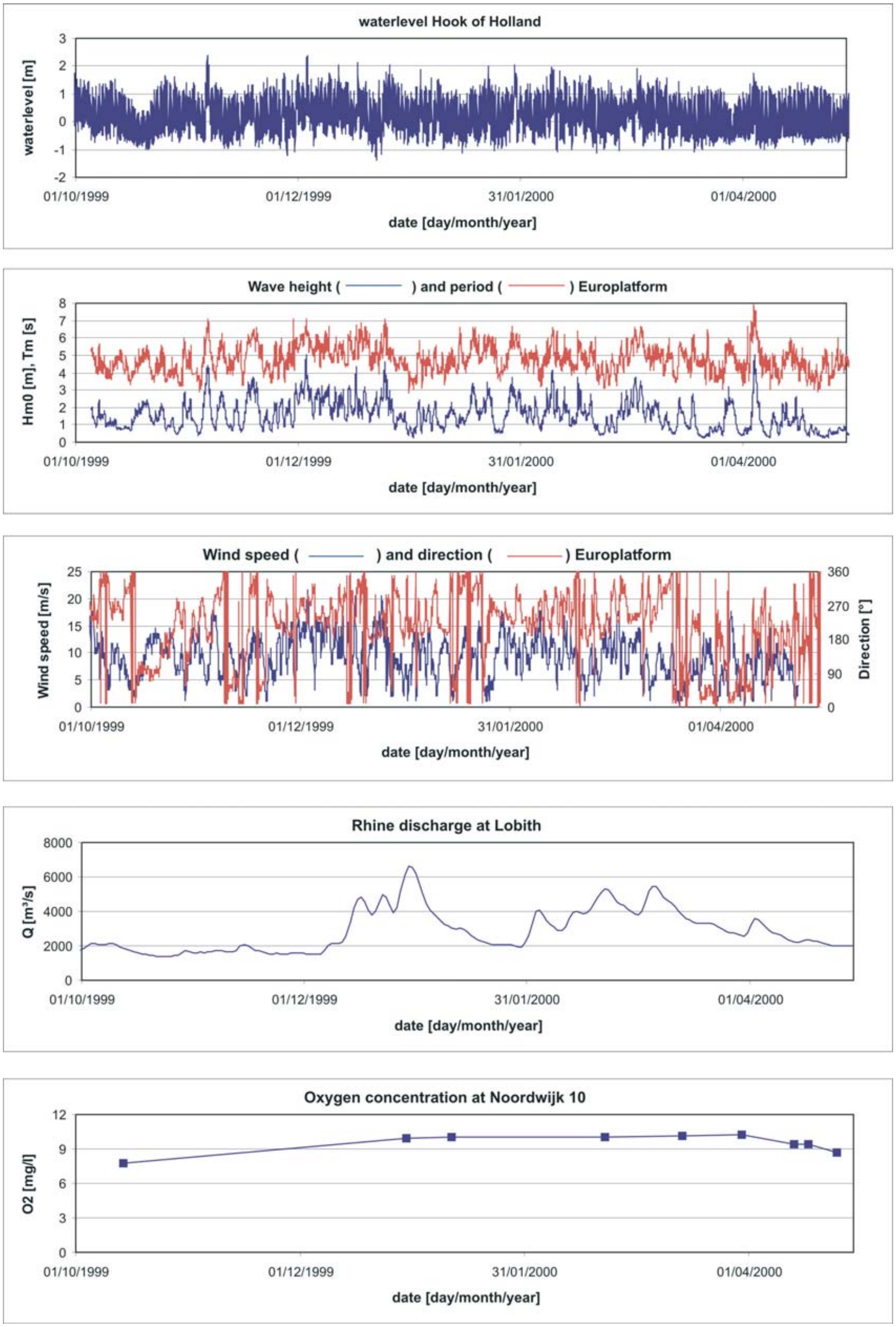
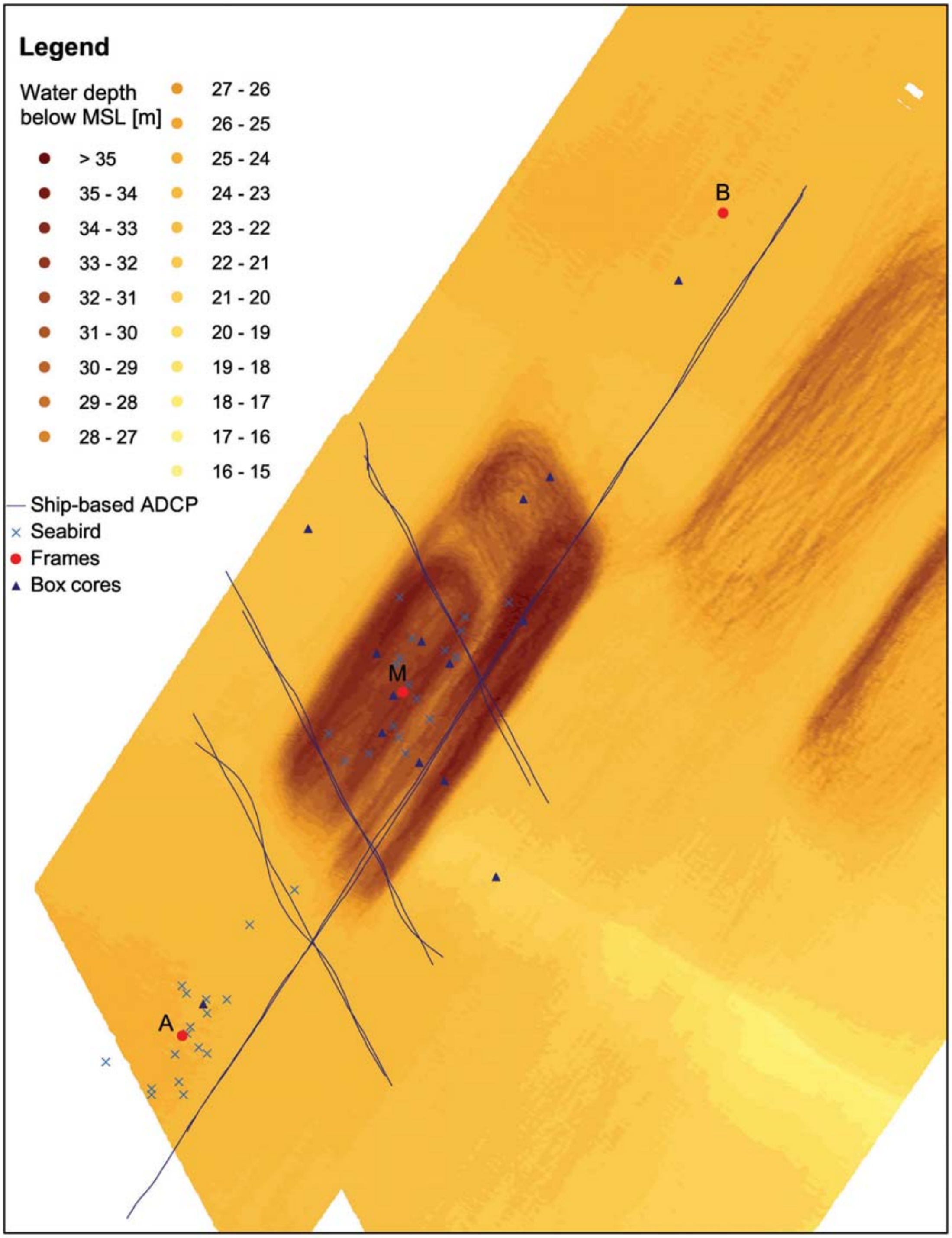


Figure 2.3
Water depths below Mean Sea Level (MSL) and the positions of measuring instruments during the PUTMOR campaign



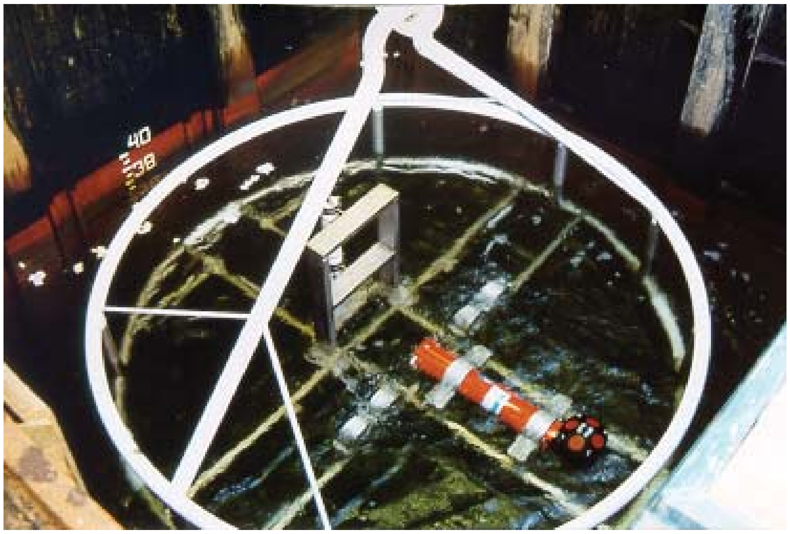


Figure 2.4
The ADCP (in red) fixed to its frame and ready to be placed at Location M [From Hoogewoning (2000)]

The frame-mounted measurements were carried out during four successive measuring periods:

1. October 14th, 1999 - November 24th, 1999
2. December 14th, 1999 - January 14th, 2000
3. January 20th, 2000 - February 21st, 2000
4. February 22nd, 2000 - March 27th, 2000

After each period the frames were serviced, but no checks were carried out on the performance of the instruments. When the frames were returned to the measuring location, the horizontal position sometimes differed a few metres from the previous position.

Ship-based measurements

Four types of ship-based measurements were carried out [Figure 2.3]:

- Ship-based ADCP instruments measured vertical velocity profiles during the flood phase and the ebb phase along tracks perpendicular and parallel to the sand pit [Figure 2.5]. The measurements included maximum ebb and maximum flood velocities and were carried out on November 23rd, 1999 and March 20th, 2000. Only the measurements of the last survey gave reliable data.
- Seabird instruments measured water temperature, salinity and oxygen concentration over the entire water column. These measurements were carried out many times inside and outside the sand pit, in the vicinity of Locations A and M.
- Bed material samples were taken from the seabed with box cores, inside and outside the pit.
- Depth soundings were carried out with Multibeam Sonar. During the 10 months that the sand pit was open, the bathymetry of the LDS was measured seven times. Figure 2.3 shows the bathymetry of October 1999.

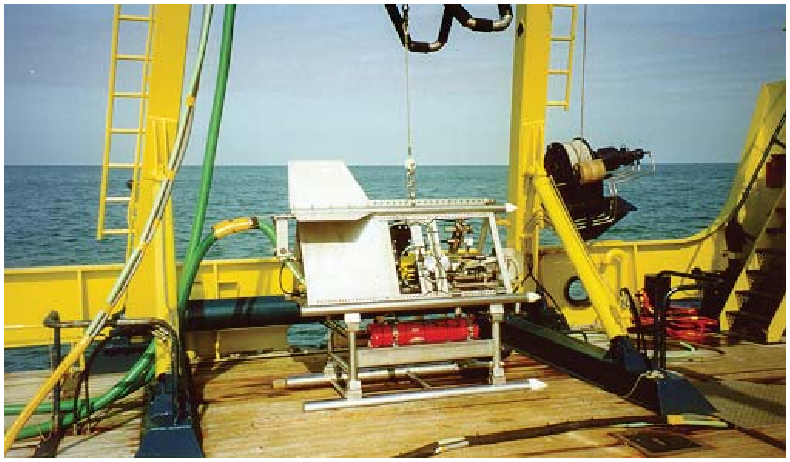


Figure 2.5
The “measuring fish” with ADCP on deck at the 22nd of November 1999, ready for measuring [from Hoogewoning (2000)]

Table 2.1
Overview of measured physical parameters during the PUTMOR campaign

Physical parameter	Instrument	Location	Temporal resolution	Elevation
water level	Hydrolab	A, M	continuous time series	related to MSL
water level	Mors	B	continuous time series	related to MSL
flow velocities (3d)	ADCP	A, M	continuous time series	vertical profile
flow velocities (3d)	ADCP	four tracks sailed over the pit	two surveys during ebb and flood	vertical profile
temperature	Hydrolab	A, M	continuous time series	seabed
temperature	Mors	B	continuous time series	seabed
temperature	Aanderaa	M	continuous time series	seabed + 2, 7, 12 22, 28 m
temperature	Seabird	inside and outside pit	1 – 2 surveys a week	vertical profile
salinity	Hydrolab	A, M	continuous time series	seabed
salinity	Aanderaa	M	continuous time series	seabed + 2, 7, 12 22, 28 m
salinity	Seabird	inside and outside pit	1 – 2 times a week	vertical profile
oxygen concentration	Seabird	inside and outside pit	1 – 2 times a week	vertical profile
turbidity	Hydrolab	A, M	continuous time series	seabed
seabed elevation	Multibeam	LDS	seven bathymetry soundings	related to MSL
sediment characteristics	Box cores	inside and outside pit	two surveys	seabed

Overview of measured physical parameters

Table 2.1 gives an overview of the physical parameters, measured during the PUTMOR campaign. These parameters comprise water level, three-dimensional velocity, temperature, salinity, oxygen concentration, turbidity, seabed elevation and sediment characteristics. In this report we will also use additional data from other sources than the PUTMOR measuring campaign.

2.4 Data processing and analysis

Hoogewoning (2000) gave a first impression of the measuring data. For the greater part, Svašek carried out the further analysis of the data. Hydrest

Figure 2.6
Sub-samples of the Reineck box corers, which were taken on February 23rd, 2000 [from Gieske and Van der Spek (2000)]

Inc. was counselled by Rijkswaterstaat for the quality control. The reports and processed data are available on the DVD enclosed with the present report. In this section we summarize the main findings; details can be found in the extensive reports of Svašek (2001A, 2001B and 2001 C).

Data processing

We have gathered an impressive dataset on flow velocity, water quality and morphology. However, part of the measurements encountered problems, with sometimes loss of data. We mention the following ones:

- The frame-mounted ADCP's at Frames A and M had many problems. For the first period no data of the ADCP on Frame A was stored. For the other three periods, this ADCP had disturbed beam velocities of one of the four beams, which means that the flow velocities had to be recalculated with the data of the other three beams. The direction of the flow velocity, which was measured with a flux compass appeared wrong and had to be calibrated with the ship-mounted ADCP measurements. With the exception of the upper part of the vertical profile, most of the data has been recovered and is available for further research. Moreover, both ADCP's gave inaccurate measurements for the upper 9.5 metres of the water column.

- The first ship-based ADCP gave a wrong direction of the flow velocity due to the disturbance of the flux compass by the hull of the vessel. These data have been rejected.
- There were doubts about the calibration of the Aanderaa String. Especially its mean values should be used with care.
- The geographical positions of two Seabird measurements are unknown: these data have been rejected.
- The first bathymetry sounding of 2000 has been rejected.

The box cores were processed by Netherlands Institute of Applied Geoscience / TNO-NITG. Gieske and Van der Spek (2000) described the first survey with the box cores, Van der Klugt (2000) described the second survey. Figure 2.6 shows a picture of sub-samples from the box cores from the first series.

Data analysis

The data analysis, carried out by Svašek (2001B and 2001C), was aimed at answering the previously defined research questions in Section 2.2. The influence of tide and wind on the measured water level and flow velocities has been investigated by means of a harmonic analysis. Furthermore, a possible correlation between water quality parameters and the hydraulic conditions has been investigated.

2.5 Validation of hydrodynamic and morphodynamic models with PUTMOR data

An important objective of the PUTMOR project is to obtain knowledge on the physical effects of a deep sand extraction pit, specifically the type of knowledge that is also applicable to other deep sand pits on the NCS. It is therefore that the PUTMOR project also includes the validation of hydraulic and morphodynamic models with the measuring data. Svašek (2001 B) performed a small model exercise with the finite-element model FINEL. Extensive model calculations have been carried out within the Co-operative Framework of Rijkswaterstaat/RIKZ and WL|Delft Hydraulics for Coastal Research (VOP Project 2). The calculations were carried out with the models DELFT3D [Walstra *et al.* (2002 A)], SUTRENCH and UNIBEST-TC [Walstra *et al.* (2002 B)]. The model exercises were aimed at the hydro- and the morphodynamic response of a deep sand pit (water level, wave heights, flow velocities, salinity, sediment transport and morphological changes).

2.6 PUTMOR project and the EU-project SANDPIT

Rijkswaterstaat is partner in the EU-project SANDPIT, which aims at measuring and modelling the physical effects of sand extraction. The PUTMOR data are input to the evaluation of the mathematical models of the SANDPIT partners. After the validation has been carried out, the design of the PUTMOR pit is applied as a reference case for scenario testing of sand pits under different hydraulic conditions.

3 Hydraulic responses of a deep sand pit

3.1 Hydraulic responses and the effect on values and user functions

In this chapter we aim at a good understanding of the hydraulic responses of a deep sand extraction pit, so that we can assess the impact of that pit on existing values and user functions. The hydraulic parameters that are possibly influenced by a deep sand pit are: flow velocities, water levels, waves and stratification [Figure 3.1]. We discuss the results of the PUTMOR measurements, using the analysis carried out by Svašek (2001B, 2001C). Furthermore we discuss the application of hydrodynamic models, using the work described by Walstra *et al.* (2003), who validated the numerical model DELFT3D with the PUTMOR measurements. Finally, we give an advise about the use of hydrodynamic models for the assessment of deep pits at other locations.

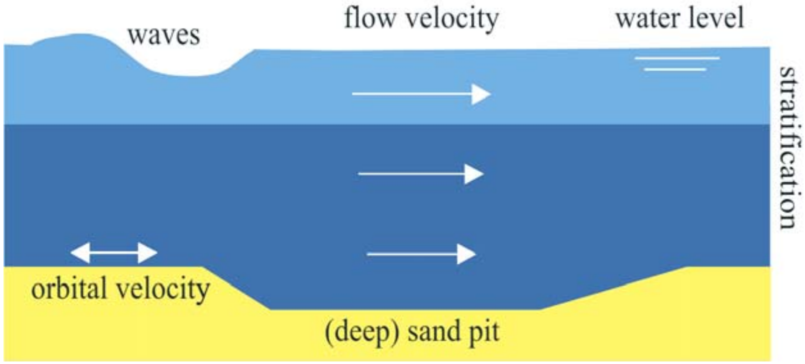


Figure 3.1
The influence of a deep pit on the hydraulic parameters flow velocities, water levels, waves (including orbital velocities) and stratification

The direct impact of the hydraulic responses of a deep sand extraction pit on values and user functions in the North Sea is very small. Considering the values and user functions, mentioned in Section 1.1, the modified currents and waves might only influence shipping traffic and coastal safety. Looking at the magnitude of the responses, we expect that vessels and the coast will hardly feel the presence of a deep sand pit.

The indirect impact on values and user functions is more important. The changed hydraulic conditions may have an effect on oxygen concentration, sediment transport and deposition of fines. In turn, these parameters can influence local ecology, the safety of the coast, offshore structures and other values and user functions [Hoogewoning and Boers (2002)]:

- When the deep sand pit causes stratification, we may expect a decrease of the oxygen concentration near the bottom. Oxygen depletion will affect benthic communities and thus the ecosystem, including fish stocks.
- Another effect is the sediment composition within the pit. Due to a decrease of the orbital velocity and current velocity near the bed, there is an increased chance on deposition of fines, which also has an effect on benthic communities.

- The modified flow velocity and waves influence the magnitude and direction of sediment transport, resulting in near field and far field bottom changes. Near field changes are those related to the pit, which can, e.g., migrate and fill up. Far field changes might occur at the sandy coast, because of a possible change in longshore current due to altered waves [Kelly *et al.* (2001)]. We thus can expect an impact on near field cables, pipelines and offshore structures and on far field shoreline position.

Table 3.1 gives an overview of the hydraulic parameters that have an impact on existing values and user functions. This table points only to the existing relationships, it does not tell whether there will be any damage on values and user functions, since this depends on the local situation.

Table 3.1
Overview of the hydraulic parameters that have an impact on existing values and user functions. Only in case of shipping traffic and coastal safety, there is a direct impact. For other user functions, there is an indirect impact through oxygen concentration, deposition of fines and bottom changes.

User function (direct) of parameter (indirect)	Flow velocity	Waves	Water levels	Stratification
Shipping traffic	X	X		
Oxygen concentration	X			X
Coastal safity		X	X	
Deposition of fines	X	X		
Bottom changes	X	X		

This chapter is focussed on the impact of a deep pit on the hydraulic conditions. The measurements carried out during the PUTMOR campaign contain also much information about the hydraulic conditions at the site in general. Where appropriate, we will use this information in the report, e.g., the residual current in Figure 4.16. A much more extensive description is found in Svašek (2001B, 2001C).

3.2 The hydraulic responses of the PUTMOR pit

The PUTMOR project provides a unique dataset of flow velocities, water levels and stratification within and outside a deep sand pit. With these measurements, we are able to determine the hydraulic response of the PUTMOR pit, concerning flow velocities, water levels and stratification. Although we did not measure waves during the PUTMOR measuring campaign, we will discuss that parameter, as well.

Flow velocities

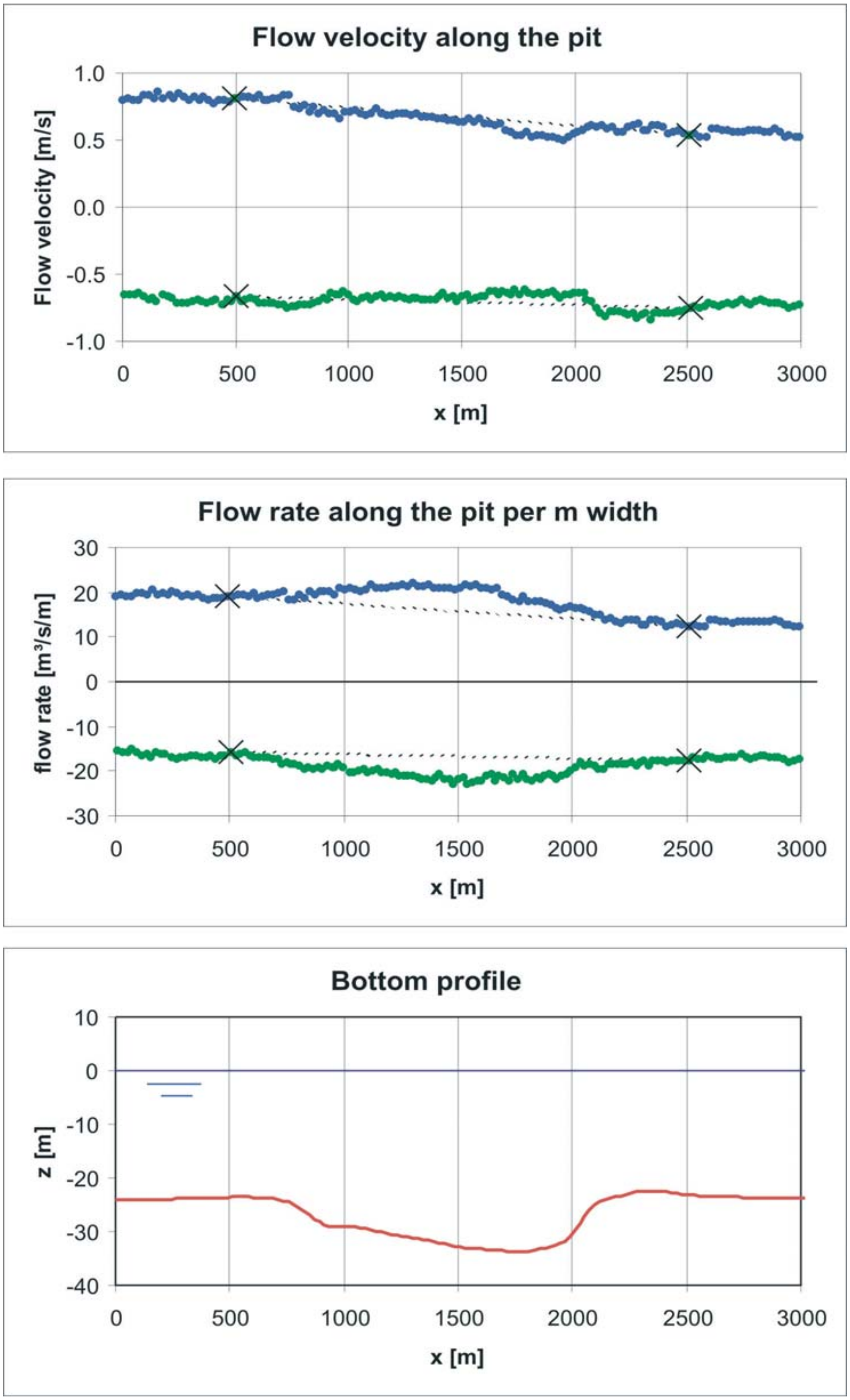
The measured flow velocities were driven by the neap-spring tidal cycle, winds and density gradients. The tide gave the largest contribution of 85% to the flow velocity, while wind contributed less than 1% near the bed up to 10% near the surface. Density gradients played a role, when river discharge conditions were high.

The presence of the pit had a noticeable effect on the measured flow velocity and flow rate (discharge per metre width). Most informative are the ship-based measurements, which covered almost the entire water column, where the frame-mounted measurements did not cover the upper 9.5 m of the water column [Section 2.4]. Since it is not possible to extrapolate those measured velocities to the surface, due to the present haline stratification, it is not possible to estimate the flow rate from the frame-mounted measurements.

. . . .

Figure 3.2

Depth-averaged flow velocities and flow rates from ship-based measurements during ebb (green, negative) and flood (blue, positive) along the longitudinal axis of the PUTMOR pit on March 20th 2000. The dashed lines in the upper two panels are interpolations between two mea-suring locations outside the pit (x = 500 m and x = 2500 m). These lines represent the undisturbed situation without the PUTMOR pit.



In Figure 3.2 we see the ship-based measured flood and ebb flow velocity and flow rate along the PUTMOR pit; the measuring track was already presented in Figure 2.2. It appears that the flow rate at the centre of the pit was 32% larger than outside the pit, both for ebb and flood. The depth-averaged flow velocity inside the pit varied a lot: in the shallow southern part, it was almost equal to the undisturbed situation, while in the deep northern part, at x = 1800 m, it decreased about 26% during flood and 11% during ebb. More detailed velocity profiles are shown in Figure 3.14.

We compare the vertical velocity profile inside and outside the PUTMOR pit, using the analysis carried out by Svašek (2001B, 2001C), for the velocity measurement 1.5 m above the bed [Bin 1] and for three different layers in the water column [Figure 3.2]. Table 3.3 shows the maximum flood velocity at High Water, and Table 3.3 shows the maximum ebb velocities Five Hours after High Water. These tables give the measured flow velocity at Bin 1 and the layer-depth averaged velocities for Layers 0 (in brackets), 1 and 2. Also the relative increase / decrease is presented. Positive values indicate a larger flow velocity inside the pit than outside the pit, and vice versa.

Table 3.2
Comparison of the average flood velocity at High Water, for the frame-based measurements at Location A (outside pit) and Location M (inside pit). Location A is situated upstream of the pit.

	Outside pit [m/s]	Inside pit [m/s]	Relative increase/decrease [%]
Bin 1	0.41	0.30	-36
(Layer 0	0.42	0.44	5)
Layer 1	0.56	0.59	5
Layer 2	0.68	0.73	7

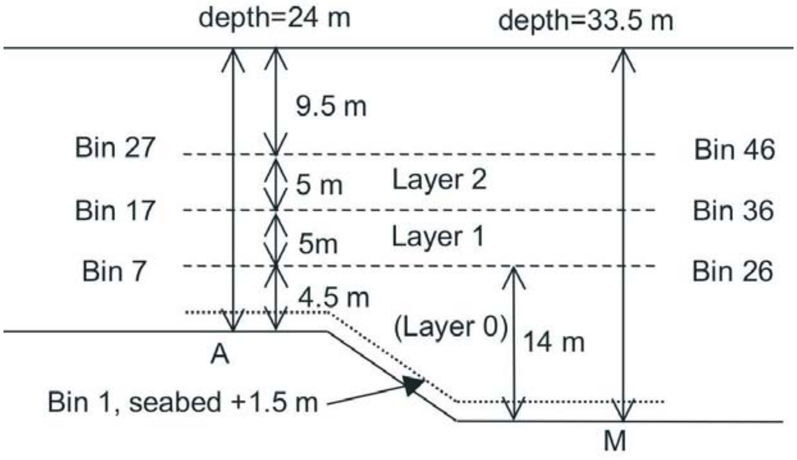


Figure 3.3
Definition of the layers, used in the analysis by Svašek (2001B, 2001C). The Layers 1 and 2 have the same elevation and thickness inside and outside the pit. However, Layer 0 has a larger thickness inside the pit (14 m) than outside the pit (4.5 m), and we consider that the comparison for Layer 0 is not very meaningful. We therefore give the results for Layer 0 in brackets.

For flood, we see an increase of the flow velocity in the upper part of the water column, while the flow velocity near the bed is much smaller inside the pit than outside the pit. For ebb, this picture is similar concerning the flow velocity near the bed. However, we see that the flow velocity in the upper part of the water column is smaller inside the pit than outside the pit.

Table 3.3
Same as Table 3.2, but for ebb velocity at 5 hours after High Water. Location A is situated downstream of the pit.

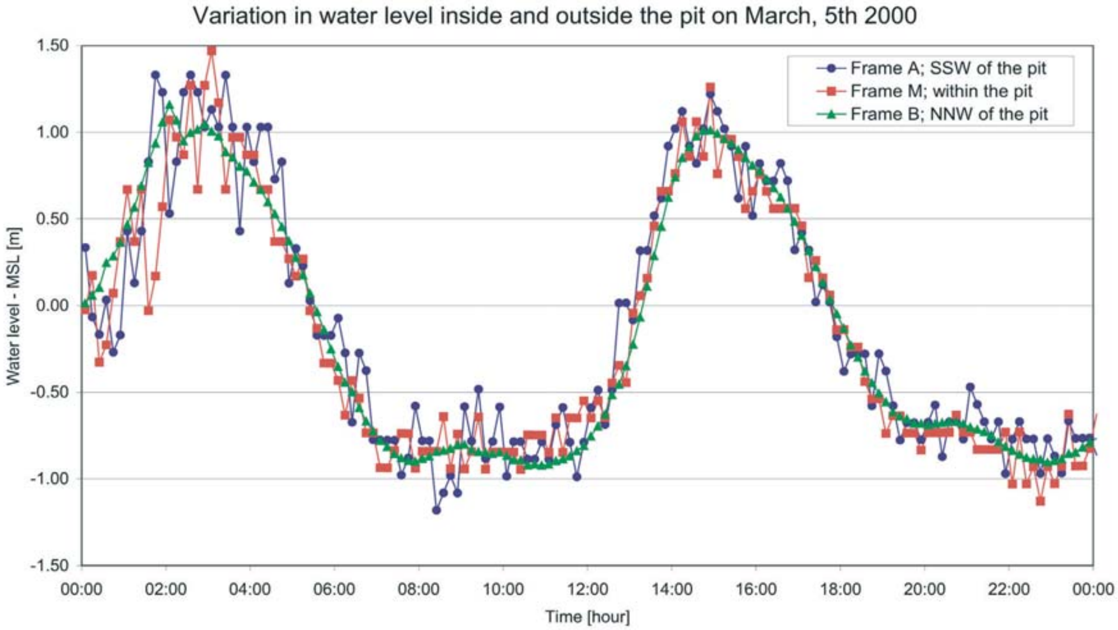
	Outside pit [m/s]	Inside pit [m/s]	Relative increase/decrease [%]
Bin 1	0.37	0.27	-27
(Layer 0	0.38	0.41	7)
Layer 1	0.54	0.54	0
Layer 2	0.62	0.58	-6

Considering these results, we expect that shipping traffic, which is sensible to the flow velocity in the upper part of the water column, will hardly feel the presence of the PUTMOR pit. Sediment transport, especially sand transport, is however most sensible to the flow velocity in the lower part of the water column, which showed a large decrease inside the sand pit. We therefore may expect a deposition of fines and sand on the bottom of the PUTMOR pit.

Water levels

The PUTMOR measurements show that the differences between the water levels within and outside the sand pit are small; the measured M2 amplitudes had differences less than 1 cm [Svašek (2001b)]. Figure 3.3 shows the variation of the water level during the tidal cycle, at the three locations. These measurements were taken on March 5th, 2000, during neap tide with relatively large waves [Figures 3.6 and 3.7].

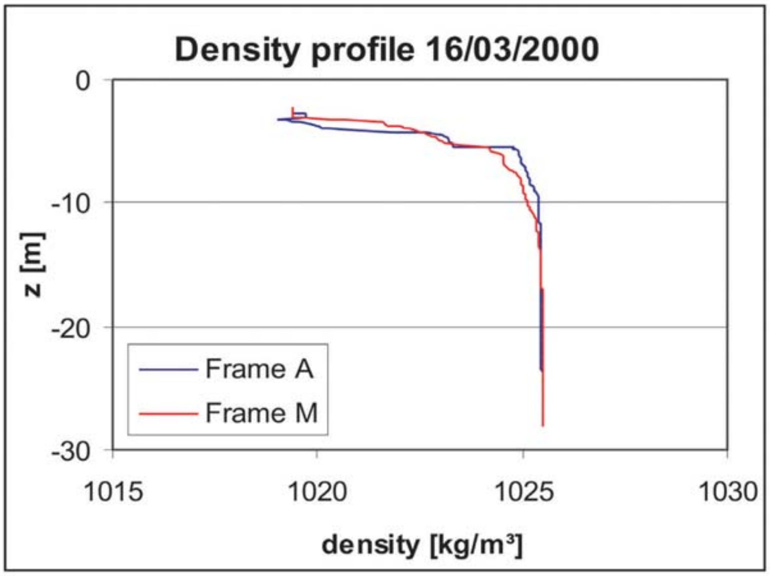
Figure 3.4
Measured water level variation at the three measuring frames during the PUTMOR project. The Hydrolabs at Frames A and M show instantaneous water depths with a resolution of 0.10 m, while the Mors pressure sensor at Frame B stored average values over a 10 minutes time-interval [Svašek (2001a)]. Apart from this aspect, we do not see clear differences between the measurements.



Stratification

Stratification might occur in case of an increased water depth, in combination with a decreased current velocity. For the PUTMOR pit, we see that the impact of the pit on the density profile is not noticeable. Figure 3.4 shows a representative example of the density profile at March 16th, 2000; none of the measured profiles shows a significant difference between the locations inside and outside the pit Svašek (2001b). Since stratification is a major cause for oxygen depletion, we will further discuss this topic in Chapter 4.

Figure 3.5
Ship-based measured density profile at Frame A and M. The differences are small, which is also the case for most other measured density profiles. The figure shows haline (salinity) stratification due to the river Rhine runoff.



Waves

We do not have measurements that give information about the effect of the PUTMOR pit on waves. A deep sand pit might change the wave height due to dissipation, refraction and reflection. Model calculations on sand extraction at other locations indicate how the significant wave height changes. Boers and Jacobse (2000) showed that sand extraction on the Zeeland banks might increase the significant wave height with a maximum of 10 % relative to the present wave height, just shoreward from the banks. Kelly *et al.* (2001) computed the same order of wave height increase for sand extraction on sand banks east of the United States. Allersma and Ribberink (1992) calculated that a 5 meter deep sand pit at a water depth of 14 meter increases the significant wave height with a maximum of 5%. Roelvink (2001) came with similar conclusions. In all cases, we see that the effect of the sand pit on the wave height decreases from the pit to the coast, where it can affect the longshore sediment transports. For sand pits at water depths deeper than 20 meter, we expect that the increase of the significant wave height will be less than 5% in the vicinity of the pit and that the increase at the coast is negligible.

Waves manifest themselves not only in a vertical movement of the water surface, but also in orbital flow velocities below the surface. These velocities attenuate downward from the water surface, so, if the water depth increases due to a sand pit, the orbital velocities near the bottom will decrease and sediment deposition is enhanced.

3.3 Hydrodynamic models applied to a deep sand pit

When we assess the possible hydraulic responses of a proposed deep pit and the influences on existing values and user functions, we usually do not have detailed information, like the PUTMOR data. In that case we can opt for reliable, validated hydrodynamic models.

Before the PUTMOR project started, there were already a number of model predictions on hydraulic responses of a sand pit. Most of them concerned schematized sand pits and hydraulic conditions. Svašek (1998) modelled a rectangular sandpit of 20 km X 2 km with the length axis parallel to the flow direction. The model predicted a 2DH, depth-averaged flow velocity for a stationary case and a tidal case. Klein (1999) predicted the flow velocity for a number of pits with varying length, width, extraction depth and orientation against the flow. He considered stationary and tidal flow, both with and without Coriolis effect. Van Rijn and Walstra (2004) and Hoogewoning and Boers (2002) gave more information about hydrodynamic models. As part of the PUTMOR project, WL|Delft Hydraulics validated the model DELFT3D in 2DH and 3D mode, including density effects, using the PUTMOR field data. This implies application of realistic bottom data and hydraulic boundary conditions [Walstra *et al*. (2002B) and Walstra *et al.* (2003)].

In the following of this section we borrow parts of Walstra *et al.* (2003) (with small modifications). The full publication can be found on the enclosed DVD.

Overview of the Delft3D model

The Delft3D model fully integrates the effects of waves, currents, and sediment transport on morphological development [Nicholson *et al*. (1997)]. The model simulates these processes on a curvilinear grid system, which allows for a very efficient and accurate representation of complex areas. The SWAN-model is used as the wave module in Delft3D. The flow module of Delft3D is a multi-dimensional (2D or 3D) hydrodynamic and sediment transport simulation program which calculates non-steady flow and transport phenomena resulting from wave, tidal and meteorological forcing on a curvilinear, boundary fitted grid.

Data selection and model schematisations

For the validation two representative periods were considered [Figure 3.6]. The first period is during neap tide with relatively high waves and strong winds. The second period is during spring tide with low waves and winds. During Period 1 the wind mainly comes from the West with an average wind speed of about 12 m/s. For Period 2 the wind speed is usually less then 5 m/s [Figure 3.7].

The hydrodynamic evaluation is performed as a hindcast in which all (measured) forcing conditions are imposed on the model as accurately as possible. Measured waves, wind and river discharges were used in the simulations, while the tidal forcing was obtained from the HCZ-model [Roelvink *et al.*, (2001)] , covering a large part of the Dutch coastal zone [Figure 3.8]. The horizontal computational grid of the local model has a resolution varying from 40 m in the pit to 1500 m at the model boundaries [Figure 3.9]. The bathymetry in the surroundings of the LDS was obtained from the PUTMOR survey after construction of the pit. The remaining

Figure 3.6
Measured deep-water wave conditions
at Licht Eiland Goeree (LEG).

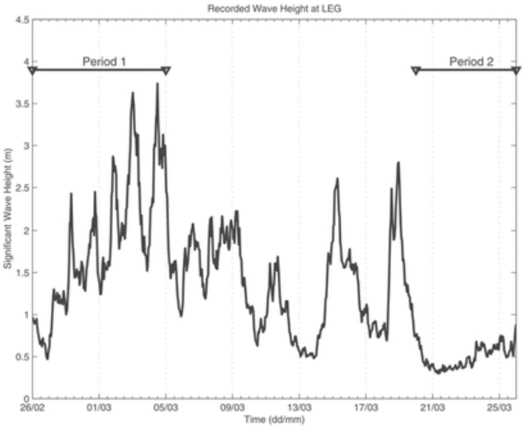
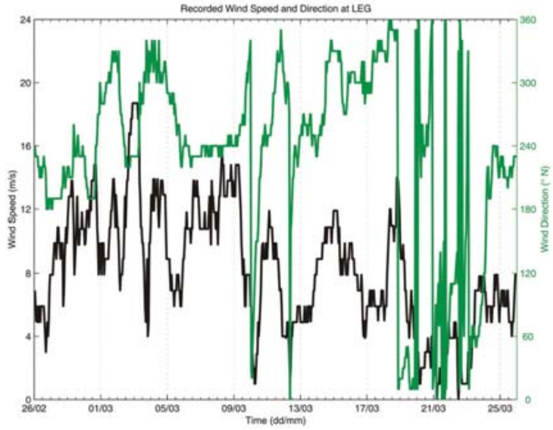


Figure 3.7
Measured wind speed and direction
at Licht Eiland Goeree (LEG).



bathymetry was obtained from the HCZ model bathymetry. Both lateral boundaries were velocity boundaries, whereas the coast parallel seaward boundary was largely a water level boundary. Depth-averaged (2DH) and 3-dimensional (3D) simulations were carried out for both periods. For the hydrodynamic validation of the 3D model a vertical grid with 10 equidistant layers was used. In the 3D morphodynamic simulations the flow-model used a non-equidistant vertical grid of 10 layers, as a relative high resolution is required near the bed. The layer distribution was set to (in % of the water depth from surface to bottom): 10.00, 10.00, 15.00, 22.50, 15.75, 10.50, 6.75, 4.50, 3.00, and 2.00. In Table 3.4 an overview is given of the simulations that were carried out.

Figure 3.8
HCZ-model grid.

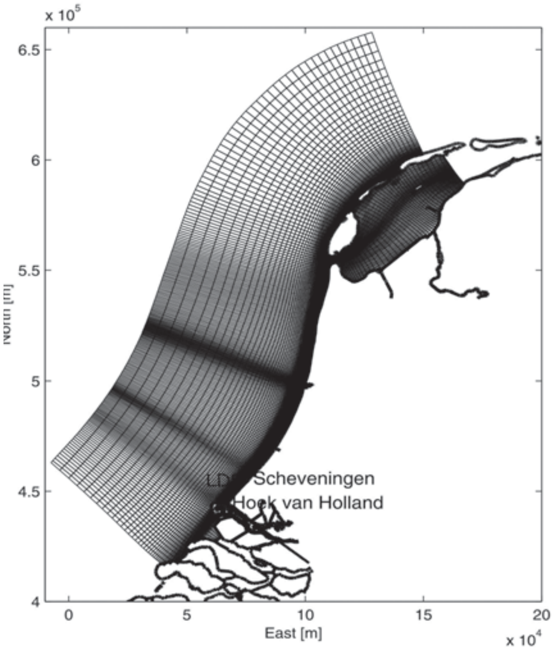


Figure 3.9
Local model grid.

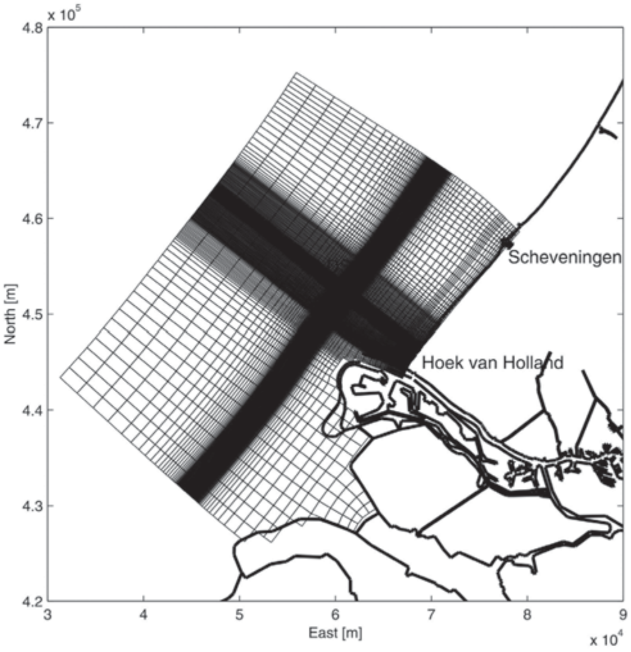


Table 3.4
Overview of Delft3D simulation

	Simulations for Period 1			Simulations for Period 2			
Parameter	**2DH-1.1**	**2DH-1.2**	**2DH-1.3**	**3D-1**	**2DH-2.1**	**2DH-2.2**	**3D-2**
Waves	+	−	−	+	−	−	−
Salinity	+	+	+	+	+	−	+
Wind	+	+	−	+	+	+	+

Overview of statistical parameters

For an objective evaluation of the model performance the following statistical parameters are used: the linear correlation coefficient (*r*), the best-fit slope forced through the origin (*m*), the root mean square error (ϵ_{rms},) and the Relative Error Vector (REV):

$$REV = \frac{\left\langle \sqrt{(u_{meas} - u_{calc})^2 + (v_{meas} - v_{calc})^2} \right\rangle}{\left\langle \sqrt{(u_{meas} + v_{meas})^2} \right\rangle} \qquad (1)$$

The REV is used to evaluate the velocity vectors and was developed in the Coast3D project [Van Rijn *et al.* (2002)]. As experience with this parameter is limited, only a preliminary indication was given of the interpretation of this statistic, which is summarized in Table 3.5. In the statistical analysis the error ranges in the measurements were not included even though these may have a considerable influence on the outcome of the statistical parameters.

Validation of Delft3D

Table 3.5
Qualification of the Relative Error Vector (REV).

Qualification	**REV**
Excellent	<0.2
Good	0.2-0.4
Reasonable/Fair	0.4 - 0.7
Poor	0.7 - 1.0
Bad	>1.0

The hydrodynamic validation is primarily based on the statistical parameters described above. However, to give an indication of the model performance first a limited number of time series and vertical velocity profiles will be compared with measurements. The visual comparison is made for a part of Period 1 in which the 2DH and 3D results are shown with all effects (wind, waves and salinity) included.

In Figure 3.10, where the predicted and measured water levels are compared, occasionally relative large errors are present, which are probably caused by poor boundary conditions of the HCZ model, since moving pressure fields or other meteorological effects are not taken into account in the model. The difference in water levels between the 2DH and 3D simulations was negligible.

Figure 3.11 compares the depth-averaged longshore and cross-shore velocities for the 2DH and 3D simulations. Both in 2DH and 3D the model performs reasonably well, but in 3D the model shows an improved agreement in both the longshore and cross-shore direction. Notice that the large deviations in the water level predictions on 27/02 are not reflected in the velocity predictions. The relatively large phase error between 29/02 12:00 to 1/03 00:00 in water level predictions does result in deviating velocity predictions. In Figure 3.12 predicted and measured velocities at the lowest and highest available vertical measuring positions are shown for Locations A and M. The agreement at the upper level is reasonable for the longshore component, whereas the cross-shore component has a large amount of scatter that occasionally results in relatively large deviations. Near the bed there is a remarkable agreement for most of the time in both longshore and cross-shore direction. The deviations on 29/02 are again caused by the phase error mentioned earlier.

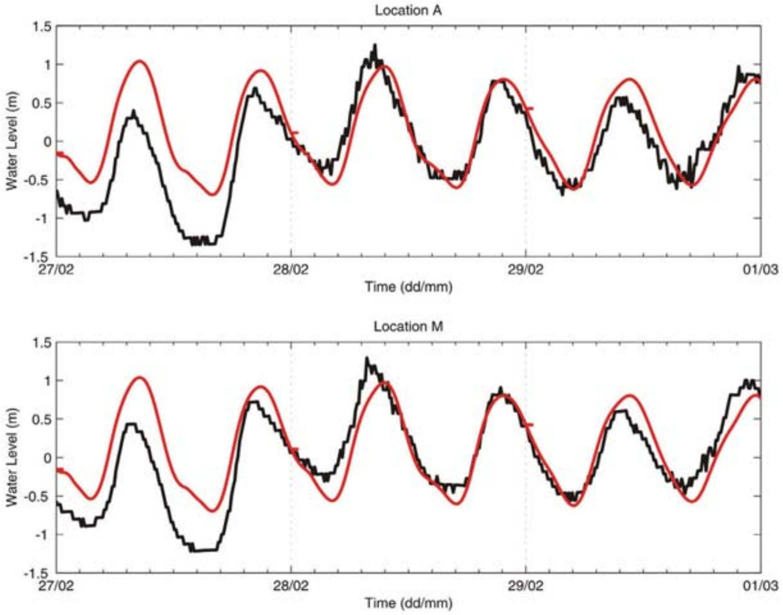


Figure 3.10
Comparison of water levels at Locations A and M (red: Delft3D, black: measurements).

Figure 3.11

Comparison of depth-averaged longshore and cross-shore velocities at Locations A and M (red: 2DH, blue: 3D, black: measurements).

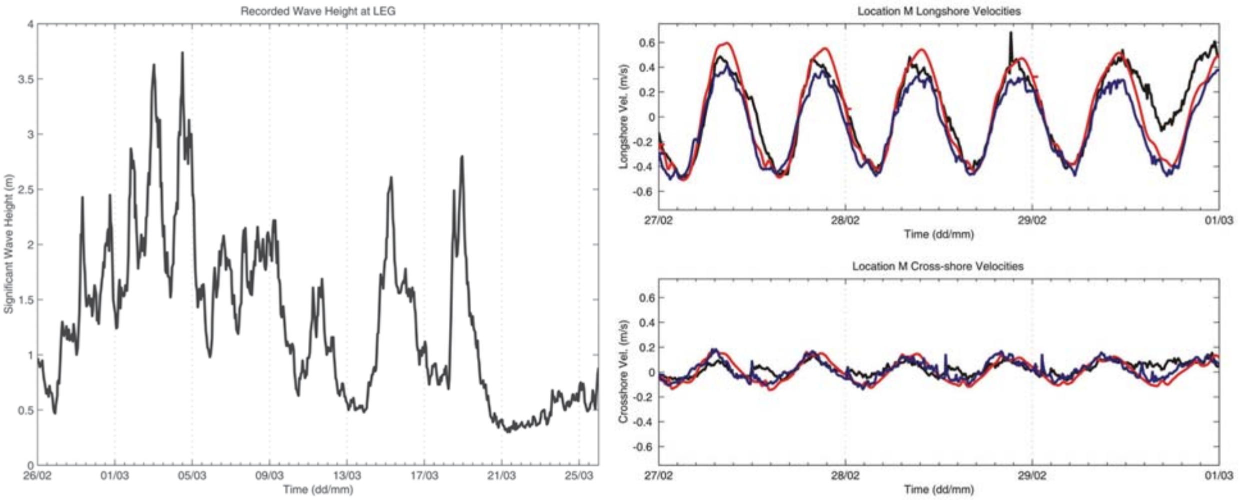
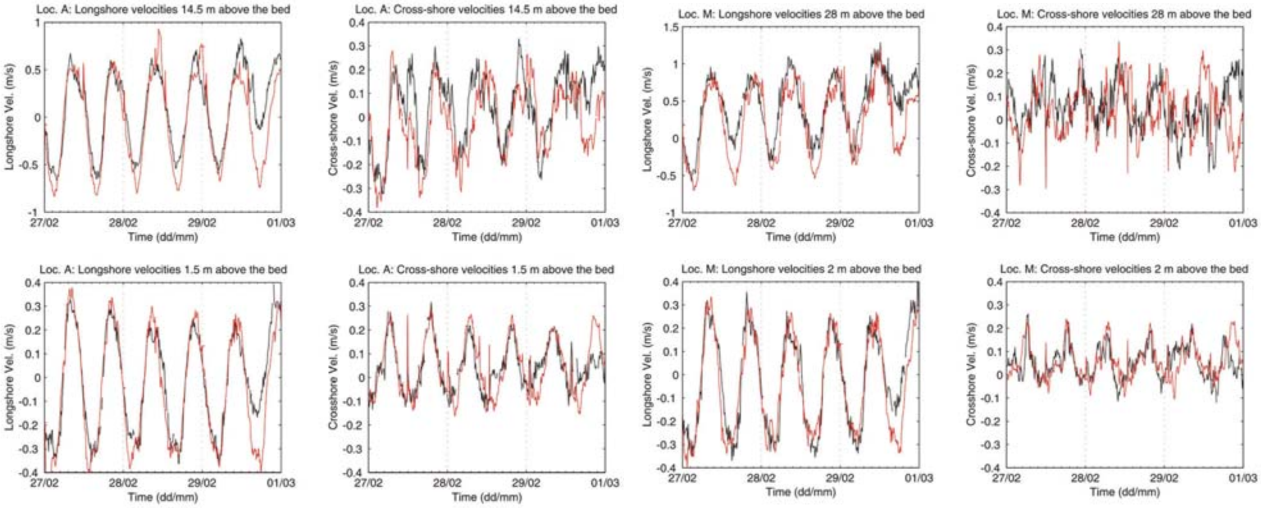


Figure 3.12

Comparison of longshore and cross-shore velocities at Locations A and M (red: Delft3D, black: measurements).blue: 3D, black: measurements).

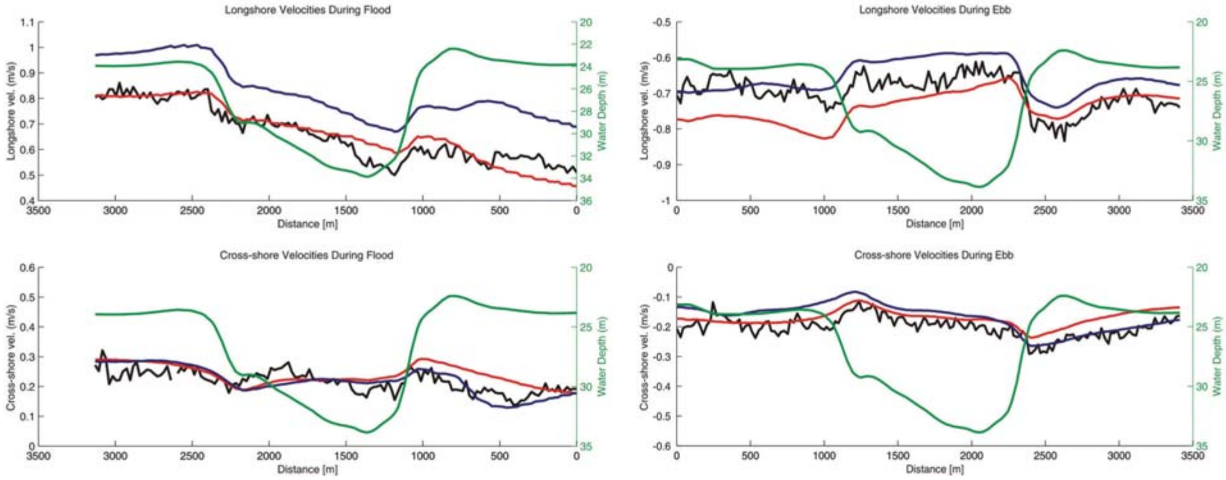


In Figure 3.13 the depth-averaged velocities along Track 1 (approximately 35N, directed parallel to the main tidal direction, see Figure 2.3) are compared during maximum flood and ebb. The pit causes a deceleration in the longshore velocities, which is also predicted by the model. The pit approximately has the same effect on the cross-shore velocities but to a smaller extent. The accuracy with which the cross-shore velocities are reproduced in both 2DH and 3D is remarkable. It is somewhat disappointing to see that the longshore flood velocities are somewhat over-estimated by the 3D simulations. This is investigated further by examining the vertical velocity profiles in Figure 3.14.

The over-predictions during flood, shown in Figure 3.14, are mainly caused by an over-estimation of the velocities in the upper part of the water

Figure 3.13

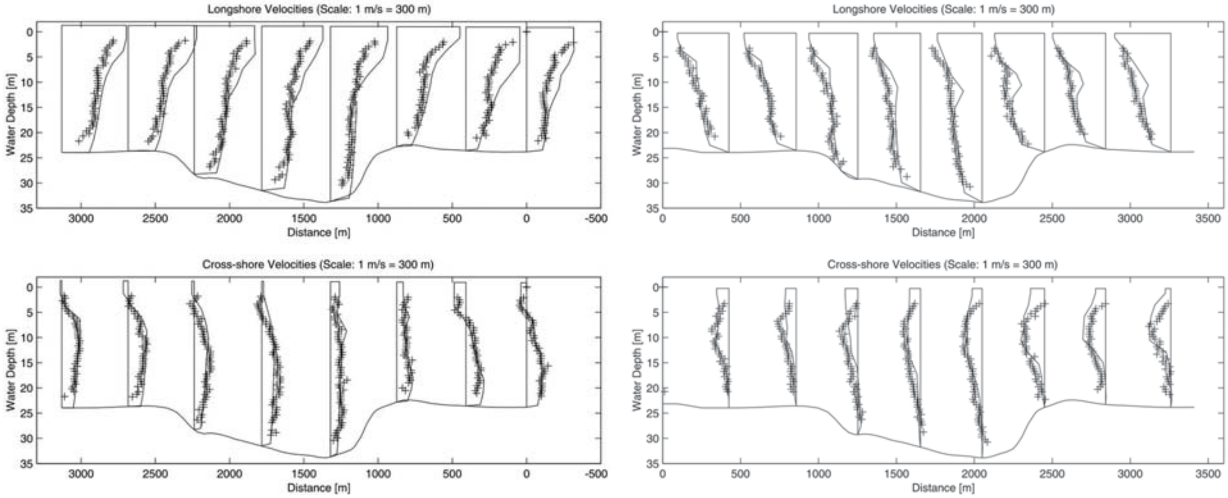
Comparison of depth-averaged longshore and cross-shore velocities along Track 1 during maximum flood (red: 2DH, blue: 3D, black: measurements on March 20, 2000).



column. However, in the lower part of the water column the model gives an accurate prediction of the longshore velocities. During ebb the longshore velocities are well predicted for the entire water column.
The vertical distribution of both the measured and computed longshore velocities has a logarithmic-shape in the lower half of the water column. However, the longshore velocities near the water surface increase significantly especially during flood. The increase seems related to haline stratification due to the outflow of the river Rhine as wind and waves were low during the time period considered (Hs < 0.5 m and wind < 5 m/s). This feature is over-estimated, but qualitatively reproduced well by the model.
The cross-shore velocities have a complex vertical distribution in which reversal of the flow direction is occasionally present. This phenomenon is also reproduced well by the model.

Figure 3.14

Comparison of measured (crosses) and calculated (solid) velocity profiles (top: longshore; bottom: cross-shore) for Track 1 during maximum flood (left) and maximum ebb (right).



Statistical evaluation of model performance

The statistical results, based on an evaluation of the time series at Locations A and M, are summarized in Table 3.6. The statistics of the 3D model performance were determined by depth-averaging the statistics calculated at each available vertical measurement. We discuss the vertical distribution of the error statistics later.

Table 3.6

Statistics for Water Levels and Depth-averaged Velocities at Locations A and M.

Loc. A	**Water Levels**			**Longshore Velocity**			**Cross-Shore Velocity**			**Vector**
Run-ID	**R**	**m**	ϵ_{rms}	**r**	**m**	ϵ_{rms}	**R**	**M**	ϵ_{rms}	**REV**
2DH-1.1	0.76	0.67	0.42	0.89	0.99	0.18	0.73	0.66	0.09	0.51
2DH-1.2	0.76	0.68	0.44	0.89	1.01	0.18	0.75	0.70	0.09	0.50
2DH-1.3	0.75	0.67	0.45	0.88	0.98	0.19	0.74	0.71	0.09	0.50
3DH-1	0.76	0.67	0.42	0.86	0.93	0.21	0.71	0.75	0.11	0.54
2DH-2.1	0.97	0.99	0.28	0.98	1.15	0.13	0.90	0.79	0.07	0.32
2DH-2.2	0.97	1.01	0.25	0.98	1.15	0.13	0.91	0.73	0.07	0.31
3DH-2	0.97	0.99	0.28	0.97	1.02	0.12	0.83	0.83	0.11	0.31
Loc. M	**Water Levels**			**Longshore Velocity**			**Cross-Shore Velocity**			**Vector**
Run-ID	**R**	**m**	ϵ_{rms}	**r**	**m**	ϵ_{rms}	**R**	**m**	ϵ_{rms}	**REV**
2DH-1.1	0.77	0.73	0.39	0.91	1.01	0.16	0.71	1.06	0.06	0.46
2DH-1.2	0.78	0.71	0.41	0.91	1.01	0.15	0.73	1.07	0.06	0.44
2DH-1.3	0.77	0.70	0.42	0.91	0.99	0.16	0.73	1.08	0.06	0.45
3DH-1	0.77	0.73	0.39	0.88	0.88	0.19	0.63	0.78	0.09	0.50
2DH-2.1	0.97	0.96	0.31	0.98	1.12	0.11	0.89	1.15	0.06	0.26
2DH-2.2	0.97	0.98	0.29	0.99	1.14	0.11	0.89	1.08	0.05	0.24
3DH-2	0.97	0.96	0.31	0.98	0.96	0.12	0.84	0.86	0.09	0.28

The error statistics show that the trends in water level predictions are reasonable with correlation coefficients of 0.76 and 0.97 for Periods 1 and 2, respectively. The velocities are reproduced well with correlation coefficients generally exceeding 0.9, whereas the root mean square error for the velocities lies between 0.11 and 0.21 m/s for the longshore velocities and between 0.06 and 0.11 m/s for the cross-shore velocities. The effects of wind, waves and salinity on the 2DH-simulations had only limited effect on the error statistics. The error statistics of the depth-averaged velocities from the 3D simulations are comparable to the results of the 2DH-simulations. As it was the case for the 2DH-simulations, the 3D cross-shore velocities had lower correlations and m-values compared to the statistics of the longshore velocities. According to the definition given in Table 3.5, the REV indicates a 'reasonable' prediction for Period 1, when the wind speed was large, and a 'reasonable to good' prediction for Period 2, when the wind speed was low.

Figure 3.15 shows the statistics of the 3D simulations as a function of the vertical coordinate for Periods 1 (solid) and 2 (dashed), red indicates the longshore component and green the cross-shore component. The

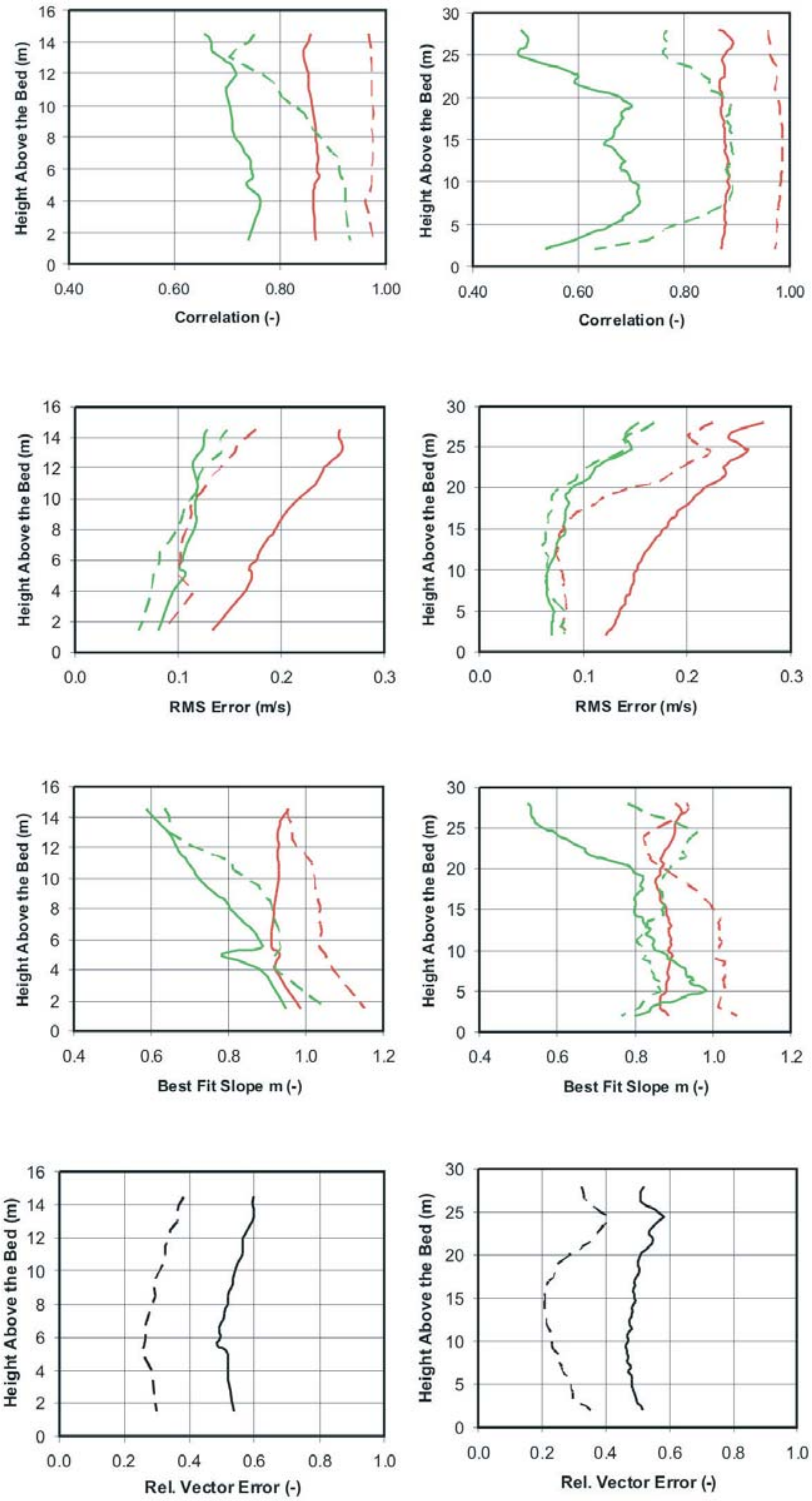
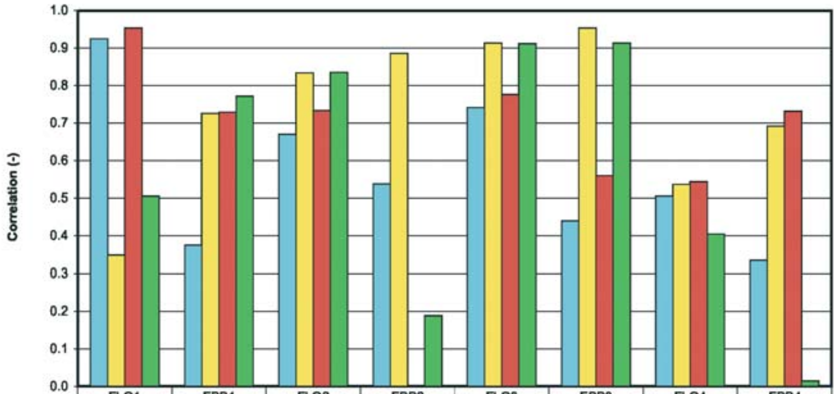


Figure 3.15
Statistic results for comparison of measured and computed velocities for Period 1 (solid lines) and Period 2 (dashed lines) at Locations A (left column) and M (right column), colors indicate longshore (red) and cross-shore components (green).

correlation (top row of plots) for the longshore velocities is almost constant along the vertical. However, the cross-shore velocities show a decreasing correlation higher in the water column which is most pronounced for Location M. The model has a higher correlation for the longshore velocities than the cross-shore velocities at both locations.

It is interesting to see that for both periods the cross-shore velocity correlation has a similar vertical distribution at Location M with relatively low correlations (0.55 and 0.65 for Period 1 and 2) near the bed. The lower correlation of the cross-shore velocities compared to the longshore correlation is mainly due to the significantly lower cross-shore velocities. This is confirmed by the ϵ_{rms} (second row of plots), which is significantly lower for the cross-shore velocities. The ϵ_{rms} values for both locations are comparable and show a gradual increase higher in the water column. The best-fit slope, *m*, decreases significantly, higher in the water column for the cross-shore velocities. This seems to give a somewhat negative impression of the cross-shore velocity predictions, which is not confirmed by the time series comparisons. The decreased *m*-values are probably caused by outliers, which have a large effect on the resulting best-fit slope. The REV is also approximately constant across the vertical with values in the range of 0.5 to 0.6 for Period 1 and 0.2 to 0.4 for Period 2 which results in a 'reasonable to fair' and 'good' qualifications for Period 1 and 2, respectively.

The vertical distribution of most statistics is approximately similar for both periods, which illustrates the capability of the model to give accurate predictions under different conditions over most of the water column.

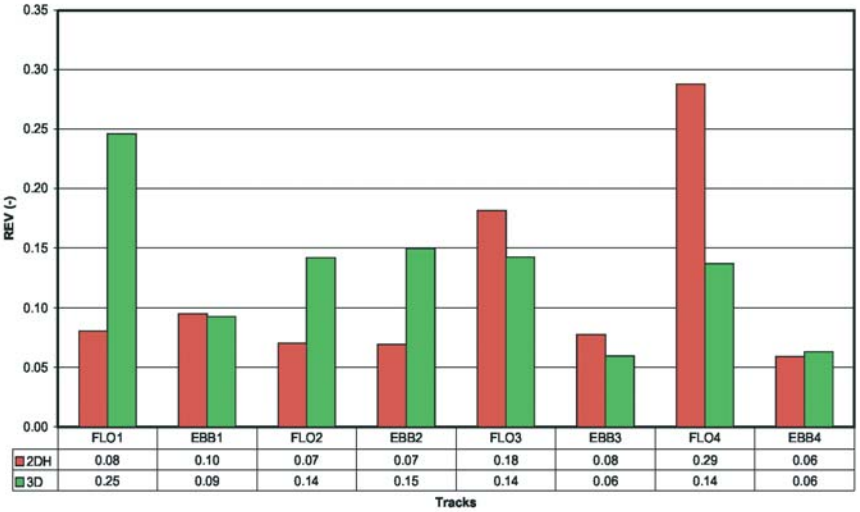


	FLO1	EBB1	FLO2	EBB2	FLO3	EBB3	FLO4	EBB4
🟦 2DH-Ulong	0.92	0.37	0.67	0.54	0.74	0.44	0.50	0.33
🟨 2DH-Ucross	0.35	0.73	0.83	0.89	0.91	0.95	0.54	0.69
🟥 3D-Ulong	0.95	0.73	0.73	-0.74	0.78	0.56	0.54	0.73
🟩 3D-Ucross	0.50	0.77	0.84	0.19	0.91	0.91	0.40	0.01

Tracks

Figure 3.16
Correlations of depth-averaged velocities derived from the 2DH and 3D simulations along the four tracks.

The performance of the model for the tracks of the ship-based velocity measurements is summarized by comparing the correlation [Figure 3.16] and Relative Error Vector [Figure 3.17] along all four tracks. The relative large variation of the correlations is mainly due to the limited number of data points. The 3D-simulations have a slightly higher overall correlation for longshore as well as cross-shore velocities. Interestingly, the cross-shore velocity correlations have, on average, approximately the same value as the longshore correlation. In general the Relative Error Vector lies below 0.2 for both the 2DH and 3D simulations, which classifies these model results as 'Excellent' according to the qualifications of Table 3.5.



	FLO1	EBB1	FLO2	EBB2	FLO3	EBB3	FLO4	EBB4
🟥 2DH	0.08	0.10	0.07	0.07	0.18	0.08	0.29	0.06
🟩 3D	0.25	0.09	0.14	0.15	0.14	0.06	0.14	0.06

Figure 3.17
Relative Error Vectors of depth-averaged velocities derived from the 2DH and 3D simulations along the four tracks.

3.4 Reliability of hydrodynamic models for deep sand pit assessment

The results of the hydrodynamic model validation gives an impression of what is possible with hydrodynamic models for predictions on deep sand pits in a complex environment. It appears that the flow velocity calculations are reasonable to good *[for definition of these qualifications see Table 3.5]*. With this validation, the DELFT3D model has been qualified for flow velocity and water level predictions on a deep sand pit (with an extraction depth up to 10 m) for an environment with pronounced density differences. We recommend that other hydrodynamic models also be validated with the PUTMOR measuring data, to increase the number of qualified models.

4 Oxygen and stratification in a deep sand pit

4.1 Concerns about hypoxia in a deep sand pit

In In this chapter, we investigate if we can expect oxygen depletion at deep sand pits on the NCS. It has been a major concern in The Netherlands that hypoxia or oxygen depletion can develop near the bottom of deep sand pits with negative effects on benthos and other sea life inside these pits. It has also been feared that sudden releases of oxygen-depleted water from those pits cause ecological harm in their vicinity [Van Breukelen and Van Woerden (2002)].

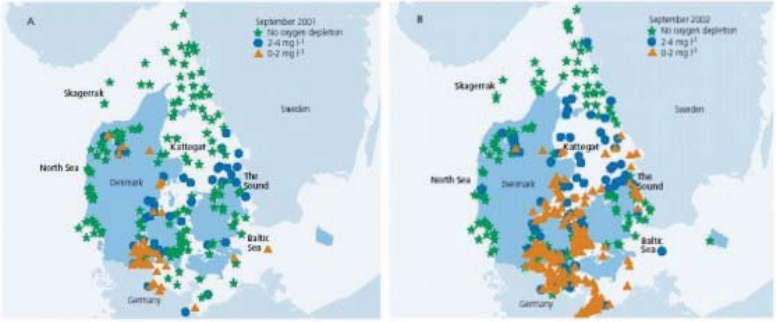


Figure 4.1
Oxygen depletion is a major problem in the Kattegat, the Sound and the Baltic Sea between Denmark, German and Sweden [Ærtebjerg *et al.* (2003)]. It is caused by haline and thermal stratification and a large supply of nutrients.

Although there is no record of severe oxygen depletion on the NCS, neither in the undisturbed environment, nor in former extraction sites, we know that oxygen depletion is a problem in adjacent areas like the former estuaries of Rhine-Meuse Delta (Lake Grevelingen, Lake Veere, Kramer, Volkerak) and the Kattegat and Sound between the North Sea and the Baltic Sea [Figure 4.1]. Even in the German Bight, eastward from the NCS, low oxygen concentrations were observed during the early eighties of the previous century. Those low concentrations were caused by eutrophication, due to the high nutrient load from the Rhine and Elbe rivers during that time.
An illustrative example of oxygen depletion due to sand pits is found in the Grevelingen Lake, a former estuary of the Rhine-Meuse Delta in The Netherlands. In 1971, the Brouwers Dam closed the western, seaward entrance of this estuary, while the Grevelingen Dam had already closed the eastern riverward entrance in 1965 [Figure 4.2]. The length of the lake is about 23 km, the width varies between 4 and 10 km, and the area covers 108 km^2. Near the Brouwers Dam, two sand pits are found, the pits of Scharendijke, with a water depth of 48 m, and Den Osse, with a water depth of 38 m [Figure 4.2; Locations 3 and 6]. The closure of the estuary implies that the tidal motion has ceased to exist, resulting in low current velocities, minimal vertical mixing, an increased haline and thermal stratification, and a long residence time of the water in the sand pits. These processes enhance the possibilities of oxygen depletion near the bed. For the pit of Scharendijke oxygen depletion happens from May till November [Figure 4.3]. There are plans to increase oxygen levels by an increased water exchange with the North Sea, so that stratification does not occur for water depths shallower than 15 meters. However, in the sand pits, stratification and low oxygen levels are still expected in the future.

Figure 4.2

Map and oxygen profile Grevelingen [Hoeksema (2002)] (The oxygen concentration assessment criterion in the Netherlands is 5 mg/l for fresh water.)

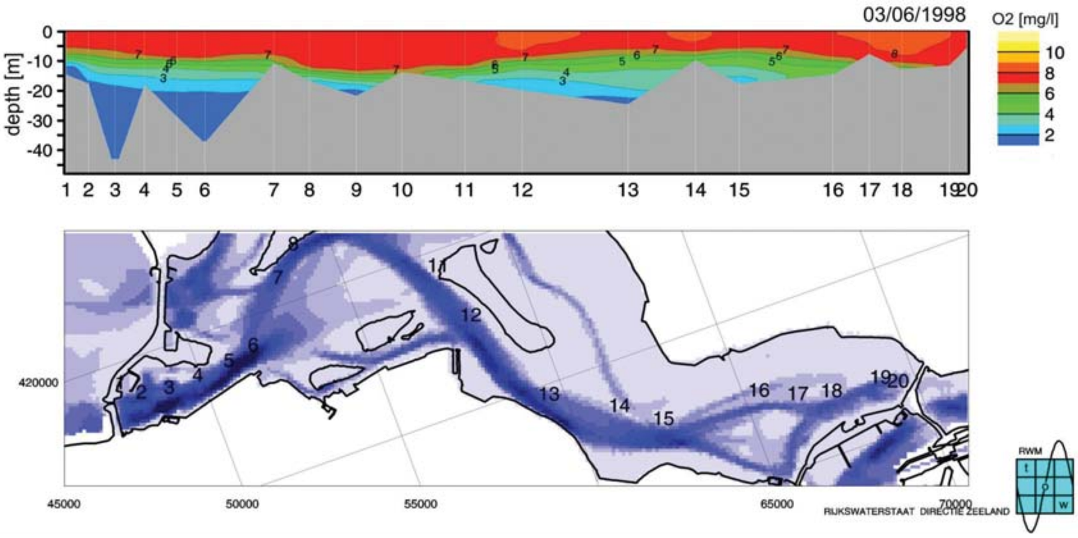
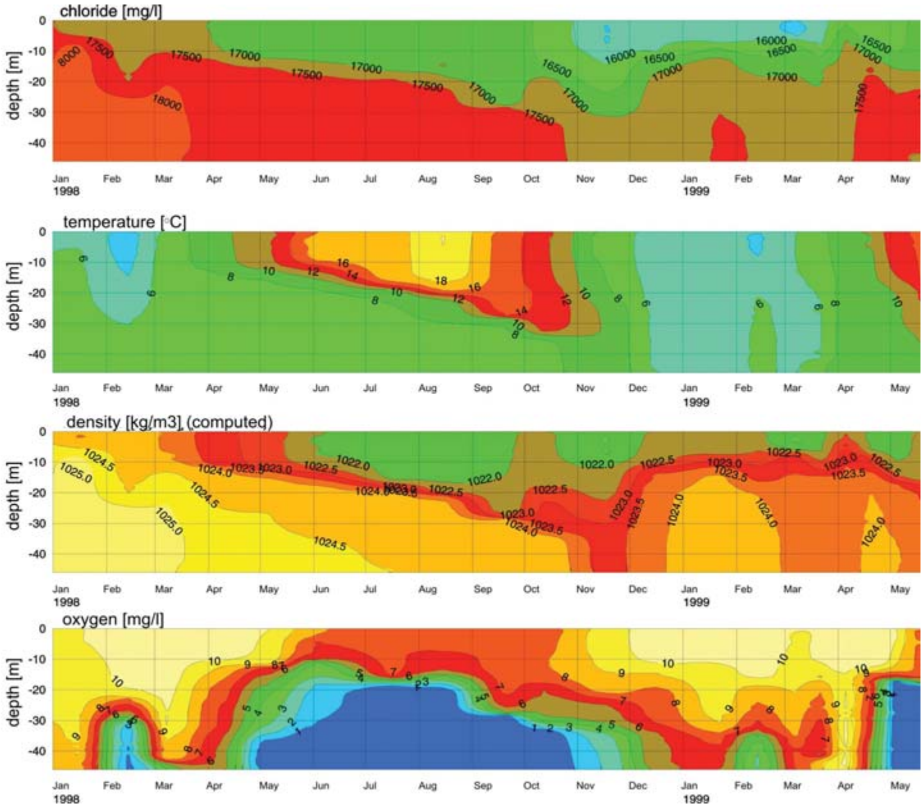


Figure 4.3

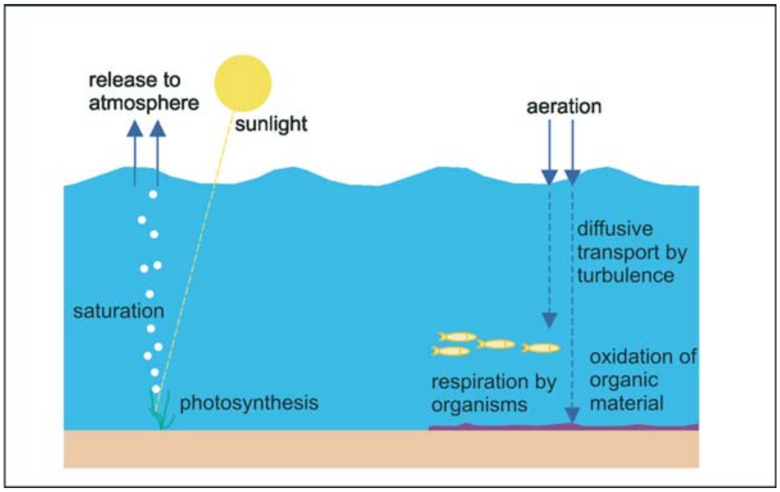
Pit of Scharendijke: Salinity, Temperature and Oxygen in time



4.2 Description of oxygen depletion and stratification in seawater

There are many processes that influence the dissolved oxygen concentration level near the bed. In this section, we give a description of the main processes that govern the oxygen concentration in the water column, illustrated in Figure 4.4. In particular we focus on the relevant processes, which may cause hypoxia within a deep sand pit.

Figure 4.4
Main processes that govern the oxygen concentration in the water columnn



Oxygen production

Within the water column, oxygen is produced by photosynthesis. Primary producers, such as phytoplankton, convert water (H_2O) and carbon dioxide (CO_2) to organic material and oxygen (O_2). To that end, the primary producers need sunlight and nutrients like nitrogen (N), Phosphate (P) and Silicate (Si). An increase of nutrient load (from industries, rivers or atmospheric deposition) may cause an increase of the primary production, which has also positive effects on the other organisms like zooplankton and fish. Abundance of nutrients is called eutrophication, which may boost large algae blooms from spring till autumn.

When the dissolved oxygen concentration level increases, due to photosynthesis, the seawater becomes saturated and the oxygen is released to the atmosphere. Especially in summer, when the water is warm, the oxygen saturation concentration is low: the water column cannot store large amounts of oxygen. Furthermore there is a small dependency of the saturated oxygen concentration on the salinity of the water [Table 4.1].

Table 4.1
Oxygen concentration of saturated water, for different water temperature and salinity. This table covers the normal conditions found on the NCS.

Saturated oxygen concentration [mg/l]	Salinity [PSU]				
Water temperature [°C]	**15**	**20**	**25**	**30**	**35**
5	11.6	11.2	10.8	10.5	10.1
10	10.3	9.9	9.6	9.3	9.0
15	9.2	8.9	8.6	8.4	8.1
20	8.3	8.1	7.8	7.6	7.4
25	7.6	7.4	7.2	6.9	6.8

Oxygen supply from the atmosphere

Besides primary production, there is also atmospheric oxygen supply due to aeration by the wind on the water surface. Considering the North Sea, we see that there are often strong winds, which is reflected by a high level of oxygen concentration at the surface.

Aerated oxygen is transported to the seabed by vertical mixing through turbulence. This oxygen transport is significantly reduced at a picnocline (a halocline or thermocline) in stratified waters: here the turbulent diffusivity is very low. We saw already a dramatic effect of stratification on the oxygen concentration near the bottom of the Grevelingen Lake in Figure 4.2.

Oxygen consumption

In Figure 4.4 we see two types of oxygen consumption. In the first place there is respiration by living organisms, in the second place we see oxidation of dead organic material. If the oxygen consumption surpasses the primary production and supply from the atmosphere, there is an increased chance on oxygen depletion. This happens especially in summer, when algae produce large amounts of organic material. Small floating organisms called zooplankton eat these algae. Most of the smallest ones are filter feeders, pulling in small particles from the water, digesting the food portions of the particles, and ejecting the residue as faecal pellets. Another important factor causing the settling of organic particles is marine snow. Marine snow consists of large clusters of organic matter that coagulate together and sweep up all small particles in the surrounding. The organic matter includes the contents of ruptured cells, slime secreted by algae cells, slime traps secreted by some organisms to capture food, etc. The faecal pellets and marine snow are inhabited by large numbers of marine bacteria that make their living by consuming all the waste organic matter falling through the water column. At the seabed, benthic organisms also take their share. The activities of the benthic organisms and bacteria require oxygen, which is extracted from the seawater.

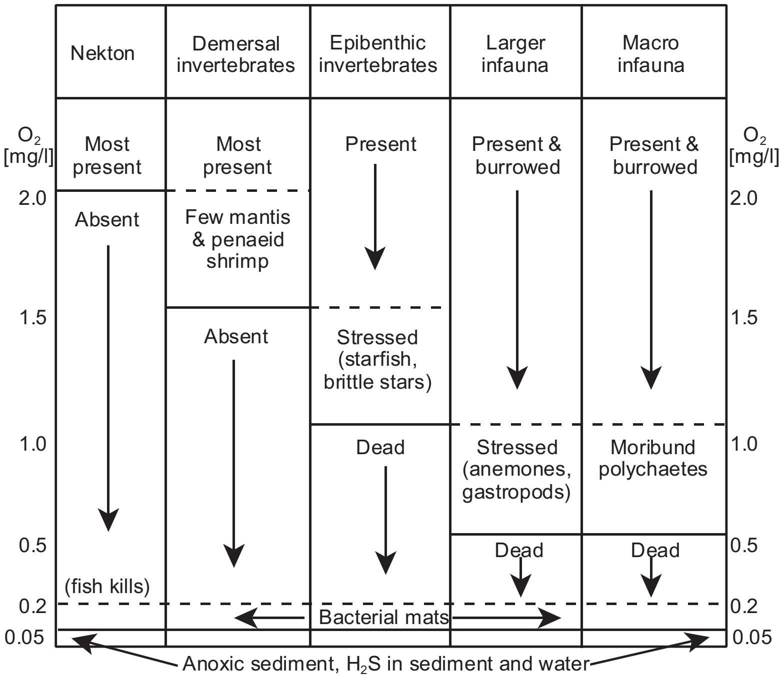
Impact of oxygen depletion on organisms

In Table 4.2, we see the impact of oxygen depletion on organisms, dependent on the oxygen concentration level. Also the size of the affected

Table 4.2
Table with the impact of oxygen depletion on organisms [after: http://internat.environ.se (Swedish Environmental Protection Agency)]

Class	Level	Lowest oxygen level during year (mg/l)	Description
1	High	> 8.6	Adequate oxygen supply and no known negative effects
2	Moderately high	5.7-8.6	Probably no negative effects.
3	Low	2.9-5.7	Negative effects begin to appear. Many fish and bottom-dwelling animals are significantly affected and attempt to leave the area.
4	Very low	0-2.9	Negative effects over a longer period lead to death of most animals that are unable to leave the area. A few species of bottom-living animals can survive short periods with total lack of oxygen.
5	Hydrogen sulfide (H_2S)	Total absence of oxygen	Formation of hydrogen sulphide leads to widespread extinction of plant and animal life (e.g. extensive fish kills).

Figure 4.5
Progressive changes in fish and invertebrate fauna as oxygen concentrations decrease from 2 mg/l to anoxia [Rabalais *et al.* (2001)]



area and the time that oxygen is depleted play a role: Can animals move to locations with sufficient oxygen concentration? Do plants and animals survive the oxygen depletion period?

Rabalais *et al.* (2001) assembled twelve years of diver and five years of video observations on the responses of nekton (motile fish) and demersal and benthic fauna to decreasing concentrations of dissolved oxygen. Figure 4.5 shows that the responses of the fauna vary. Motile organisms like fish, portunid crabs, stomatopods, penaeid shrimp and squid) are seldom found in bottom waters with oxygen concentrations less than 2 mg/l. When the oxygen concentration becomes lower than 1.5 to 1 mg/l, less motile and burrowing invertebrates exhibit stress behaviour, such as emergence from the sediments, and eventually die if the oxygen remains low for an extended period. At minimal concentrations just above anoxia (0 mg/l), sulphur-oxidizing bacteria form white mats on the sediment surface, and at anoxia, there is no sign of aerobic life, just black anoxic sediments.

The effect of a deep sand pit on oxygen concentrations

At the bottom of a deep sand pit, there is an increased risk of oxygen depletion, which depends on a number of possible circumstances [Figure 4.6]:

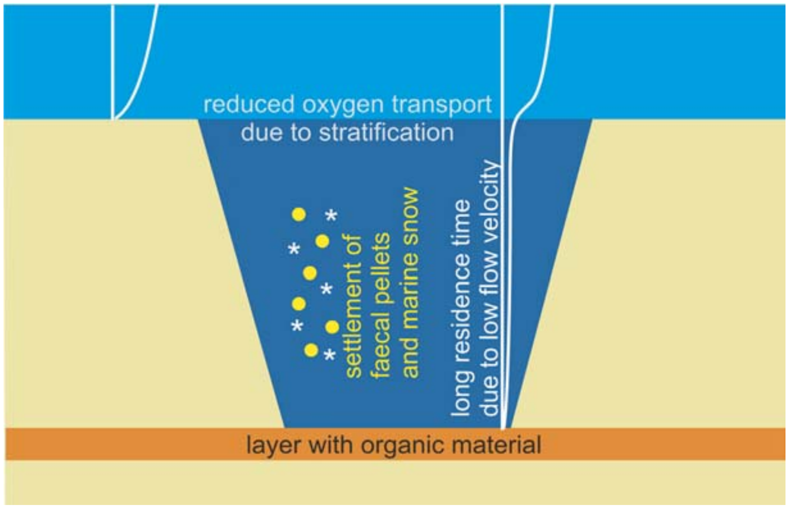
- A deep sand pit has an increased chance on stratification, which hinders the downward oxygen transport by turbulence. This stratification might be caused by (more) saline water captured in the pit and by the increased water depth and reduced flow velocity, so that thermal stratification can be developed.
- When the vertical supply of oxygen is blocked by stratification, there is still oxygen supply possible from adjacent, oxygen-rich areas. If the residence time inside the pit is short, i.e. shorter than one day, the oxygen concentration inside the pit will be almost equal to the oxygen concentration in the adjacent areas. If the residence time is long, i.e.

longer than about ten days (this is very dependent on the oxygen consumption), we can expect that the oxygen concentration inside the pit is much lower than in the adjacent areas. The residence time of the water depends on the flow velocity inside the pit, the size of the pit and the presence of vortices downhill sand pit slopes steeper than 1:6 [Alfrink and Van Rijn (1983)]. We however think that vortices do not play an important role on the NCS. Vortices in a sand pit are only found in the upstream part of a sand pit. Due to the tide, the flow reverses twice a day and the vortices will only last during half of the tidal period, which is about six hours. This is too short for the development of oxygen depletion.

- If there is a reduction of the flow velocity inside the pit, there is an increased settlement of faecal pellets and marine snow, which increases the oxygen consumption near the bed.
- Organisms, especially larvae, can be trapped in a deep pit, where they consume oxygen and supply organic material [Thatje *et al.* (1999)].
- If the bed of the sand pit cuts a layer with a high level of organic material, there may be an increase of the oxygen consumption near the bed.

Figure 4.6

Circumstances that influence oxygen concentration levels in a deep sand pit



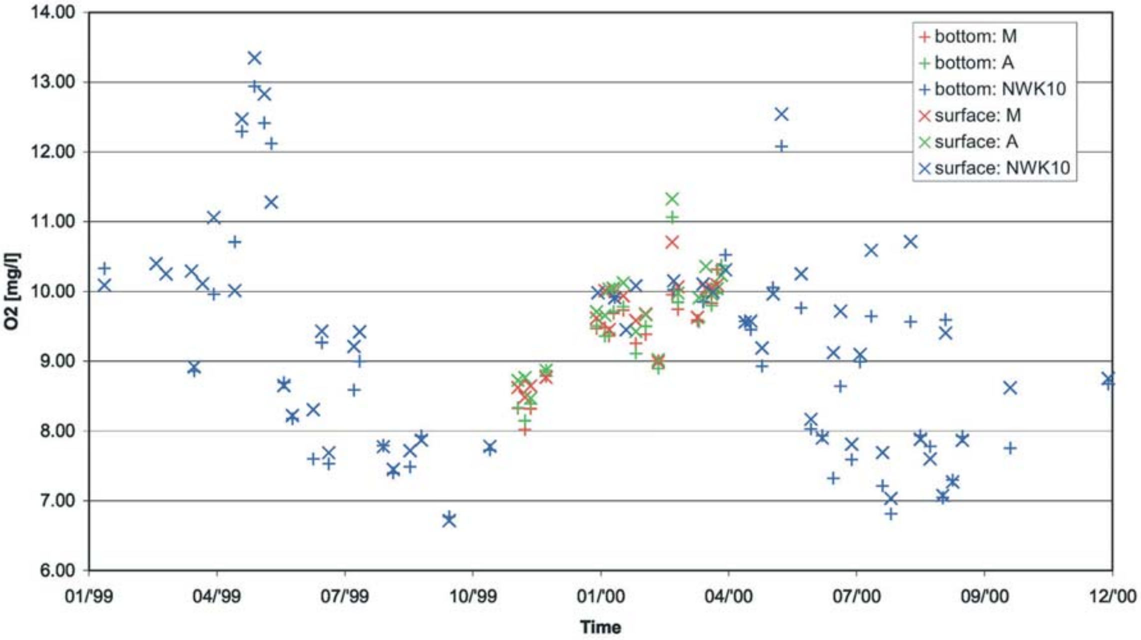
In this chapter, we focus on the possibility of haline and thermal stratification within a sand pit and the residence time of the water inside the pit. The settlement of organic matter and the trapping of living organisms are described in the following chapter. The level of organic matter within the newly created seabed at the sand pit is very dependent on the local geological circumstances and the design of the sand extraction pit.

4.3 Oxygen concentration levels in the PUTMOR pit

During the PUTMOR campaign, oxygen concentration profiles were measured inside and outside the PUTMOR pit [Figure 2.3]. The chance on oxygen depletion during the PUTMOR measuring campaign was very small, because the measurements were carried out during winter, when the oxygen consumption is low and the storage capacity of the seawater is high due to the low water temperature. Therefore, these measurements cannot exclude the possibility of oxygen depletion, if the PUTMOR pit had stayed open. It is therefore, that we compare the PUTMOR measurements with oxygen concentration measurements at Noordwijk (NWK10), 10 km offshore of the coast and 32 km northeast from the PUTMOR pit. These measurements are part of the regular, year-round survey of the NCS. When

Figure 4.7

Measured oxygen concentrations inside and outside the PUTMOR pit, at the bottom and at the surface. These measurements correspond quite well with the oxygen measurements at Noordwijk 10, which are also added to this graph.



we compare the Noordwijk measurements with the PUTMOR measurements, we see a very good agreement [Figure 4.7]. Oxygen concentration levels varied between approximately 7 and 14 mg/l, which is (moderately) high according to Table 4.2. There is a provable seasonal pattern in the oxygen concentration at Noordwijk. The oxygen concentration reaches a minimum at the end of the summer when the seawater temperature is high, and there is an abundance of dead material from algae blooms. During winter the oxygen concentration increases again and reaches a maximum in May. The PUTMOR measurements follow that seasonal pattern during the time-span of the campaign. The spatial differences between the measuring locations of Noordwijk and the PUTMOR Locations A and M are small in comparison with the temporal variations. The differences between surface and bottom are usually less than 1 mg/l, where it seems that the differences are larger in summer than in winter. Most important is that there is not a noticeable effect of the PUTMOR pit on the oxygen concentration in winter and early spring. In general the oxygen concentrations outside the sand pit are only slightly higher than inside the pit. Differences are seldom larger than 0.2 mg/l [Svašek (2001 C)].

Considering the measured oxygen concentration profiles of one PUTMOR survey [Figure 4.8], we see large vertical gradients in the upper part of the water column, which we attribute to haline stratification due to the Rhine runoff [see also Figure 3.4]. We never observed a picnocline below a depth of 10 metres, including the inside of the pit. In this part of the water column, the oxygen concentration level is almost constant, both inside and outside the pit. Even the differences between the measured oxygen concentration levels at the surface and at the bottom are always smaller than 1 mg/l.

Figure 4.8
Measured oxygen concentration profile on Locations A and M. The vertical and horizontal differences are small, which is also the case for most other oxygen concentration profiles [see Table 3.4].

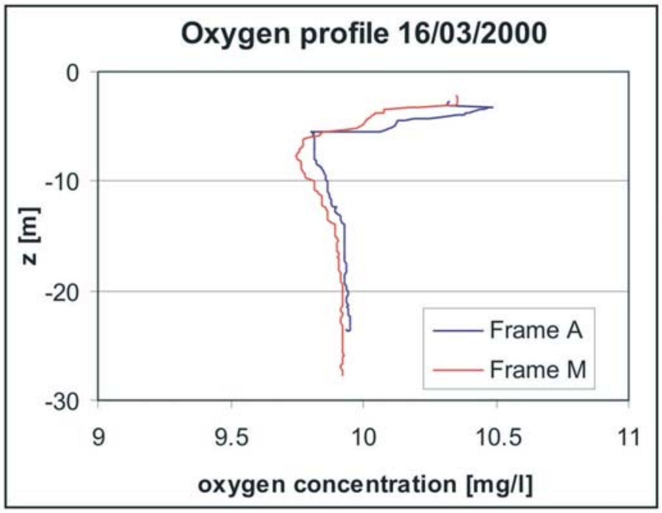
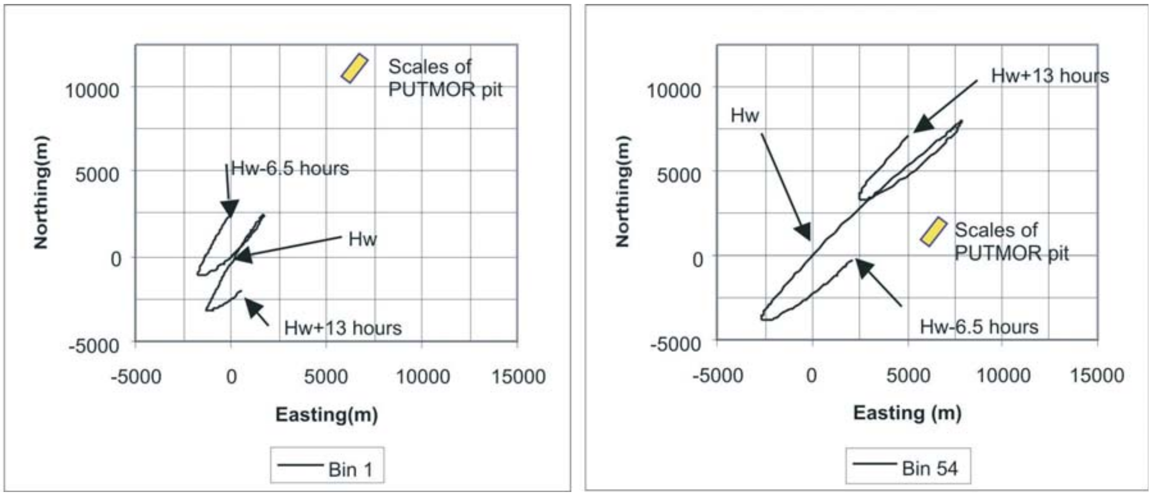


Figure 4.9
Estimated tidal excursion from observed velocities at Location M (0,0). Bin 1 is 1.5 m above seabed; Bin 54 is 28 m above seabed [Svašek (2001 C)]



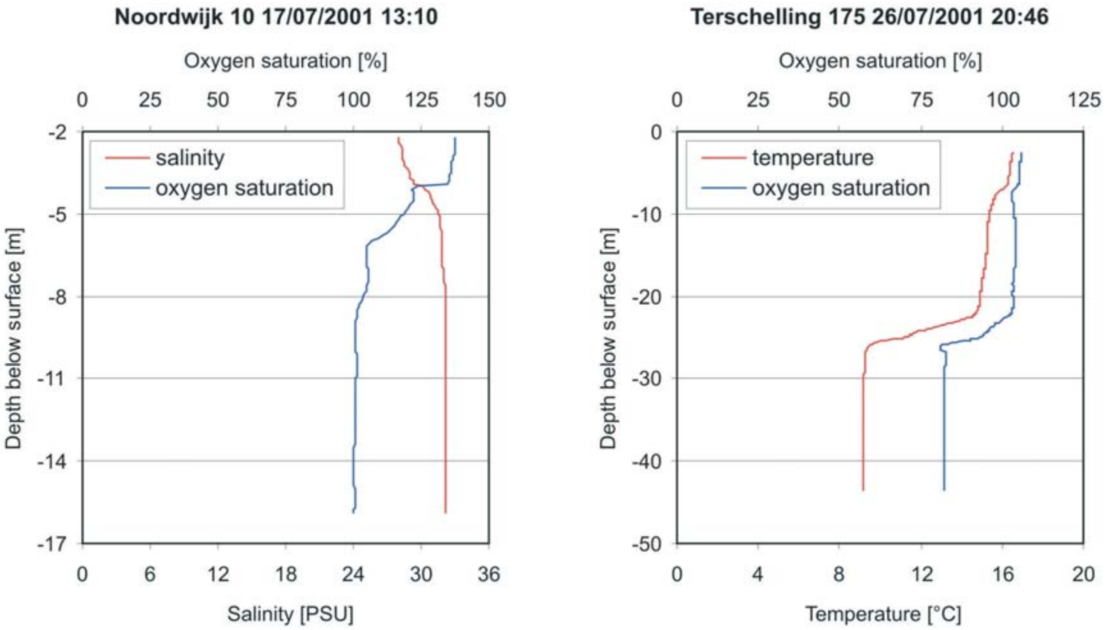
Besides the vertical oxygen transport inside the PUTMOR pit, which was not hindered by the presence of a picnocline, Svašek (2001 C) showed that the water inside the pit is renewed four times per day by the tidal current. Figure 4.9 shows the tidal excursion of water particles at the seabed and at the surface at Location M. The excursion of several kilometres is much longer than the length of the PUTMOR pit (1300 m).
We conclude that the risk of hypoxia in the PUTMOR pit is small, due to high level of oxygen concentration in this area, the absence of stratification inside the pit, and the very short residence time of the water inside the pit.

4.4 Stratification and oxygen concentration on the NCS

In this section, we describe the chances on stratification and oxygen depletion on the NCS for the undisturbed situation. When we consider stratification on the NCS, we observe haline stratification near the Holland coast and thermal stratification in the Northern regions. Both types of stratification have an effect on the vertical oxygen profile, which is illustrated in Figure 4.10. At Noordwijk 10 we see that the oxygen saturation decreases from 137% at the surface to 100% at the bottom due to the presence of haline stratification, and at Terschelling 175 we see a decrease from 106% at the surface to 82% at the bottom due to thermal stratification.

Figure 4.10

Haline stratification at Noordwijk 10 and thermal stratification at Terschelling 175 and the impact on oxygen saturation. At Noordwijk the oxygen concentration at the surface is 9.1 mg/l and at the seabed 8.1 mg/l. At Terschelling this is 8.4 mg/l respectively 7.6 mg/l.



Haline stratification at the Holland coast

The river Rhine discharge through the New Waterway and the Haringvliet causes haline stratification off the Holland coast. Van Alphen *et al.* (1988) identified near field stratification, which is dominated by the buoyant spreading of the fresh water, and far field stratification, where the stratification diminishes by vertical mixing due to tide and wind. The extent of the far field stratification depends on the river discharge, neap or spring tide and the wind. Under normal conditions the stratification has a width of 15 km cross-shore and a length of 30 km alongshore [Figure 4.11]. This description corresponds with the measured vertical salinity differences (defined as the difference in salinity at 10 m and 1 m below the surface), averaged over 19 hydrographical surveys conducted between 1986 and 1990 by De Ruijter *et al.* (1997) [Figure 4.12].

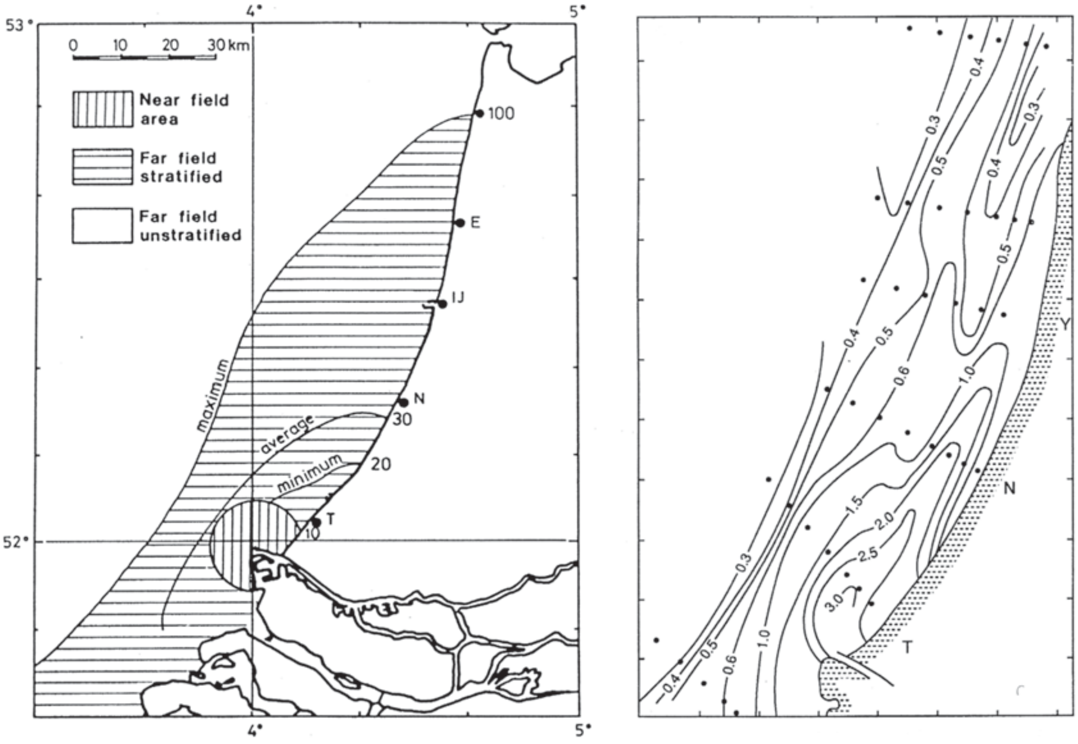
Also the thickness of the upper fresh water layer is rather sensitive to the river discharge. For an average Rhine discharge of 2200 m^3/s, this layer varies between 4 and 8 m [Van Alphen *et al.* (1988)], while in January, 1986 a thickness of 10 m was measured, when the Rhine discharge reached 6000 m^3/s; Figure 4.12 shows the transects at Ter Heijde and

Noordwijk, for that time [De Ruijter et al. (1992)]. In the PUTMOR campaign, a comparable thickness was measured at January 20th, 2000, when the discharge at Lobith reached 6,600 m^3/s [Figure 2.2]. Due to vertical mixing, the thickness of the fresh water layer diminishes to zero at the outer edge of the far field stratification zone.

The position of the PUTMOR pit coincides with the near field stratification zone, where salinity differences have their maximum (about 3‰). This means that this pit is very representative for a deep sand pit in the near field haline-stratified zone near the Holland coast. Since sand extraction is only allowed in the deeper parts of the North Sea, it appears that the major part of the near field and far field haline-stratified zones are excluded from sand extraction.

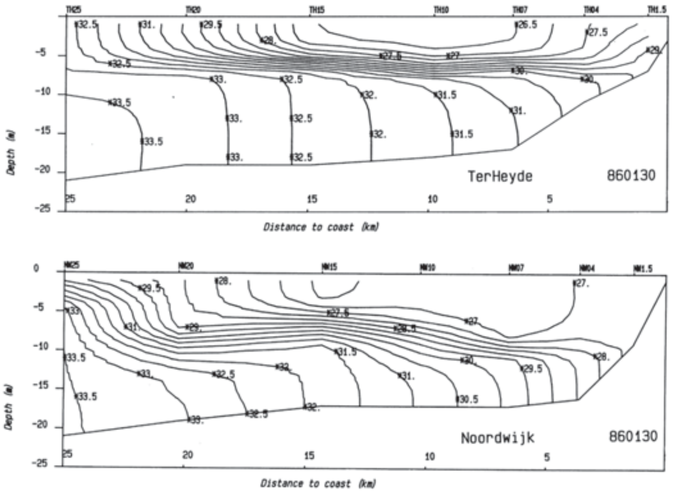
Figure 4.11

Left: Extension of near field and far field stratification zones according to Van Alphen *et al.* (1988); Right: vertical salinity differences byDe Ruijter *et al.* (1997) Units are ‰.(T = Ter Heijde, N = Noordwijk, IJ/Y = IJmuiden, E = Egmond).



Since oxygen depletion occurs usually in summer, it is interesting to analyse the annual variation of the haline stratification off the Holland coast. We collected salinity and the oxygen concentration measurements at Noordwijk 10 between 1991 and 2004, and sorted them according to the time in the year [Figure 4.13]. The salinity near the bed varies during the year between 30 and 32 PSU. At the surface, we sometimes see low values down to 24 PSU, especially in winter and spring. During summer, we do not see large differences in salinity between seabed and water surface: in this period stratification is rare at this location, which is probably related to low fresh water discharge.

Figure 4.12
Salinity distributions at the Ter Heijde and Noordwijk transects at high discharge conditions 6000 m3/s [De Ruijter *et al.* (1992)]



Considering oxygen concentration, we see very small temporal variations in winter and spring, but significant vertical differences with values of about 10 mg/l near the surface and 8 mg/l near the bed. In spring and summer, the temporal variations are larger, probably due to algae growth and decay, while the vertical differences are smaller, which is probably caused by the absence of stratification at Noordwijk 10. The minimum oxygen concentration level is about 7 mg/l, which is moderately high and has probably no negative effects on sea life, according to Table 4.2.

Figure 4.13
Haline stratification at Noordwijk 10, between 1991and 2004. For a number of years we had only measurement at the surface. The upper graph shows the salinity, the lower graph oxygen concentration levels. Day 1 is the 1st of January, Day 365 the 31st of December.

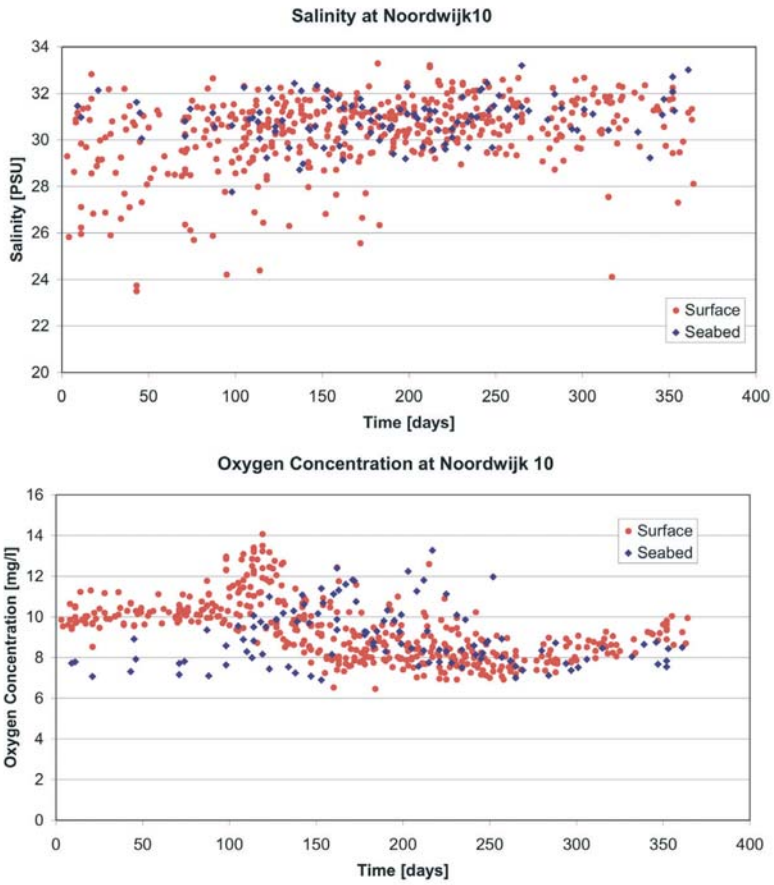


Figure 4.14

The measured salinity and the surface elevation at Location A. Besides the influence of the river discharge, there is a clear correlation between tide and salinity. Stratification only exists during part of the tidal cycle.

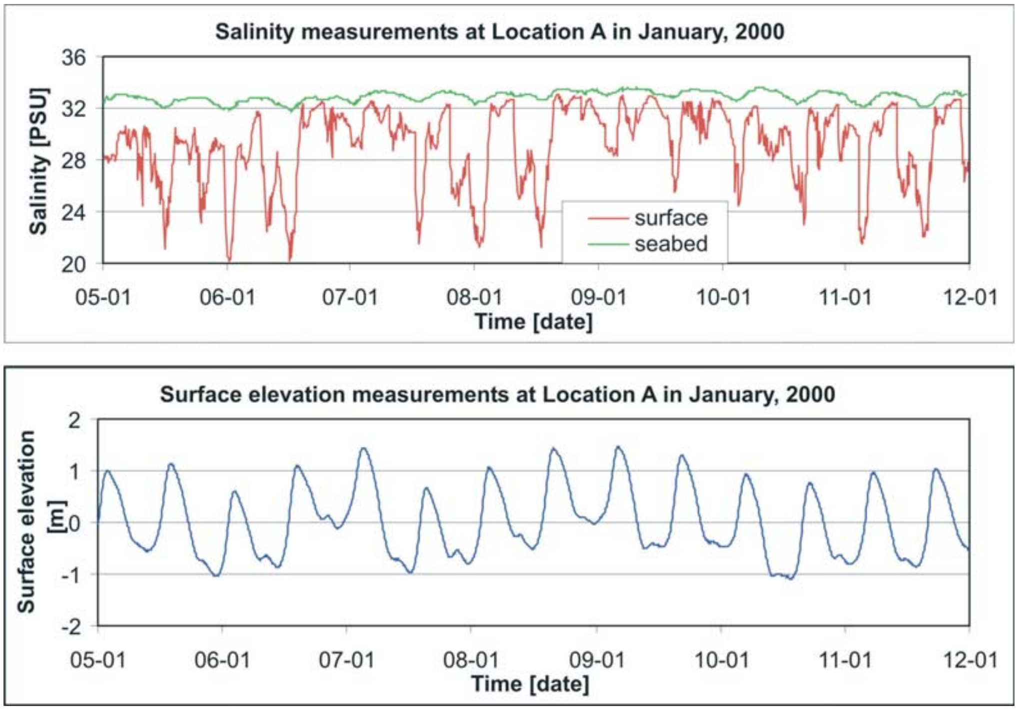
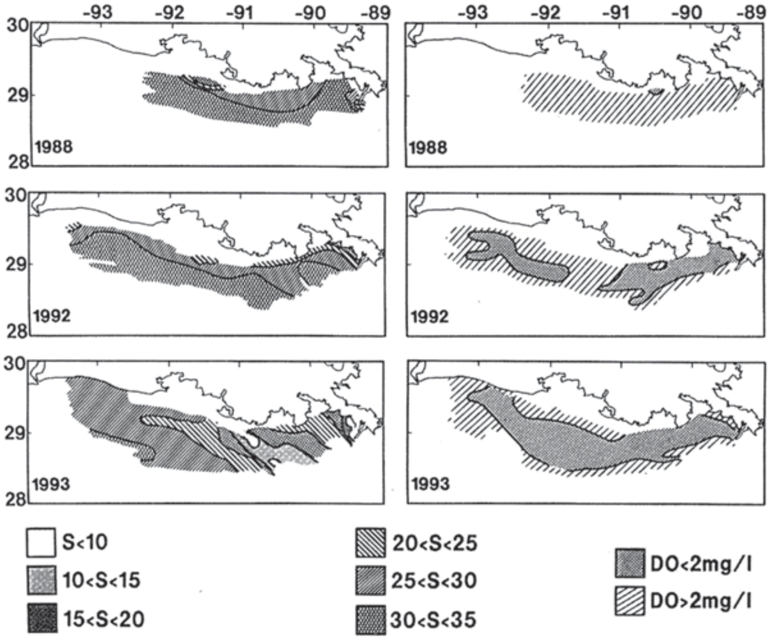


Figure 4.15

Correlation between haline stratification (right panels, S) and hypoxia (left panels, DO) at the western Louisiana Shelf in the Gulf of Mexico. In 1988, there was a major drought, 1992 had a normal discharge, and 1993 had a discharge above average throughout the year [Wiseman *et al.* (1997)]

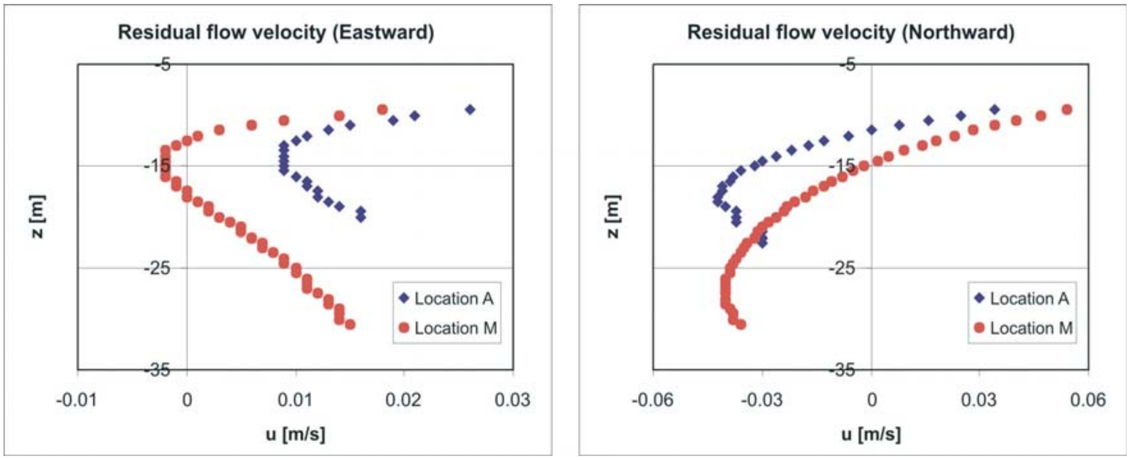


An example of the negative impact of haline stratification on the oxygen concentration near the seabed is given in Figure 4.15, where the haline stratification due the Mississippi discharge shows an apparent correlation with the occurrence of hypoxia in the Gulf of Mexico [Wiseman *et al.* (1997)]. This raises the question why the haline stratification off the Holland coast does not lead into oxygen depletion. We argue that there are three reasons, which make the difference:

- In summer, haline stratification off the Holland coast is found in a relatively small region, due to the low Rhine discharge.
- The stratification at a certain position does not only vary with the river discharge, but also with the tide [Figure 4.15]. Stratification is only present during a part of the tidal cycle. During the other part, there is a free vertical exchange of oxygen by turbulence through the entire water column.
- There is an onshore drift to the coast of about 1.5 cm/s, which transports oxygen from the deeper parts of the North Sea to the coastal zone [Figure 4.16].

Figure 4.16

Residual flow velocity measured during the PUTMOR campaign. At the bottom, we see an onshore drift with a velocity of 1.5 cm/s, which is probably the result of upwelling.



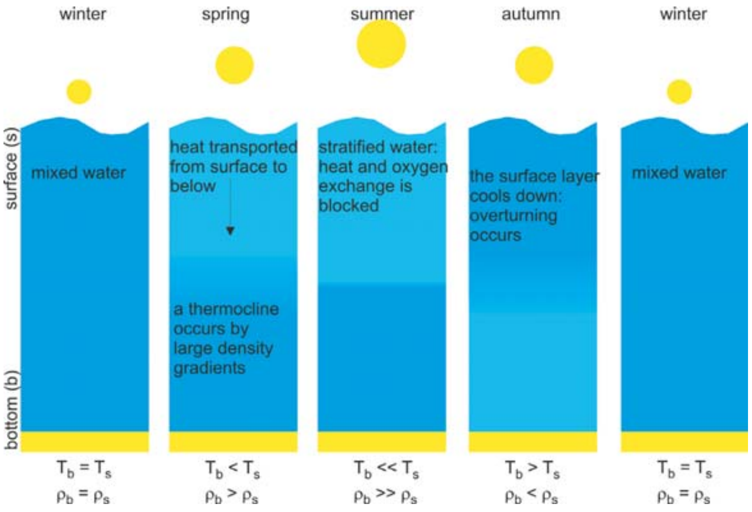
Thermal stratification in the northern part of the NCS

In the northern part of the NCS, north of the 40 m depth contour, we have mixed water during winter and thermal stratification during summer [Figure 4.17].

In *winter*, the water temperature at the water surface is almost equal to the water temperature at the bottom, and we have mixed water. This means a free exchange of heat and oxygen through turbulent diffusion. This situation changes during *spring*. At the surface, the water gets heat from solar input and exchanges heat with the air above. Through turbulent mixing, heat is transported to the water layers below the surface. Since it takes time for the water layers to warm up, a phase lag appears between the water temperature at the surface and at the bottom. With increasing water depth and decreasing turbulent mixing, the vertical temperature gradient becomes so large that density gradients come into being, which further reduces the heat exchange from surface to the bed. This results in

Figure 4.17

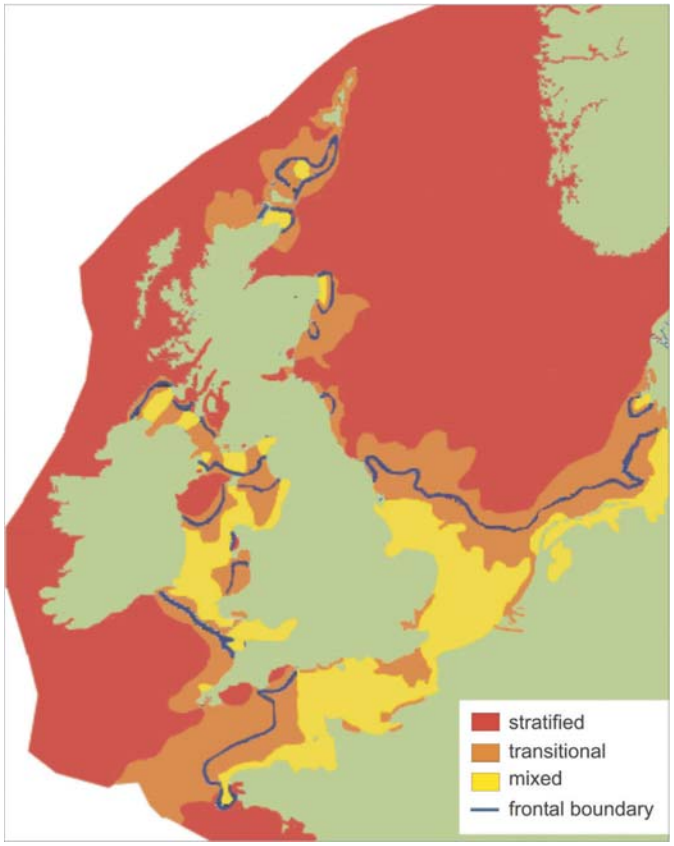
Annual cycle of thermal stratification, where T_b and T_s represent the water temperature at the bottom and at the surface, and ρ_b and ρ_s the density at the bottom and at the surface



stratification in summer, which leads to a blocking of oxygen and heat exchange between the surface and the bottom layer at the thermocline. This stratification lasts until *autumn*, when the water temperature at the surface becomes equal or lower than at the bed, and the density at the surface becomes equal or higher than at the bed. Then, the gravitational instability produces the autumnal overturning and the vertical turbulent mixing sets in, resulting in a well-mixed water column during the following *winter*.

Figure 4.18

Prediction of stratified and mixed regions after Pingree and Griffiths (1978). The blue line represents the boundary between the two regimes.



The development of a thermocline demands a sufficiently low level of turbulence. Pingree and Griffiths (1978) carried out numerical calculations to predict the stratification in the shelf seas surrounding the British Isles, using the Simpson-Hunter stratification parameter S [Simpson and Hunter (1974)]:

$$S = \log_{10}[\frac{h}{C_D < |u|^3 >}]$$

, where h is the water depth, u is the depth-averaged tidal flow velocity

and C_D is the bottom drag coefficient. The result of this prediction is presented in Figure 4.18, where the blue line indicates the boundary between the region that is mixed throughout the whole year and the region that is stratified during the summer. This prediction agrees well with the measurements analysed by Elliot *et al*. (1991). It further appears that the boundary between mixed water and summer (thermal) stratification coincides with the 40 m depth contour.

The annual cycle of thermal stratification and oxygen concentration is illustrated in Figure 4.19, which shows the water temperature at the surface and at the seabed at Terschelling 135, which is northward of the 40 m depth contour. The data were obtained between 1988 and 2003. We see that until April – May the water temperature at the seabed is almost equal to the temperature at the surface, which means that the water column is mixed. Between April and July, the upper part (layer) of the water column is heated up from 5-7 °C to 15-20 °C, while the lower layer is heated up until September with a maximum of 13-15 °C. Between August and October the upper layer cools down until the water temperature in the upper layer becomes equal or less than the water temperature in the lower layer. Then we get overturning and the mixed conditions are restored during the next winter. During that period, measurements are usually carried out at the surface only.

Figure 4.19 also presents the measured oxygen concentration levels at Terschelling 135. It appears that the oxygen concentration differences between surface and seabed are less pronounced than the temperature differences. The annual maximum oxygen concentration level is measured around April with values up to 11 – 12 mg/l. Between April and June, the oxygen concentration decreases, probably due to an increased water temperature in the upper layer and an increased oxygen consumption in the lower layer. Differences in oxygen concentrations appear in July and August with typical oxygen concentrations of about 7 mg/l in the lower layer and 8 mg/l in the upper layer, which are moderately high according to Table 4.2.

During a few years, the oxygen concentration in the lower layer becomes much lower than as usual. This was especially the case in 2003, for which the measurements are connected with red and blue lines in Figure 4.19. This year was a very warm year, with probably an overwhelming algae growth and decay. In such a year, oxygen concentration levels become smaller than 5.7 mg/l, which means oxygen depletion with negative effects on fish and benthic communities [Table 4.2].

We attribute the usually moderately high oxygen concentration levels near the seabed at Terschelling 135, to the low level of nutrients at this location. This low nutrient concentration restricts the production of organic material and thus the oxygen consumption. Summer stratification at, e.g., Noordwijk 10 would probably lead to a yearly oxygen depletion near the bed, due to eutrophication.

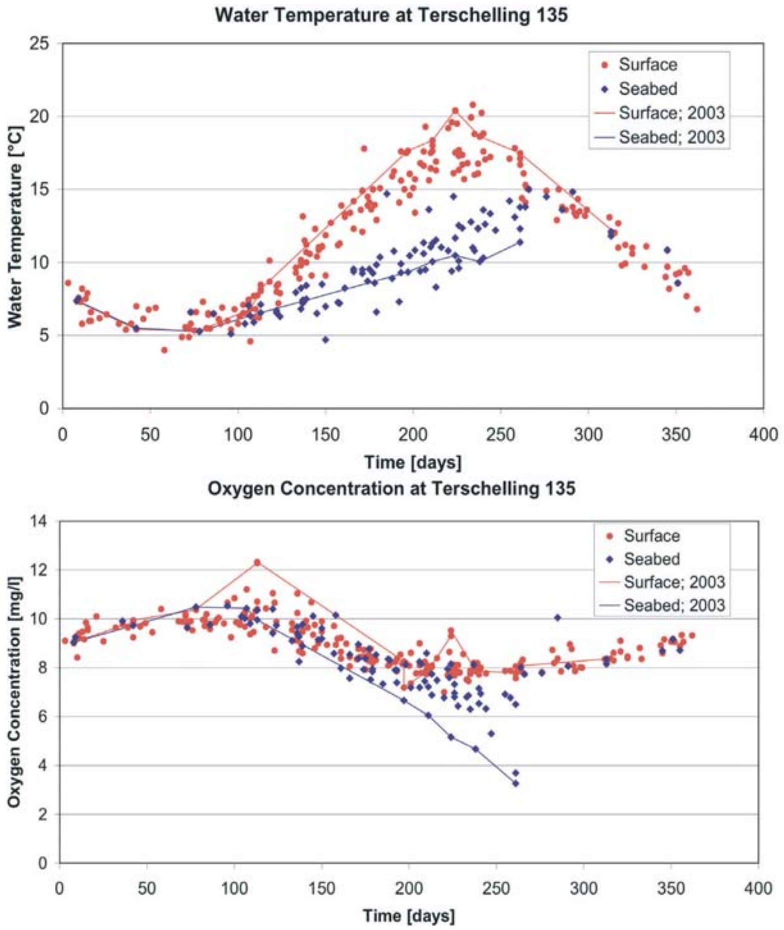


Figure 4.19
Thermal stratification at Terschelling 135, where the water depth is about 43 m. Data was collected between 1988 and 2003. The upper panel shows the water temperature at the surface and at the bed, the lower graph the oxygen concentration. Between April-May and September-October, we see thermal stratification, which sometimes results into low oxygen concentrations near the bed. This is especially the case during the summer of 2003 [see the red and blue lines].

4.5 Oxygen supply to deep sand pit on the NCS

In this section we describe under what conditions we can expect a sufficient supply of oxygen to a proposed deep sand pit on the NCS. This is probably the most important provision to prevent oxygen depletion inside such a pit. In this chapter we already described that the absence of stratification and a short residence time of the water inside the pit are favourable conditions for the oxygen supply.

Although haline stratification naturally occurs off the Holland coast, it does not form a risk for deep sand pits on the NCS. The halocline is always found in the upper 10 m of the water column, while the seabed where the sand pit is extracted is always deeper than 20 m. This means that there is never a halocline inside the pit, which might seal of the oxygen supply. Furthermore, we learned in Section 4.4, that the oxygen concentration levels within the haline-stratified region off the Holland coast are usually high.

Thermal stratification does not form a risk for deep sand pits on the NCS, if the bottom of the pit has a water depth less than 40 m. It appears that under those conditions the turbulent mixing on the NCS is strong enough to prevent the development of a thermocline.

Even if the bottom of the deep sand pit has a depth more than 40 m, it is still not sure that a thermocline will develop. If the water in the sand pit is renewed fast enough, there is not only a fast supply of oxygen, but also of heat, through horizontal advection by the tidal flow. If there are plans to extract sand to a depth deeper than 40 m, we advise to analyse the possibility of a thermocline beforehand.

5 Deposition of fines in a deep sand pit

5.1 Deposition of fines in a deep sand pit and the effect on benthos

In the assessment of a deep sand pit, we have to deal with a possible deposition of fines, in the form of organic matter (marine snow, faecal pellets) and inorganic matter (mud). Such a deposition plays an important role in the recovery of benthic communities on the bottom of the new sand pit:

- The bottom of the sand pit could get a different bed composition (more fines) than the surrounding area, which leads up to different types of benthos inside the pit than outside the pit.
- An increased deposition of organic matter increases the oxygen consumption inside the pit, and thus decreases the oxygen concentration level near the bed. The effects on the benthos were already described in Section 4.2.
- When the seabed contains a very large fraction of fines, the oxygen exchange within the upper layer of the seabed strongly declines, which results in anoxia inside the upper layer, and poor conditions for the infauna (animals that live in the seabed).
- Deposition of fines can bury the benthos; some species cannot handle this load and will not repopulate the sand pit.

In this chapter we discuss the effect of a deep extraction pit on the deposition of fines in general and on the PUTMOR pit in particular. We first give some examples from literature in which the influence of the deposition of fines on the benthic communities inside a pit is illustrated.

A deep seafloor crater in the German Bight [Thatje et al. (1999)]

In 1963 a deep crater with a depth of 30 m below the initial seabed and a width of 400 m was formed in the western part of the German Bight, due to a gas eruption caused by drilling by the platform 'Mr. Louie'. The initial seabed has a water depth of 35 m, and is composed of sand with a small fraction of fines (about 5%). The crater acts as a sediment trap, with sedimentation rates of about 50 cm per year. The composition of the crater floor has a much larger fraction of fines, about 30 to 40 % of the bed material.

It appeared that the benthic community in the crater differs from the surrounding area, which is characterized as an Amphiura Filiformis association (a type of Brittle Star). Polychaeta (segmented worms) and Molluscs cannot survive the high sedimentation rate, while Echinoderms, like the Echinocardium cordatum (Heart-Urchin) and the Amphiura Filiformis, profit from the trapped larvae in the crater. Although the number of species inside the crater became less, the biomass and the number of individuals became larger than in the surrounding area. During the measurements, anaerobic conditions were never observed.

Sand pits in the Dutch Wadden Sea [Van der Veer et al. (1985)]

Van der Veer *et al.* (1985) studied the effects of dredging on macrobenthic infauna at several sand extraction sites in the estuarine Dutch Wadden Sea. Dredging in tidal flat areas had long-lasting effects. The backfill of those pits took more than 15 years and consisted up to 63% of fines, whereas the surrounding area consisted of sand. The recovery of benthos in the pit was virtually absent, due to unsuitable settling conditions: the upper layer of black sediment almost entirely consisted of fines and was almost totally anaerobic.

Sand extraction sites in tidal channels with strong currents showed a totally different picture. Here, the deposited sediment had the same composition as the surrounding of the pit, with a maximum fraction of fines of about 10%. The backfilling time of the pit varied between one and three years, at the same time the biomass within the pit returned to the records prior to the sand extraction.

In a sand extraction site at a tidal watershed, the backfilling of the pit was completed within one year, while the deposited sediment had a fraction of fines of about 30%, which was similar to the vicinity of the pit. However, four years after the extraction, the biomass within the pit was still 40% of the value outside the pit.

Settlement of organic matter in the Euro-Maas Channel [Koeman and Bijkerk (1998)]

On the 4th of May 1998, a survey was carried out to measure the settlement of organic matter in the Euro-Maas Channel during an algae bloom of Phaeocystis. The measurements were carried out within a pit at the bottom of the Euro-Maas Channel, where the water depth was 31 m (The “Trough of Tom”). Besides, two reference measurement were carried out, one at a location south of the Euro-Maas Channel, where the water depth was 18 m, and the other north of the Euro-Maas Channel, where the water depth was 17 m. The following observations were made:

- The spatial differences in suspended matter were small. The largest concentrations were measured near the bottom of the pit (27 mg/l), these concentrations were 8% larger than outside the Euro-Maas Channel.
- The concentrations Particulate Organic Carbon (POC) did not show a large difference either. The pit showed concentrations of 3.5 mg/l, which were intermediate to the measured concentrations outside the Euro-Maas Channel.
- Oxygen concentration levels were high in the entire water column, with values of about 11 mg/l. Haline stratification was present in the upper part of the water column; no thermal stratification was observed.
- The fraction of carbon in the bottom of the pit (between 0.24 and 0.37%) was about three till five times larger than outside the Euro-Maas Channel.

It is possible that the pit in the Euro-Maas Channel acts as a sediment trap, which results in larger fractions of carbon in the bed material, which had accumulated during the two years that the pit was present. However, the measurements in the water column did not reveal an increased concentration of fines near the bottom of the pit. It is probable that deposition of the fines only occurs during calmer conditions than at the time of the measurements.

5.2 General description of deposition of fines in a deep sand pit

For a general prediction of deposition of fines in deep sand pits, there is a need for a numerical model that includes erosion, sedimentation and transport of fines. However, we only know one example of the modelling of deposition of fines in a (deep) sand pit. Pluijm and Bossinade (1986) calculated the deposition of fines and sand in the Simon Stevin pit, which was located a kilometre and a half northeast of the Dump Site North [Figure 2.1]. They had to deal with many uncertainties considering the critical bed shear stress and the density of the deposited fines inside the pit.

In the PUTMOR project, we did not carry out model predictions for the deposition of fines in a deep pit. In this section, we will only discuss a number of aspects, which are important for the modelling of this topic. One part is a description of the sources of fines to be deposited; the other part is a brief description of the physical processes related to deposition.

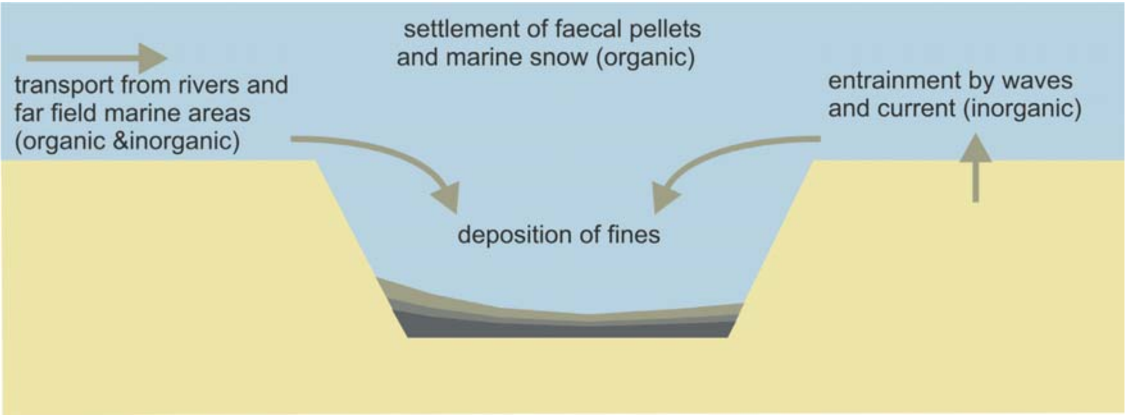
Sources of fines

We identify three natural sources of fines that can deposit in a deep sand pit [Figure 5.1]:

- The first source of fines is the suspended material brought by the tide. This material comes from river runoff and far field regions, and may contain organic and inorganic components. The quantification of this source, e.g., with a model, requires the identification of all contributing boundary fluxes.
- The second source comes from the near field seabed, which contains (mostly inorganic) fines. During storms and spring tides this material is entrained from the bed and brought into suspension [Suijlen and Duin (2001)]. Quantification of this source asks for an analysis of the wave and flow conditions and the composition of the bed material in the surrounding of the sand pit.
- In Section 4.2, we mentioned already the fines in the form of marine snow and faecal pellets that originate from organisms in the surrounding of the sand pit. Most of this material is organic, although inorganic parts are also present (calcium). Quantification of this source requires insight in the presence and activities of sea life, especially algae blooms.

Figure 5.1

Sources of fines that can deposit in a deep sand pit



Physical processes related to deposition

There are a number of physical processes related to deposition in a deep sand pit, which we mention briefly:

- The flow velocity near the bottom of a deep sand pit may be smaller than near the bottom of the surrounding area. In Section 3.2, we saw a decrease of 36% during flood and 27% during ebb. This enhances the settlement of suspended particles and reduces the entrainment of bed material.
- The increase of the water depth at the sand pit results in a decrease of the wave orbital velocity near the bottom of the pit. For instance, a wave with a wave height of 5 m and a period of 8 s [Section 2.3] gives an orbital velocity amplitude of 0.84 m/s for a water depth of 23 m and an orbital velocity amplitude of 0.46 m/s for a water depth of 33 m. The effects on deposition of fines are comparable to the effects of a reduced flow velocity near the bed.
- Bruens (2003) showed that the presence of a layer with concentrated benthic suspension strongly reduces the entrainment of bottom sediment, due to a decrease of the turbulence above the bed. The reduction of entrainment is in the order of 75% after the water has moved over a length of 70 times the water depth. When such a layer is formed during calm conditions, it can maintain itself under rougher conditions.
- The settlement of fines in a deep sand pit is further related to the settling velocity of the particles in the water column, which depends on turbulence level, particle size and particle density. Shanks (2002) for example measured settling velocities of marine snow of 10 –100 m/day in the Cape Lookout Bight, North Carolina, while Van der Lee (2000) measured settling velocities of fines of 150 - 330 m/day in the Eems-Dollard Estuary, at The Netherlands – German border.

5.3 Deposition of fines in the PUTMOR pit

When we analyse the deposition of fines in the PUTMOR pit, there are four sources of data that give useful information. These sources are: bed soundings, box cores, turbidity measurements and erosion of dumped sediments. From these measurements, we conclude that deposition of fines in the PUTMOR pit is quite small, and we think that it would not have harmed the recovery of benthic communities.

Bed soundings

According to the bed soundings between October 1999 and August 2000, the bottom changes inside and outside the pit are very small. If considerable amounts of fines had settled, it would have been visible in the soundings. The bed soundings are further described in Chapter 6.

Box cores

Two series of box cores were taken during the PUTMOR campaign. It appears that the bed of the PUTMOR pit consisted of a thin Holocene layer; below there was a Pleistocene layer of the Kreftenheye formation.

On February 23, 2000, nine Reineck box cores were taken, four outside and five inside the PUTMOR pit [Gieske and Van der Spek (2000)]. Outside the pit, sand of the Bligh Bank formation was found, which had a median diameter of 215 –280 _m and a fraction of fines of 1 to 3 %. Inside the pit, the structure of the samples shows that deposition of the sediment occurred under both dynamic and quiet conditions. Except for one sample, which contained fines and medium-sized sand, the median diameters varied between 280 – 450 _m. The box cores indicate that the sediment on the floor of the PUTMOR pit was deposited under conditions typical for an estuarine environment. Geochemical analyses of the box cores within the sandpit did not reveal traces of lead contamination from modern industries. This finding indicates that the fines that are present in these box cores have not been suspended during the last century.

The second series consists of five hydraulic vibrocores, which were taken at August 7, 2000 [Van der Klugt (2000)]. Two of them revealed traces of recently dumped material within a layer with a thickness less than 10 cm.

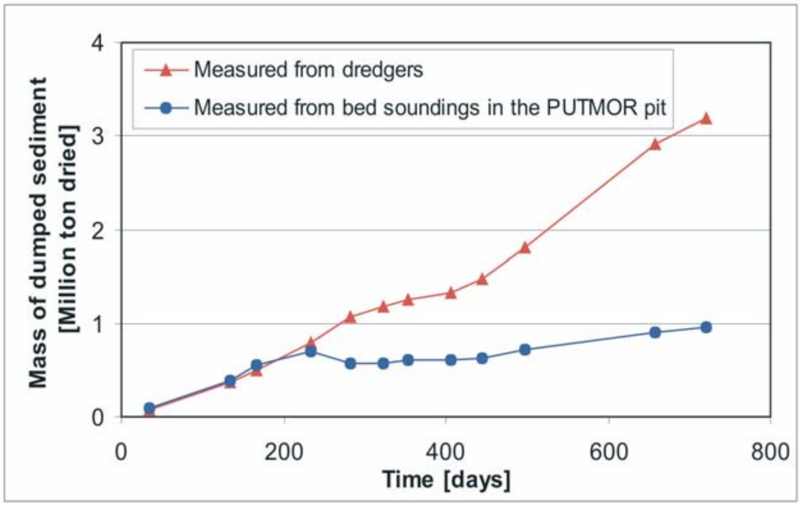
Turbidity measurements

The frame-mounted turbidity measurements give an indication of the concentration of suspended matter inside and outside the pit. The analysis of Svašek (2001C) reveals a strong relationship between the tidal flow and the concentration of fines in suspension. Mostly, the maximum turbidity near the seabed coincides with the slack tide between flood and ebb. If the current velocities are almost zero, the suspended sediment particles sink to the seabed where they pass the turbidity sensor. We see that the largest turbidity occurs at slack tide after the flood current, rather than after the ebb current. In general, the turbidity observed near the centre of the sand pit at Location M is higher than outside the sand pit at Location A. The mean of a measuring period varied between 37 and 126 NTU for Location M, and between 24 to 50 NTU for Location A.

Erosion of dumped sediment

After the PUTMOR measuring campaign was finished, the PUTMOR pit has been refilled with dredged sediment from the Port of Rotterdam. Stutterheim (2002A) estimated the mass of dumped sediment, and compared the records of the dredgers with the mass found in the PUTMOR pit from soundings. It appeared that, after a dumping period of less than one year, a significant loss appeared of up to 70 % of the cumulative dumped material [Figure 5.2]. This loss is even (much) larger than the loss of dumped material at Dump Site North West [Stutterheim (2002B)].

Figure 5.2
Comparison between the sediment mass dumped by dredgers and the sediment mass found in the PUTMOR pit, which reveals a significant loss after less than one year.



6 Morphological response of a deep sand pit

6.1 Introduction to the morphological response of a deep sand pit

The morphological response is an important element in the assessment of a deep sand extraction pit, since it may have an impact on the coast, offshore infrastructure and ecology:
- The backfilling of the deep sand pit can result in a loss of sediment on the coastal zone, which may cause retreat of the shoreline and a deterioration of the coastal defence system on the long term.
- The backfilling and migration of a deep sand pit may interfere with existing offshore infrastructure, which may cause scour around the foundation and damage of cables and pipelines.
- Flora and fauna may be disturbed by the erosion and deposition rates, caused by the morphological response.

In this chapter we study the morphological response of sand pits. We have collected a database with data on historical sand pits, trenches and dump sites, which give useful information about the time scale of morphological changes. Besides numerical models have been validated with this database, so that these may be applicable for an environmental impact assessment of a deep sand pit.

6.2 Morphological changes of the PUTMOR pit and other sites

The morphological changes of the PUTMOR pit are quite small during the time span of the bed soundings during the PUTMOR measuring campaign. Svašek (2001A) carried out a first analysis of the bottom soundings and concluded that the measuring error was greater than the real variation of the bottom elevation during the measuring campaign. As a consequence, they did not give an indication of the morphological response of the PUTMOR pit. Subsequently, we reduced the measuring error, by calculating the bias from a comparison of the successive soundings in a region where morphological changes are expected to be minimal. After we have subtracted this bias from the soundings, we were able to recognize some morphological trends within and outside the PUTMOR pit. For every location (grid cell), we approximated the bottom change for one year, with a linear trend based on six bathymetry soundings [Figure 6.1]. The accuracy of this approximation is presented in Figure 6.2, which gives the squared correlation factor between trend and soundings for each grid cell. For large areas there is a relatively low correlation (less than 0.4), which implies that in those regions the measured bottom changes were close to, or smaller than, the accuracy of the measurements. The approximated bottom changes on the northern and southern slopes seem inaccurate, while the bottom changes on the eastern and western slopes seem more accurate.

Although the squared correlation factor is low for a large part of the sounded area, Figure 6.3 shows, in a 3-dimensional way, some erosion – sedimentation patterns that are worth to mention. We notice that the bottom of the pit is not smooth, but consists of ridges and runnels, which

Figure 6.1
Bottom changes for one year; blue is erosion, brown is sedimentation.

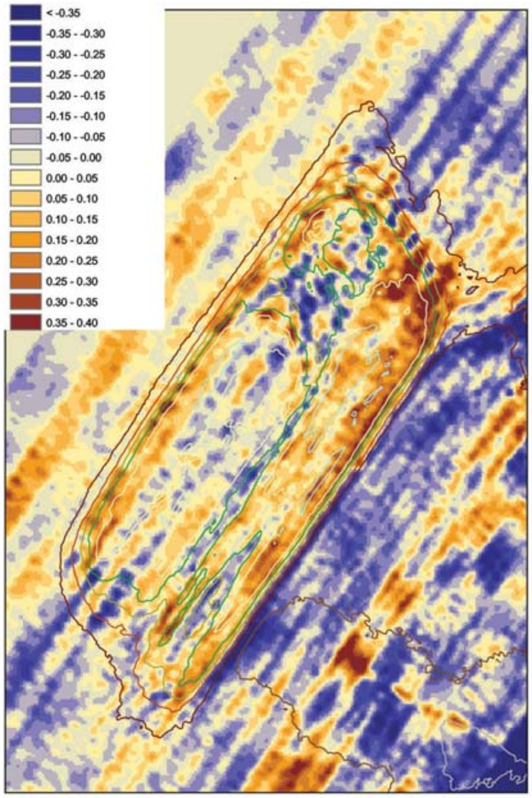


Figure 6.2
Map of squared correlation factor of the six bathymetric surveys.

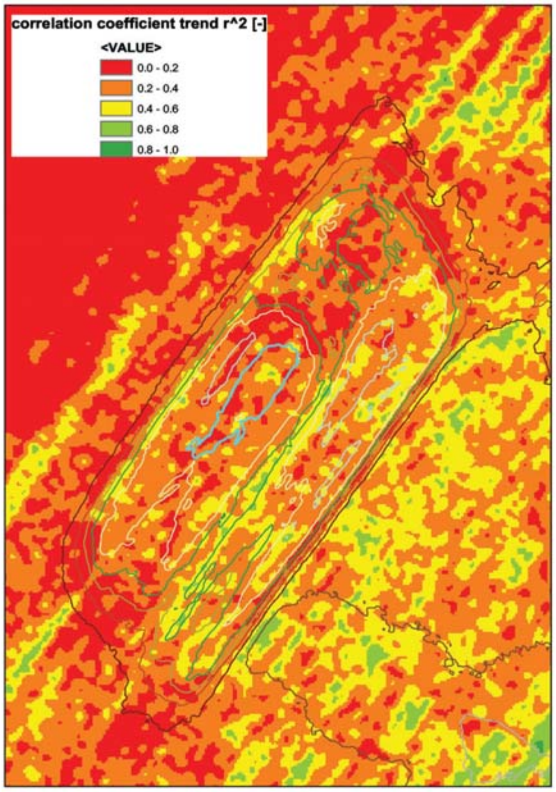
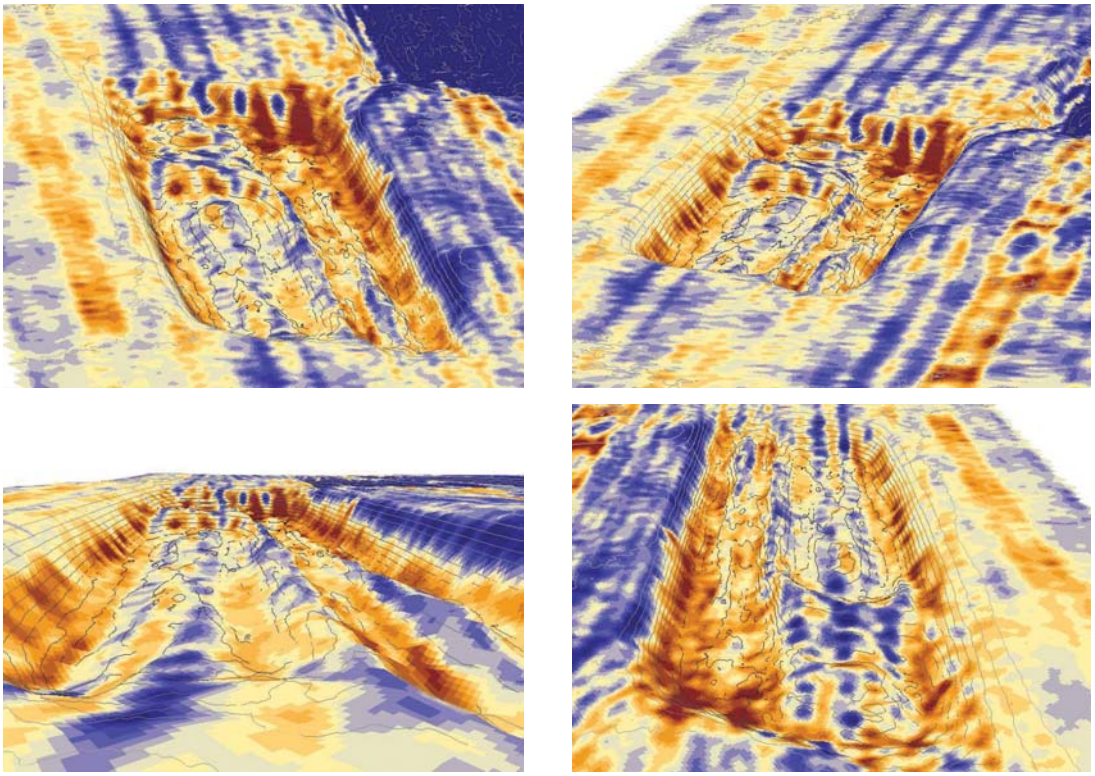


Figure 6.3
Erosion (blue) and sedimentation (red) in the PUTMOR pit from different perspective



were left behind after the sand extraction with suction hopper dredgers. It appears that the bottom is smoothing out by erosion of the ridges and backfill of the runnels. Moreover, we see that the slopes of the PUTMOR pit are levelling off, especially in the northern and eastern part of the pit. Outside the pit, we see erosion eastward from the PUTMOR pit. Considering the total volume of sedimentation within the PUTMOR pit, we see that the pit fills with an amount of about 20,000 m^3 per year, which means that the natural backfill of the pit has a period in the order of centuries.

Since we are interested in the morphological behaviour of deep sand pits everywhere on the NCS, we have collected a database with other morphological data. Table 6.1 gives an overview of Dutch bathymetry data of 10 sand pits, trenches or dump sites near the Dutch coast. The sites are visible on the map of Figure 6.4. We draw attention to the following aspects:

Table 6.1

Overview of data Dutch bathymetry data on historical sand pits, trenches and dump sites

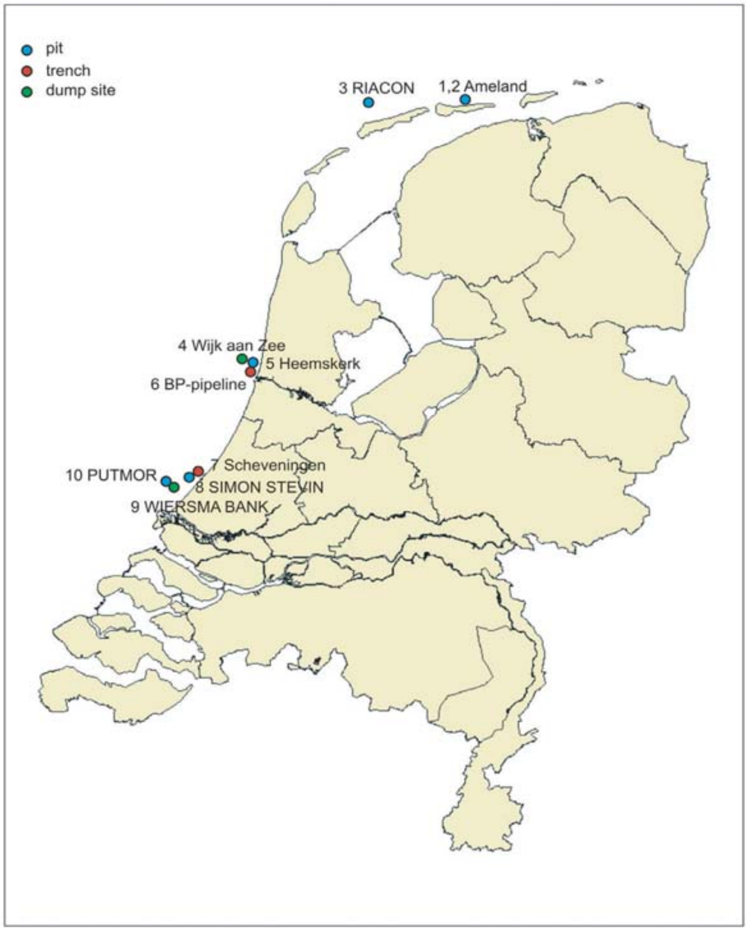
Number on the map:	Field site:	Type of extraction:	Volume dredged/ dumped (m^3):	Year of dredging/ dumping:	Local water depth:	Available:	Number of surveys:	Time span surveys:	Characteristic timescale:
1	Ameland I	Pit	140,000	1990	9-10	lost	5	7 months	1 year
2	Ameland II	Pit	257,000	1992	9-10	digital	4	10 months	6 months
3	RIACON	Pit	2,500,000	1993	20	digital	5	6 years	6 years
4	Wijk aan Zee	Dump site	950,000	1982	11-15	chart	11	9 years	18 years
5	Heemskerk	Pit	154,000	1996	7-8	digital	2	6 weeks	7 months
6	BP-pipe line	Trench	90,000	1986	5.5-7.0	digital	4	1 year	11 months
7	Scheveningen	Trench	20,000	1964	7-10.5	digital	3	6 months	6 months
8	SIMON STEVIN	Pit	60,000	1981	15.5	chart	4	10 years	7 months
9	Wiersma Ridge	Dump site	3,500,000	1982-1986	15-23	digital	> 9	20 years	80 years
10	PUTMOR	Pit	4,500,000	1999	23	digital	6	10 months	220 years

- **Type of extraction**
  We have collected data on sand pits [6], trenches [2] and dump sites [2]. Sand pits were left after the extraction of sand. The pits at Ameland I, Heemskerk, SIMON STEVIN and PUTMOR were refilled afterwards by dredgers. Trenches were dredged for the construction of pipelines; at dump sites a certain amount of sand is dumped.
- **Volume dredged/dumped**
  The volume of dredged material varies between 20,000 m^3 for the Scheveningen trench and 4,500,000 m^3 for the PUTMOR pit; the volume of dumped material varies between 950,000 m^3 for Wijk aan Zee and 3,500,000 m3 for the Wiersma ridge.
- **Year of dredging/dumping**
  Except for the Wiersma ridge, dredging or dumping occurred within one year at all field sites. The earliest measured data come from the Scheveningen trench in 1964, the latest from the PUTMOR pit in 1999.

- **Local water depth**
  The local water depth is the initial water depth below Mean Sea Level (MSL) before dredging or dumping. The local water depth varies between 5.5 m for the BP-pipe line and 23 m for the PUTMOR pit.
- **Available**
  Not all data are digitally available. Some of the data are still missing; other data is only available on chart. The Ameland I data are probably lost, which is also the case for the SIMON STEVIN data. The volumes of these pits are known, however.
- **Number of surveys**
  The number of surveys is the number of bathymetry soundings after dredging or dumping. The number varies between 2 for the Heemskerk pit and 11 for the Dump Site Wijk aan Zee.
- **Time span surveys**
  The time span of the surveys is the time span between the first and the last survey. This time span varies between 6 weeks for the Heemskerk pit and 20 years for the Wiersma ridge.
- **Characteristic time scale**
  The characteristic time scale is based on the assumption that the dredged or dumped volume shows an exponential decrease (V_0: initial volume, V_t: volume at time t, T_k characteristic time scale):

$$V_t = V_0 (1 - e^{-\frac{t}{T_k}})$$

Figure 6.4
Map with the locations of sand pits, trenches and dump sites



This function is fitted through the volumes in time, to determine the characteristic time scale, at which time the volume has decreased by 62%. This characteristic time scale varies between 6 months for the Scheveningen trench and 220 years for the PUTMOR pit.

Table 6.1 shows much variation in the characteristic time scale of the various sand extractions and dump sites. This variation is due to the local environmental conditions (waves, flow velocity, sediment characteristics) and the characteristics of pits, trenches and dump sites (volume, shape, orientation). In Figure 6.5, we see that an increase of the water depth and of the volume leads to an increase of the characteristic time scale. For large-scale sand extractions (more than 10 million m^3) at water depths larger than 20 m, we have to deal with characteristic time scales for backfilling in the order of centuries.

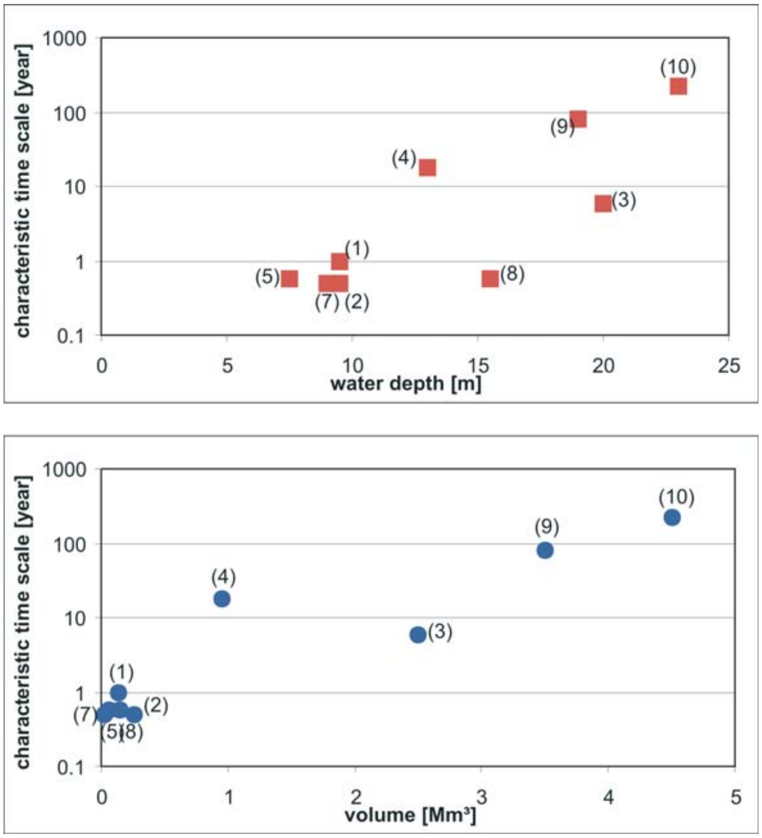


Figure 6.5
The characteristic time scale of pits, trenches and dump sites on a logarithmic scale. The upper panel shows that an increase in water depth leads to an increase of the characteristic time scale. The lower panel shows the same pattern for increasing volumes. The numbers correspond with Table 6.1 and Figure 6.4.

6.3 Prediction of the morphological response with a numerical model

In the previous section we analysed the observed morphological responses of sand pits, trenches and dump sites on the NCS. However, the collected dataset does not cover all possible environmental conditions and characteristics of a sand extraction pit. Moreover, in case of a large characteristic time scale, the time span of surveys is often too short, which is certainly the case for the PUTMOR measuring campaign.

If knowledge about the morphological response of a sand extraction is required, a morphodynamic model may help to assess the characteristic time scale and the impact on values and user functions. The reasons are:

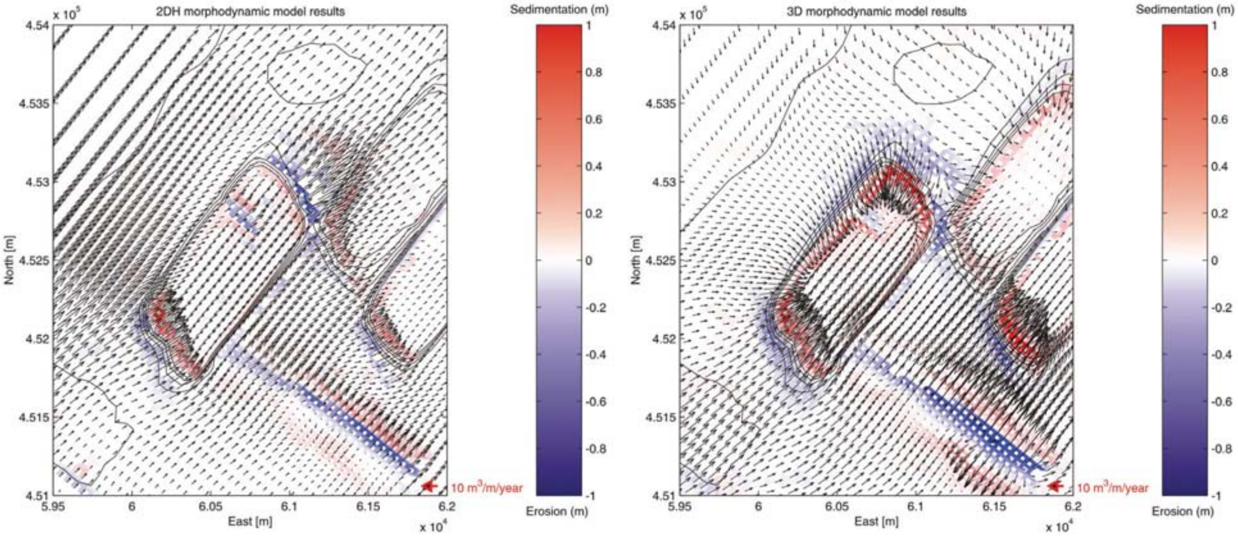
- A numerical model can handle various environmental conditions.
- A numerical model can handle various types of pit design.
- A numerical model can predict the morphological response for a large time scale.

Before we apply a numerical model, we need to validate this model beforehand, for instance with the database described in the previous section. Until the start of the PUTMOR project, most of the morphological calculations on the response of a sand pit or a trench were carried out on schematized sand pits and trenches. Examples are found in Walstra *et al.* (1998), Nemeth (1998), Klein (1999), Peters (2000), Van de Kreeke *et al.* (2001) and Walstra *et al.* (2002B).

Within the PUTMOR project, two validation studies have been carried out to validate the model DELFT3D with the PUTMOR data. The first validation was carried out for the PUTMOR pit with bathymetry data collected during the PUTMOR measuring campaign [Walstra *et al.* (2003)]. The second validation was carried out for other sand extraction pits of the Lowered Dump Site (LDS) and for the Wiersma ridge and the Scheveningen trench [Van Rijn and Walstra (2004)].

Figure 6.6

Sedimentation-erosion and yearly residual transports calculated in 2DH (left) and 3D (right).



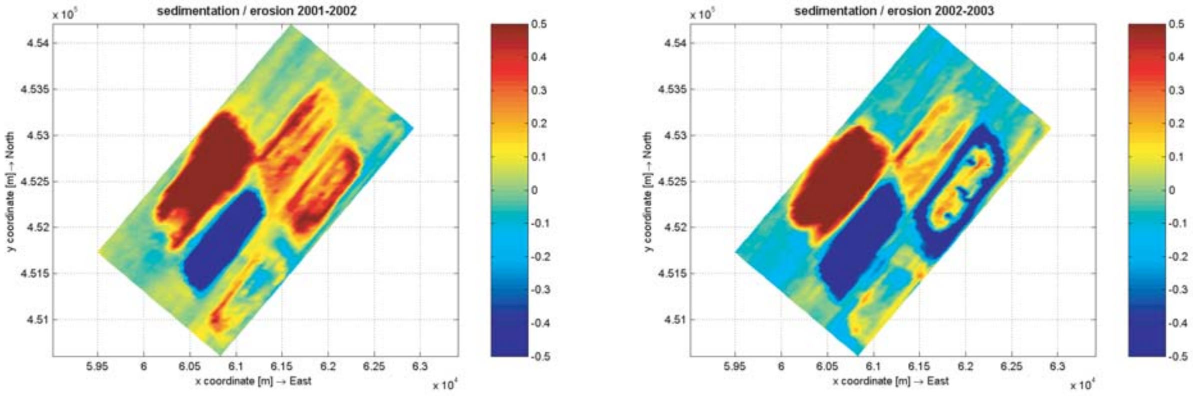
Walstra *et al*. (2003) described some indicative morphodynamic simulations to investigate the effect of the 2DH and 3D approach on the resulting morphology. The simulations were made using the hydrodynamic conditions of Period 1 in which the morphological changes were scaled to simulate one year [see Section 3.4, Figure 3.6]. In Figure 6.6 the predicted sediment-erosion patterns and the residual total depth-averaged transports are shown for both model runs (waves were included). Although for both simulations most changes have occurred in the direct vicinity of the pit, namely erosion just outside the pit and mainly sedimentation on the pit slopes, the 3D simulation has resulted in significantly larger changes in the morphology. Especially, the sedimentation at the longshore pit slopes is more pronounced in the 3D results. This is mainly caused by secondary cross-shore flows caused by the presence of the pit. This is clearly visible if the residual transports are compared. The 2DH simulation predicts northeasterly transports parallel to the main tidal direction. As a consequence, the morphological changes are mainly present on the pit slopes perpendicular to the main tidal direction due to acceleration and deceleration of the flow. However, the 3D simulation predicts that the pit attracts sediment from all directions, which results in southward transports at the northern part of the pit. Although the measured morphology [Figure 6.3] has a very ‘patchy’ distribution, the sedimentation on the landward longshore slope and the erosion in the region landward of this slope is clear. This seems to be in more accordance with the predictions made with the 3D than the 2DH results. However, it has to be stressed that no direct comparison can be made since the imposed hydrodynamic forcing conditions are not representative for longer-term morphodynamic simulations.

The second simulation is focussed to the two most onshore sand pits, aligned along the southeast boundary, of the LDS. Figure 6.7 shows the bottom changes between 2001 and 2002 and between 2002 and 2003. When we analyse these, we make the following observations:

- There is much difference between the bottom changes during the first year and during the second year. This makes a comparison with model predictions quite difficult.
- The northern pit shows more sedimentation than the southern pit.
- Comparable to the bathymetry of the PUTMOR pit, we see a levelling off of the pit slopes. This is especially the case for the northern pit.
- The partition between the two onshore pits shows significant erosion.

Figure 6.7

Sedimentation-erosion of the LDS during two successive years. Note that the PUTMOR pit has been dumped, while sand has been extracted in the middle southern pit. For the model validation only the most onshore pits, aligned along the southeast boundary, have been applied.



sedimentation / erosion 2001-2002

sedimentation / erosion 2002-2003

Figure 6.8
Sedimentation-erosion in the sand pits of the LDS. The left panel shows the initial bathymetry to the model runs; the right panel shows the predicted sedimentation and erosion for a period of one year.

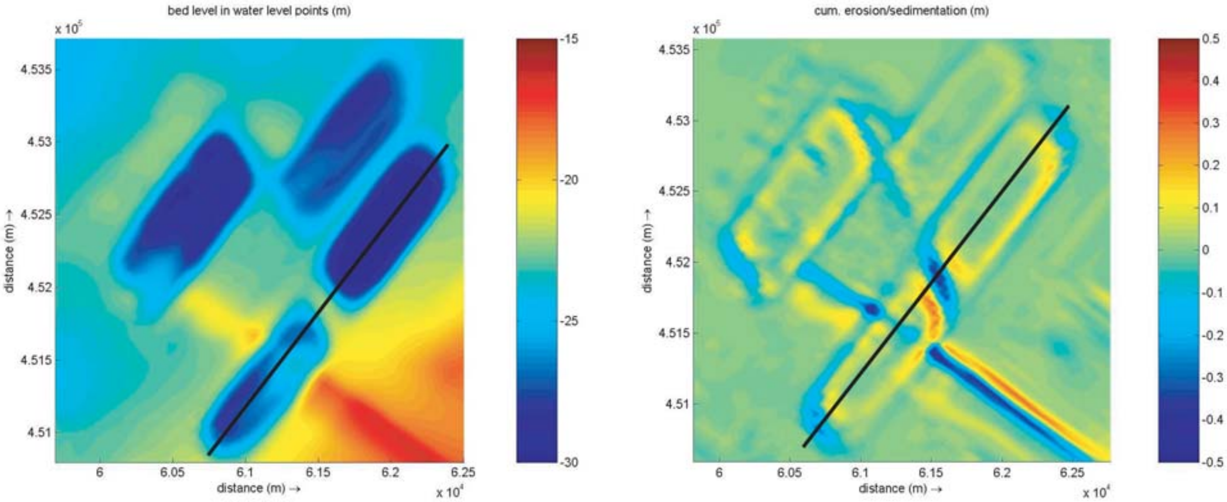
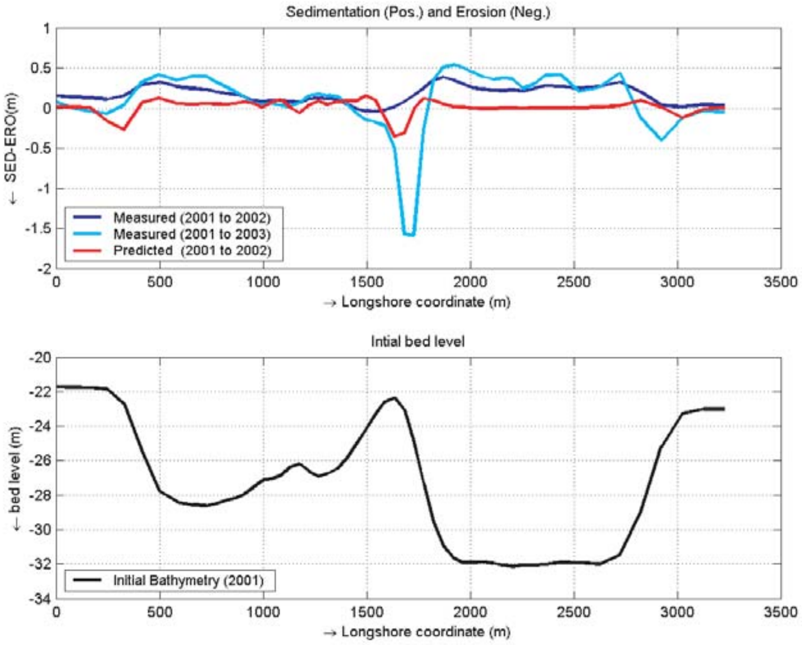


Figure 6.8 shows the initial bathymetry, which was applied in the model runs by Van Rijn and Walstra (2004), and the predicted erosion and sedimentation during one year. The model runs were carried out with DELFT3D in 2DH mode, using the recently developed sediment transport model TRANSPOR 2004. Comparison between predictions and measured bathymetry is carried out in Figure 6.9 for a longshore section through the two most onshore sand pits. This section is the black line in Figure 6.8.

Figure 6.9
Sedimentation-erosion in the sand pits of the LDS. The lower panel shows the initial bathymetry in 2001; the upper panel shows the predicted and measured sedimentation and erosion for a period of one year.

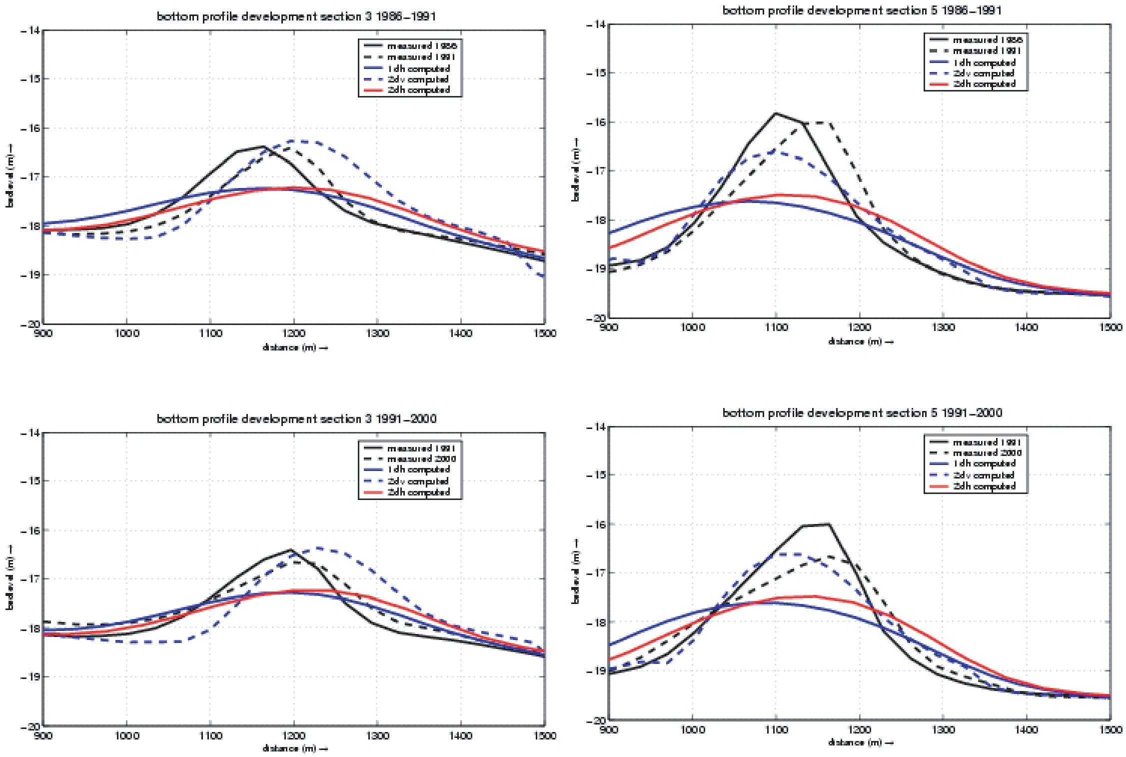


It appears from the measurements that there are large mutual differences, in space and in time. This leads up to an unclear judgement of the model performance. Perhaps the most important conclusion of the validation with the PUTMOR data is that the morphological changes of the pits go very slowly, which is also predicted by the model DELFT3D. Both the measurements and the predictions point to a large characteristic time scale of the sand pits on the LDS, although the morphological changes in the measurements seem larger than in the predictions.

Besides the model validation with the PUTMOR data, Van Rijn and Walstra (2004) validated the model DELFT3D with measuring data from the Wiersma ridge [Figure 6.10] and from the Scheveningen trench [Figures 6.11 and 6.12]. We see that the Wiersma ridge shows a migration to the north of about 50 – 100 m in fifteen years. This indicates that such a dump site does not interact with offshore infrastructure at a distance of more than 500 m away, during an exploitation time of about 30 years. The Scheveningen trench is filled up with sediment within a time span of half a year. The model predictions show the same behaviour as the measured bathymetry, a fast backfilling of the Scheveningen trench and a northward migration and flattening of the Wiersma ridge. The magnitude of the flattening of the Wiersma ridge is however too fast. The 2DV model configuration gives the best results.

Figure 6.10

Predicted (left panel) and measured (right panel) bottom changes of two profiles across the Wiersma ridge. The upper panels reflect the bottom evolution between 1986 and 1991; the lower panels reflect the bottom evolution between 1991 and 2000. Three model configurations have been applied, a 1D, a 2DV and a 2DH approach.



When we assess the applicability of the model DELFT3D to predict the morphological effects of trenches dump sites and sand pits, we come to the following conclusions:

- Predictions over a time span of a few decades are possible.
- The model can handle various environmental conditions. It predicts a very short characteristic time scale for small extractions at shallow water and a very long characteristic time scale for large sand extractions at deep water. This is in agreement with our findings in Section 6.2.
- The model DELFT3D gives a good qualitative prediction of the migration and the backfilling or flattening. Quantitatively the magnitudes of the bottom changes have to be improved further.

Figure 6.11

Predicted (left panel) and measured (right panel) bottom changes of the Scheveningen trench.

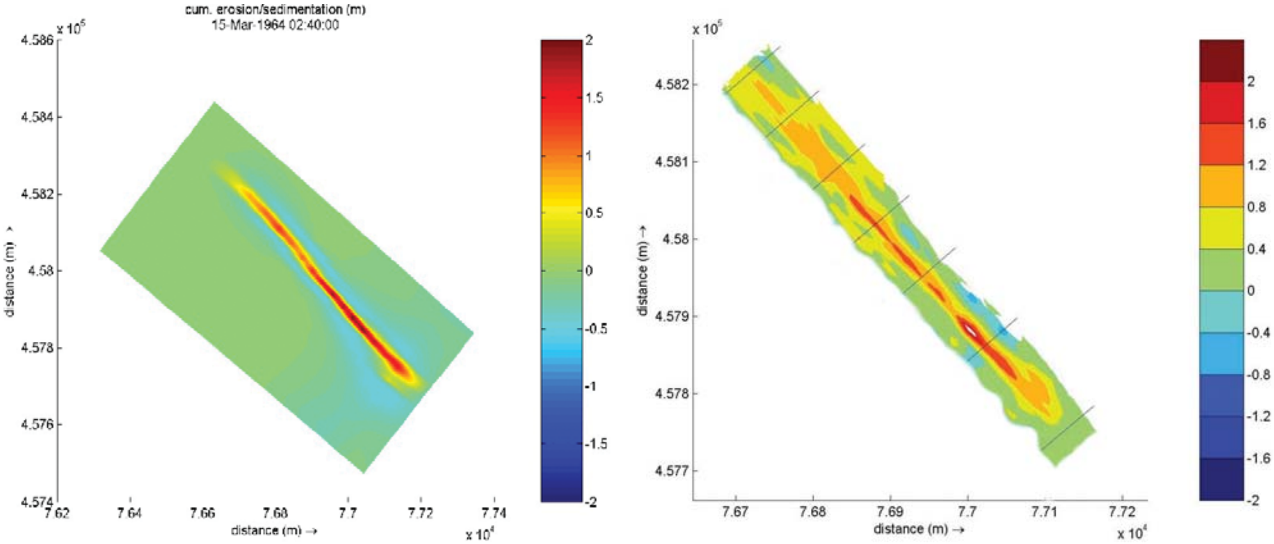
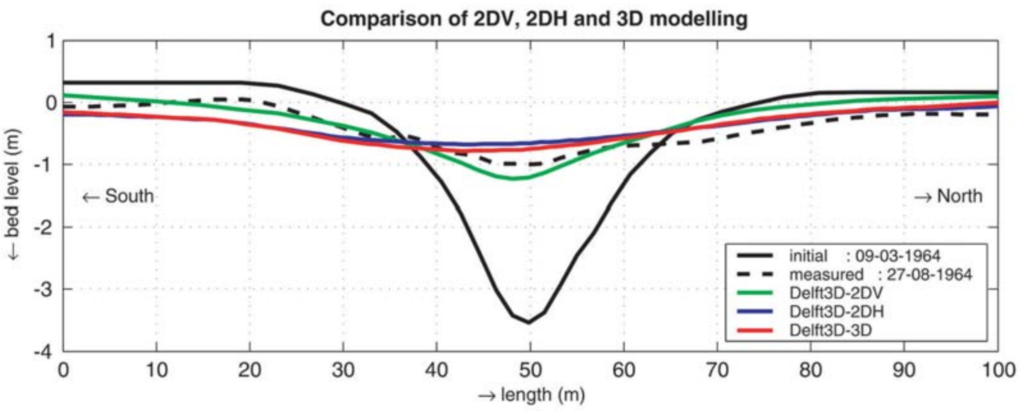


Figure 6.12

Measured and predicted profiles of the Scheveningen trench for various model configurations.



7 Conclusions and recommendations

7.1 Conclusions

General conclusion regarding deep sand extraction on the Netherlands Continental Shelf (NCS)

In the “Nota Ruimte” the Dutch Government has announced to allow for deep sand extraction on the NCS, which has been worked out in the “Regionaal Ontgrondingenplan Noordzee 2”. In this report, we conclude that after considering the results of the PUTMOR project supplied with other data from the NCS, we did not found indications that a deep sand extraction with a final water depth less than 40 m will necessarily lead to unacceptable effects on existing values and user functions. Dependent on the deep pit design, the colonizing benthic communities on the new seabed within a deep sand extraction pit will tolerate the physical conditions inside the pit. Furthermore, the morphological changes of a deep sand extraction pit will be very slow, depending on the local conditions. As a result, we expect that the backfilling and migration of a deep sand pit will not affect offshore infrastructure and the coast at a distance of more than 500 m from the pit in the foreseeable future. Therefore we expect that a deep extraction pit will be an interesting alternative for shallow sand pits with a volume of more than 10 million m^3.

The PUTMOR measuring campaign

During the PUTMOR measuring campaign, we collected field data of the hydraulic conditions, oxygen concentrations near the bed, sedimentation of fines and the morphology inside and outside a 4.5 million m3 sand pit, with an extraction depth between 5 - 12 m. In this chapter, we draw conclusions on the physical effects of such a pit, and the impact on values and user functions, following the hypotheses formulated in Section 2.2. Furthermore, we draw conclusions on the performance of hydraulic and morphodynamic models and the general applicability of this study for deep sand extraction pits at the Netherlands Continental Shelf.

Flow velocity

The PUTMOR pit, which is the first temporary pit of the Lowered Dump Site at Hook of Holland, has a clear effect on flow rate and flow velocity. At the centre of the pit, we see an increase in the flow rate with one-third compared with the situation outside the pit. However, especially the flow velocity near the bed shows a decrease in the order of one-third compared with the situation outside the pit. The flow velocity has a negligible effect on shipping traffic. Furthermore, the flow velocity may play a role in ecology, through haline and thermal stratification, oxygen transport and sedimentation of fines, and on morphology, through sediment transport.

Water levels and waves

The effects of the PUTMOR pit on water levels and waves seem negligible.

Stratification and oxygen depletion

Haline stratification on the NCS is often found in the upper 10 m of the water column, but it never leads to hypoxia at the bottom. We conclude that the risk on oxygen depletion due to a halocline is negligible for a sand extraction pit outside the straightened 20 m depth contour on the NCS. Thermal stratification on the NCS is only found at depths deeper than 40 meters, where the development of a thermocline takes a couple of weeks. We therefore conclude that the risk on oxygen depletion due to a thermocline is only possible if the water depth is deeper than 40 m and the refreshment of the water inside the pit goes very slowly. This means that the risk on oxygen depletion inside the PUTMOR pit is negligible, because this pit had a depth of maximum 34 meters, and a refreshing of the water inside the pit twice a tidal cycle. This is in agreement with the PUTMOR oxygen concentration measurements inside the pit that were very in line with the measurements outside the pit and measurements at Noordwijk 10.

Deposition of fines

Deposition of fines, both organic and inorganic, can have an effect on the oxygen concentration in and above the bed. The measurements did not show an increased deposition inside the PUTMOR pit, compared to its surroundings. This finding is however very site-specific. The outcome may differ for other environmental conditions (flow velocity, concentration of suspended fines), and the properties of the sand pit.

Morphological changes

During the period of almost a year that the PUTMOR pit had been open, the morphological changes were very small. The sedimentation was calculated to be about 20,000 m3, which means a backfilling period of about two centuries. Moreover, there was a slight levelling of the slopes and a flattening of the ridges and runnels, left by the suction hopper dredgers.

Hydraulic and morphodynamic models

The PUTMOR measurements were used for validation of the numerical model DELFT3D. It appears that especially the flow velocity data are very applicable as a benchmark for hydraulic models. The bed soundings have less value due to the short measuring period and the large effect of measuring errors relative to the slow response of the pit. It appeared that the simulation of the flow velocity by DELFT3D was rather satisfactory, which makes this model a useful tool as a predictive instrument. This model further gave a good qualitative prediction of the morphological behaviour of the PUTMOR pit, the Wiersma ridge and the Scheveningen trench. Predictions on the migration speed and the backfilling/flattening in time should be further improved.

Impact of the PUTMOR pit on values and user functions

It appears that the presence of the PUTMOR pit would have had a negligible impact on values and user functions:

- The PUTMOR pit had no risk on hypoxia and sedimentation of fines, which means that the chances would have been high for a good recovery of benthic communities inside the pit.
- The morphological changes of the PUTMOR pit were very slow, which means that the risks for existing archaeological remains, offshore infrastructures and the coast would have been very small.

Future deep sand extraction pits on the NCS

The results of this study are valuable input to the design of future deep pits on the NCS and the prediction of possible effects of such pits:

- It is possible to predict the flow velocity inside and outside the pit with a numerical model, at a satisfactory level. These flow velocity predictions can be input to the prediction of stratification, deposition of fines and morphological changes.
- It is possible to make a useful prediction of the backfilling and migration of a pit under various environmental conditions. Such a prediction can help the assessment of the impact of a pit on coast and offshore infrastructure, under the restriction that such a prediction still has a high level of uncertainty.
- We do not expect haline or thermal stratification inside a deep pit on the NCS, and negative impacts on the oxygen concentration near the bed, if the water depth after extraction stays less than 40 meters. If the water depth becomes larger, the possibility of thermal stratification depends on the residence time of the water inside the pit.

7.2 Recommendations

The flow velocity data from the PUTMOR measurements are a good benchmark for validation of hydraulic models on sand extraction pits. However, when new deep pits are developed, we recommend extending the benchmark database with additional flow velocity data.

When there are plans for deep sand pits with a final water depth of more than 40 meters on the NCS, we recommend studying the risks on thermal stratification and hypoxia beforehand.

We recommend studying the risks on deposition of fines for future deep sand pits by carrying out additional measurements and developing new numerical models.

We recommend to collect bathymetry data of historical sand pits, trenches and dump sites [see Table 6.1], and to validate morphological data with these data. Especially for new deep extraction pits, we recommend bathymetry surveys after the extraction for a time span of minimum 10 years, with surveys carried out every two years.

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Appendix A: Contents of PUTMOR DVD

Appendix A: Contents of PUTMOR DVD
Enclosed to this report, there is a PUTMOR DVD, which contains three maps with information about deep sand pits:

1) PUTMOR REPORTS
2) PUTMOR MEASUREMENTS
3) OTHER RELEVANT DATA

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PUTMOR REPORTS

The following reports are found on the PUTMOR DVD:

Boers, M., 2005
Effects of a deep sand extraction pit; Final report of the PUTMOR measurements at the Lowered Dump Site. Rijkswaterstaat, report RIKZ/2005.001 (this report).

Boers, M., 2005
Overview of historical pits, trenches and dump sites on the NCS. Submitted for the final report of the EU SANDPIT project. Rijkswaterstaat, Workdocument RIKZ/KW/2005.105W.

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PUTMOR field measurements at a temporary sand pit; Part 1: processing and validation. Svašek coastal & harbour engineering consultants. Report 01037/1177.

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Walstra, D.J.R., L. C. Van Rijn, M. Boers and J.A. Roelvink, 2003
Offshore sand pits: verification and application of a hydrodynamic and morphodynamic model. Coastal Sediments.

PUTMOR MEASUREMENTS

The following PUTMOR data are found on the DVD. Information about these data are found in Svašek (2001A)

- Aanderaa
- Bathymetry
- Fixed ADCP
- Hydrolab
- Mors
- Seabird
- Towed ADCP

OTHER RELEVANT DATA

The DVD contains also other relevant data

- Bathymetry of the pits, trenches and dump sites mentioned in Chapter 6:
  - Ameland
  - Riacon
  - Heemskerk
  - BP-pipe line
  - Scheveningen
  - Wiersma Ridge
  - HydroMeteo data during the PUTMOR campaign

Information about the bathymetry data is found in Table A.1 [See also Boers (2005)]. The filenames of the bathymetry data files reflect the date of the sounding.

NAP: Dutch Ordnance Level
MSL: Mean Sea Level

The difference between NAP and MSL is generally less than 0.3 m.

Table A.1
Units of the bathymetry of pits, trenches and dumpsites

Pit, trench or dumpsites	Coördinate system	Reference waterlevel	Unit waterdepth
Ameland	Rijksdriehoekstelsel	NAP	m
BP-pipe line	Rijksdriehoekstelsel	NAP	m
Heemskerk	Rijksdriehoekstelsel	NAP	m
Riacon	UTM	MSL	cm
PUTMOR	UTM	MSL	m/dm
Scheveningen	Rijksdriehoekstelsel	NAP	cm
Wiersma Ridge	UTM	MSL	cm