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Directoraat-Generaal Rijkswaterstaat
Rijksinstituut voor Kust en Zee/RIKZ

Analysis and modelling of sand mining pits

Report

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L.C. van Rijn and D.J.R. Walstra

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CLIENT: DG Rijkswaterstaat; Rijks-Instituut voor Kust en Zee/RIKZ

TITLE: Analysis and modelling of sand mining pits

ABSTRACT: Massive mining of sand from the middle and lower shoreface (depths of 10 to 30 m) in large-scale mining and extraction pits/areas will be required in future in many European countries. For example, around the North Sea mining of sand will be required to nourish beaches and coastal dunes in response to increased coastal erosion due to the expected sea level rise. Furthermore, the large-scale reclamation of land and the construction of large-scale artificial islands (for industrial purposes; ports and airports) in coastal seas which are presently being considered, will also require huge amounts of sand as building material. Given the scale of these undertakings, the volume of sand required in the near future (10 to 20 years) will be of the order of 100 to 1000 million m$^3$ per country surrounding the North Sea. To meet these demands, the existing areas for mining of sand need to be extended considerably and new potentially attractive areas should be explored and exploited. Massive mining of sand may take place by dredging in artificial sand pits or channels (also navigation channels) or by removal (dredging) of existing large-scale sand banks/shoals in the offshore zone (middle and lower shoreface).

The present report is focussed on the following topics of offshore sand mining:

- Update of the literature review as presented earlier by Van Rijn and Walstra (2002);
- Determine the performance of the Delft3D-Online model for pits, trenches and dams in deeper water.

The performance of Delft3D is investigate for two laboratory cases and three field experiments. To objectively assess the model performance use is made of a number of aggregated parameters (e.g. volumes, displacement of centroids) and statistical parameters (e.g. correlation, RMS-error and Bries skill score). For the experiments with sufficient amount data for comparison these parameters were determined.

The laboratory cases both determined the infill of a trench under the combined influence of currents and waves. The field experiments that were used consisted of two trench/pit cases (2nd PUTMOR pit and Scheveningen trench) and an artificial sand dam near Hoek van Holland. The cross-shore morphological changes are relatively small for pits beyond the 15 m depth contour; the migration rates are mainly affected by the local water depth and not by the pit dimensions (depth, width, length). The migration velocity of the pit in longshore direction was found to be 10 to 15 m/year. The morphological changes remain within the local surrounding of the pits. On the time scale of 100 years the overall longshore migration of the pit is of the order of 1 to 2 km. The sedimentation of the pit (infilling rate) increases strongly with decreasing water depth outside the pit.

REFERENCES: Contract RKZ-1392

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I Introduction

1.1 Problem and approach

Massive mining of sand from the middle and lower shoreface (depths of 10 to 30 m) in large-scale mining and extraction pits/areas will be required in future in many European countries. For example, around the North Sea mining of sand will be required to nourish beaches and coastal dunes in response to increased coastal erosion due to the expected sea level rise. Furthermore, the large-scale reclamation of land and the construction of large-scale artificial islands (for industrial purposes; ports and airports) in coastal seas which are presently being considered, will also require huge amounts of sand as building material. Given the scale of these undertakings, the volume of sand required in the near future (10 to 20 years) will be of the order of 100 to 1000 million m$^3$ per country surrounding the North Sea.

To meet these demands, the existing areas for mining of sand need to be extended considerably and new potentially attractive areas should be explored and exploited. Massive mining of sand may take place by dredging in artificial sand pits or channels (also navigation channels) or by removal (dredging) of existing large-scale sand banks/shoals in the offshore zone (middle and lower shoreface).

The present report is focussed on the following topics of offshore sand mining:
- update of the literature review as presented earlier by Van Rijn and Walstra (2002);
- Determine the performance of the Delft3D-Onlines model for pits, trenches and dams in deeper water.

The performance of Delft3D is investigate for two laboratory cases and three field experiments. To objectively assess the model performance use is made of a number of aggregated parameters (e.g. volumes, displacement of centroids) and statistical parameters (e.g. correlation, RMS-error and Bries skill score). For the experiments with sufficient amount data for comparison these parameters were determined.

The laboratory cases both determined the infill of a trench under the combined influence of currents and waves. The field experiments that were used consisted of two trench/pit cases (2nd PUTMOR pit and Scheveningen trench) and an artificial sand dam near Hoek van Holland.

The present report has been composed by L.C. van Rijn and D.J.R. Walstra and was reviewed by M. Boers of Rijkswaterstaat/RIKZ.
1.2 Types and effects of mining pits

Mining of sand in coastal waters to obtain sediment material for beach nourishment and industry takes place in a wide range of depths from shallow water with depths of 5 to 10 m in New Zealand and Japan (Uda et al., 1995; Hilton and Hesp, 1996) up to deep water with depths of 30 to 40 m in Japan (Tsurusaki et al., 1988; Kojima et al., 1986). Mining operations can be performed from pits, channels, trenches dredged in the seabed or from large-scale geomorphic features present on the seabed (sand shoals and sand banks).

Geomorphic features such as linear and/or arcuate shoals and banks in the marine environment are usually composed of sand or sand-gravel mixtures, and are potentially usable for extraction sources. Most of these features are of recent (modern) age but some may have been formed during the Holocene transgression and are essentially relict (formed by processes no longer prevalent). Relict features have, to some extent, been modified by existing processes. Relict status is usually evidenced by sediment size composition and sedimentary structures which deviate from existing environmental conditions.

The available mining methods basically fall into two categories: wide, shallow mining pits or small, deep mining pits. In most cases shallow pits not deeper than a few metres are excavated in deeper waters to obtain sand for beach nourishments. Deep pits have not yet been used extensively for mining of sand.

![Figure 1.1 Interaction of parameters related to offshore mining activities (Nairn et al., 2004).](image)

The mining of sea sand will affect both the ecology and morphology of the coastal system, see Figure 1.1 and Table 1.1. The ecology is affected in the sense that the flora and fauna of the system are destroyed by the mining activities, whereas also the release of very fine sediments (silt and clay) from the bed into the water column may have a direct influence on the ecological system. The local bed fauna is almost completely destroyed by the mining activities. This also has a direct negative effect on all living organisms which are for their food dependent on the bed fauna. The recovery period of shallow mining areas is of the order of 5 years, but the recovery period may increase considerably with increasing excavation depth (dead water zone at bottom of deep pit). Additional negative effects may occur due to increase of the turbidity of the water phase above the bed when fines from the bed layers are brought into the water phase by the mining activities (stirring).
The morphology is affected in the sense that locally the bed level is lowered substantially in the form of an extraction or extraction pit (or channel), which may influence the local flow and wave fields and hence the sand transport rates. Wave fields are modified by shoaling, refraction and reflection processes (interception of onshore sand transport). The pit area (slopes) may migrate towards the shore over time and/or may act as a sink (trapping) for sediments from the nearshore system (beach drawdown). On long term (100 years) the area of influence may extend over tens of km’s outside the original mining area. Furthermore, the small-scale and large-scale bed forms (from megaripples to sand waves) may be destroyed locally, which may also have an effect on the hydrodynamic system (less friction and turbulence).

The most basic question related to offshore sand mining is: what is the optimum location of large-scale mining pits and what are the optimum dimensions so that the coastal impact is minimum?

<table>
<thead>
<tr>
<th>Type of process</th>
<th>Effects/Impacts</th>
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<tbody>
<tr>
<td>Extraction process (dredging activities)</td>
<td>Increased levels of suspended inorganic and organic solids (turbidity) due to dredging activities (including overspill and plume generation).</td>
</tr>
<tr>
<td>Hydrodynamics</td>
<td>Changes in wave climate at and inshore of extraction site. Change in tide-induced, wind-induced, density-induced and wave-induced flow at and inshore of extraction site.</td>
</tr>
<tr>
<td>Sediment composition and transport</td>
<td>Changes in grain size distributions due to removal of bed material by dredging (changes in substrate) and erosion/sedimentation processes created by extraction of sediment (pit is sink/ trap). Changes in compaction and organic content. Changes of shear stresses acting on sediment grains (sediment mobility) at and inshore of extraction site resulting in modified transport patterns (modified littoral drift).</td>
</tr>
<tr>
<td>Morphodynamics</td>
<td>Creation of dredging-related furrows (&lt;1 m) and or pit (&gt;1 m) due to removal of sediment. Migration of furrows and or pit. Generation of morphological changes inshore of extraction site (shoreline).</td>
</tr>
<tr>
<td>Ecology (benthos, marine mammals)</td>
<td>Habitat loss or reduced habitat conditions due to dredging activities, modifications of hydrodynamics, sediment dynamics and morphodynamics. Recolonization by altered biological community (different species).</td>
</tr>
</tbody>
</table>

Table 1.1 Summary of physical and ecological impacts of sand mining.

To solve such a question, the coastal management increasingly relies on predictions made by computational numerical models of hydrodynamic and sediment-dynamic processes and the resulting morphodynamic changes of the seabed. Yet such models are rarely tested against real data from coastal field measurements. Evaluation of numerical models makes special requirements of the data, such as detailed measurements at the boundaries and a dense spatial coverage of measurements within the modelled area. At the same time, improvements to numerical models are mainly made through improved understanding of the field processes, so it is important to measure and interpret these processes at all scales of interest.

The problems with respect to mining of sand at the shoreface mainly fall into two categories: morphology and ecology.
As regards morphology, the most urgent problems of a mining pit to solve are:

- the trapping of sand and mud by a pit and the associated longshore and cross-shore migration rates of the slopes;
- the recovery time scales (fill rate of a pit and growth rate of a mined sand bank) after mining;
- the impact of the pit on the coast (time scale and intensity).

As far as ecology is concerned, the problems can be formulated as:

- recovery time scale of organisms (bottom fauna consisting of micro, meio and macrobenthos) living in and on the bed in terms of number of individuals per unit area and diversity of species;
- recovery time scale of the primary production of biomass in the water column, which is strongly dependent on the concentration of suspended matter (turbidity) affecting the light penetration;
- impact of a mining pit on the functioning of foodweb/chain ("eaten and to be eaten"), which is an overall indicator of the quality of the ecosystem.

Michel (2004) discussed regional management strategies for offshore sand mining activities. The following issues were identified as key activities:

- compile inventory of planned sand needs in the region of interest;
- compile inventory of known sand resource areas (sediment composition, volumes, etc.);
- identify critical data gaps and recommend actions to address these gaps;
- develop guidelines for sand resource allocation (available volume against short and long-term needs);
- develop and keep updated a master schedule of proposed sand dredging plans;
- evaluate strategies for permit streamlining;
- develop procedures for assessing sand needs under emergency conditions;
- establish monitoring requirements;
- develop methods for dredging that maximize use of the site and minimize impacts;
- identify time windows that are best/worse times for dredging to protect sensitive species.

Various studies of the morphological consequences of sea sand mining have been performed, but most of the consequences cannot yet be fully overseen and further studies are required to line up the positive and negative effects of sea sand mining, so that a rational decision with respect to location and quantity of future sea sand mining can be made. This report presents an overview and inventory of the most relevant studies performed up to now, covering:

- regulations on sea sand mining,
- sediment transport and ecological processes in marine conditions,
- morphological behaviour of mining areas,
- data sets of mining areas,
- mathematical studies related to mining areas in the North Sea.

Most of the attention will be focused on the behaviour of mining pits, channels and trenches in the plain seabed, but the removal of offshore sand shoals and banks for mining purposes will also be assessed.
1.3 Hypotheses

Large-scale mining pits will have a significant impact on the near-field and far-field (up to the coast) flow and wave patterns; the flow velocities inside the pit will be reduced and the wave heights may also be reduced, depending on the depth of the pit.

As a consequence, the sand transport capacity inside the pit will decrease and sediments will settle in the pit area, resulting in deposition. Thus, the pit will act as a sink for sediments originating from the surrounding areas and depending on the local flow and wave patterns. Hence, erosion of the sea floor will take place in the (immediate) surrounding of the pit. This may lead to a direct loss of sediment from the nearshore zone (beaches, see Figure 1.2 Top). Indirect effects result from the modification of the waves moving and refracting over the excavation area (pit), which may lead to modification of the nearshore wave conditions (wave breaking) and hence longshore currents and sediment transport gradients and thus to shoreline variations (see Figure 1.2 Bottom). Considering the massive scale of future mining of sand and hence the large spatial scales that will be affected by the mining activities, the
mining areas need to be situated in the offshore shoreface zone to minimise the effects of nearshore coastal erosion. On the other hand the mining of sand will be progressively more expensive at greater distances from the shore. Research is required to find the optimum solution between the effect on the coast and the costs of mining.

1.4 Regulations

Concessions for the offshore mining of sea sand are bound to regulations. Points of attention in formulating these regulations are:
- ecology (bottom fauna, algae, bird habitat)
- dispersion of mud,
- morphology of shoreface and coastline,
- morphological interaction with existing and future engineering works (navigation channels, pipelines, land reclamation, etc.).

Hereafter, the regulations in Japan, Great Britain, and The Netherlands are briefly presented.

Japan

The country with the largest volume (70 to 80 $10^6$ tons/year) of sand and gravel mining in coastal waters is Japan (Tsurusaki et al., 1988). The mined aggregates are mainly used for the cement and concrete industry. Major seabed mining occurs off western Japan in the Seto Inland Sea and off the north coast of Kyushu and the south coast of Shikoku. The total number of mining vessels is between 500 and 600 and their size is relatively small, ranging from 200 G/T to 1000 G/T. The mining is executed by grab-type dredgers and by pump-type dredgers.

Mining operations are regulated by local government to preserve fishery resources and to protect the natural environment and vary with each prefecture. Permission for mining is only given when the operations satisfy the following requirements:
- natural; considering distance from shoreline, water depth, distance from national parks;
- technical; considering mining methods, size of vessels, timing of mining over day, week and year, total volumes (mining plans);
- legal; considering purpose of sand, negotiation with committee of fisheries, vessel registration, etc.

The requirements vary from prefecture to prefecture. Mining has been executed in shallow and in deep water with depths ranging from 5 to 40 m (Kojima et al., 1986 and Uda et al., 1995). In Fukuoka the minimum mining depth was 30 m (date 1990), but may be increased to 35 and 40 m at later dates. The mining pit area may not be larger than about 1500x1500 m² and not closer than 3 km (6 km in future) from the shoreline. The environmental impact and the depletion of the resources in the nearshore areas caused operators to move the mining to a larger distance from the shore and to deeper water.

Great Britain

The licensing system for offshore dredging in Great Britain started in 1963. Dredging companies now submit an application for a licence to the Department of Transport, Local Government and Regions (DTLR) to dredge a defined area at a given rate, having first agreed their proposals with the landowner (normally the Crown Estate), to avoid overlapping extraction areas etc. DLTTR advises the applicants on their requirements for
consultations and assessment of impacts of proposed dredging operations. This includes both a coastal impact study and a wider-ranging environmental impact assessment and the Applicant has free choice on the selection of an appropriate consultant to carry out such studies. Once these reports have been written, with consultations normally undertaken before (to establish scope) and during the reporting, DTLR undertakes further consultations on the basis of the applicant's reports. They then decide whether refuse permission for extraction, or grant it (usually subject to conditions) or to require further studies. Permissions are now given for 15 years, but can be withdrawn without notice if adverse effects occur. Once permission has been given by appropriate "competent authority", the applicants enter a civil law contract with the seabed owners, including an agreed rate for each tonne of sediment extracted. Because the present system is non-statutory, there is no right of appeal against a decision. Guidelines are published by TSO (2002).

Within the coastal impact study, the following phenomena are studied and evaluated:

- the beach should not be affected from drawdown into the dredged area (no permanent trapping of beach sediments into dredged pit);
- the supply of sediments to the coastline should not be affected;
- bars and banks providing protection to the coast from wave attack should not be damaged/affected;
- significant changes in wave refraction patterns altering nearshore waves and hence the alongshore transport of sediment should not occur;
- significant changes to tidal currents close to the coastline should not occur.

These studies require an estimation of modified flow and wave patterns on changes to sediment transport over seabed and hence to (coastal) morphology based on regional and local modelling and existing field data (e.g. bedforms, sediment distribution/mobility calculations).

An environmental assessment report is also required, often concentrating on the production of turbid plumes and deposition of sand or finer-grained sediment on the seabed outside the extraction area. It includes a description of the existing environment and of the impacts of proposed dredging compared with alternatives. Consideration of "cumulative impacts" of multiple dredging (or other) activities in same general region is also required.

As regards regulations and criteria, no fixed limits are used, but mining is rare in water depths less than 15 m (lowest tide). Each application is subject to specific studies of effects on coast and of other environmental impacts, considering:

- **Beach drawdown:** The approximate depth limit for offshore sediment movement off the south coast of England is considered to be about 10 metres below CD. This is the minimum depth to ensure that beach drawdown will not take place; an additional limit is a minimum distance of 600 m from the shore. Almost all extraction areas are in much deeper water.

- **Seabed sediment transport:** Shingle (gravel) is unlikely to be mobile below 18 m (CD) based on field tracer studies, but more detailed and specific studies are required for sand transport (even if extraction is for shingle).

- **Sand bar and banks:** Minimum depth based on special studies depending on location; dredging of banks adjacent to coastline is not allowed; except in conditions with high accretion rates.

- **Effects on wave refraction:** An old rule-of-thumb was a minimum water depth of 14 m based on wave refraction studies along the south coast of England. Now it is sometimes simpler to carry out wave refraction modelling for areas even in much deeper water, than to risk criticism that the effect has been ignored.
- **Effects on currents**: Not a real issue except very close to the extraction area (near-field), but may affect sediment transport locally as well (and hence affect the biology of adjacent areas).

**Netherlands**

Regulations on mining activities in the Dutch Sector of the North Sea are formulated in: “Regionaal Ontgrondingsplan Noordzee” 2 (RON 2). These regulations mainly concern mining depth and mining area in relation to the water depth at the mining location. The maximum mining depth for the present mining activities in shallow pits is 2 m. The regulations for deep sand mining pits (deeper than 2 m) are (p. 48 and 49 of RON 2):

- sand mining in deep pits, outside the NAP - 20 m depth contour is conditionally allowed if the presence of sufficient amounts of coarse sand is made plausible first;
- inventory of the environmental effects of the proposed mining activities (EIA);
- a monitoring program aimed at the effects of the mining activities may be required.

No specific regulations with regard to the maximum mining depth are given in the RON 2 document. The maximum depth is restricted in the sense that irreversible negative effects on the environment are not allowed. Some criteria given for the maximum depth are:

- the new surface sediments should not deviate too much from the original ones;
- at the bottom of the pit no reduction of the water exchange is allowed, in order to prevent reduction of the oxygen content;
- ecological recovery of the mining area within a reasonable amount of time (10 years).

Deep mining pits have not yet been used extensively in the coastal waters of The Netherlands. A temporary pit with a depth of about 20 m (below surrounding bed surface) has been excavated close to the shore in a water depth of about 10 m, but this pit was refilled shortly (a few months) after construction to prevent damage to the coastal system.
2 Review of sand mining data

2.1 Introduction

In this Chapter 2 an update of the literature review of Van Rijn and Walstra (2002) on various topics related to offshore sand mining is given. The topics covered, are:

- sediment transport processes on the shoreface;
- ecological processes on the shoreface;
- morphological behaviour of mining pits.

2.2 Sediment transport processes at shoreface

2.2.1 Definitions and general characteristics

The shoreface is defined, as follows:

- upper shoreface landward of the -8 m depth contour; wave-driven processes (shoaling and wave breaking) are dominant; this zone is also known as the surf zone;
- middle shoreface between -8 and -20 m depth contours; wind-, density- and tide-driven flows are controlled by bottom friction; the currents generally are parallel to the coast; during storms a secondary circulation (in transects normal to coast) superimposed on the main longshore current is often present, yielding a spiral type of fluid motion with landward flow in the surface layers and seaward flow in the near-bed layers;
- lower shoreface seaward of -20 m contour; the currents are controlled by pressure gradients and wind forces in combination with Coriolis forces (Ekman spiral, geostrophic flows).

The fluid in the shoreface zone may be homogeneous (well-mixed) or stratified with a surface layer consisting of relatively low fluid density (fresh warmer water in summer) and a bottom layer of relatively high density (saline colder water in summer). Strong horizontal density-related pressure gradients may occur in regions close to a river mouth. In micro-tidal environments (such as Atlantic Shelf, Gulf of Mexico Shelf) the tidal currents generally are less important (<0.5 m/s) than wind-driven currents. In meso-tidal environments like the North Sea both tide- and wind-induced currents are important.

Sand can be transported by wind-, wave-, tide- and density-driven currents (current-related transport; Van Rijn 1984a,b,c; Van Rijn and Kroon, 1992; Van Rijn, 1993; Van Rijn et al., 2001), or by the oscillatory water motion itself (wave-related transport). The waves generally act as a sediment stirring agent, whereas the sediments are transported by the mean current. Wave-related transport may be caused by the deformation of short waves (wave asymmetry) under the influence of decreasing water depth. Low-frequency waves interacting with short waves may also contribute to the sediment transport process (wave-related transport), especially in shallow water in the surf zone.
In friction-dominated deeper water on the lower shoreface zone the transport process generally is concentrated in a layer close to the seabed and mainly takes place as bed-load transport in close interaction with small bed forms (ripples). Bed-load transport is dominant in areas where the mean currents are relatively weak compared to the wave motion (small ratio of depth-averaged velocity and peak orbital velocity). Net sediment transport by the oscillatory motion is relatively small in depths larger than 15 m (Van Rijn, 1995, 1997; Van Rijn et al., 1995), because the wave motion tends to be more symmetrical in deeper water.

Suspension of sediments on the lower shoreface can be generated by ripple-related vortices. Suspended load transport will become increasingly important with increasing strength of the tide- and wind-driven mean currents due to the turbulence-related mixing capacity of the mean current (shearing in boundary layer). By this mechanism the sediments will be mixed up from the bed-load layer to the upper layers of the flow. On the lower shoreface the suspended sand transport may be dominant during storm conditions, depending on conditions (wave height in relation to water depth; additional wind-driven flow). Soulsby (1987) concluded that the most important contributions to the long-term sediment transport are made by fairly large (in relation to depth) but not too infrequent waves, combined with tidal currents between mean neap and maximum spring tide. Weak currents and low waves in relation to water depth give a small contribution, because their potential for sediment transport is low, although their frequency is high. Extreme conditions also are relatively unimportant, since their frequency is too low, although their transport potential is high.

Characteristic morphological features occurring on the shoreface are breaker bars in the nearshore zone and large sand banks, ridges or shoals on the middle and lower shorefaces, which are at some places connected to the shore. Small-scale bed forms may be superimposed on these large scale features ranging from wave-induced micro ripples to mega-ripples.

Herein, the following terminology is used:

- **shore parallel breaker bars**: linear sand bars in the surf zone with heights of the order of 3 m and spacings of the order of 100 m, which are generated by breaking wave processes;
- **sand banks**: large linear sand bodies with spacings up to 30 km, crest lengths up to 70 km, heights up to 40 m and which are believed to be maintained by tidal currents larger than about 0.7 m/s (including Coriolis effect); they occur at the edges of broad shallow seas; their crest lines may be oriented slightly anti-clockwise (20° to 40° on northern hemisphere) with respect to the dominant tidal current direction; often they are covered by transverse sand ridges, transverse sand waves and mega-ripples; linear sand banks (banner banks) may also occur at erodable or inerodable headlands;
- **oblique sand ridges**: linear ridges oblique (20° to 40°) to the main (tide-or wind-driven) current direction and often connected to the shoreface; spacings of about 5 km; crest lengths up to 20 km; heights up to 10 m; migration rates up to 3 m/year; occurring in seas with (North Sea) and without tidal currents (North American shoreface);
- **sand shoals**: these features are isolated irregular underwater bodies of sand without the typical sequential characteristics of banks and ridges (spacing and orientation); inlet-attached shoals occur near the inlets/mouths of major estuaries; ebb-tidal deltas in the entrance of inlets/estuaries can be seen as large shoals; headland-attached shoals occur on the shoreface of prominent headlands (southeast Australia) where they form shore-parallel sand deposits of 20 to 30 m thick, 2 to 5 km wide and extend alongshore for distances of 5 to 30 km in depths of 25 to 80 m; shoals in shallow areas serve to naturally limit the wave energy approaching the shore (bottom friction, reflection and wave breaking);
- **transverse sand waves**: sand bodies transverse to the main current direction; spacings up to 1 km, crest lengths up to 5 km; heights up to 5 m; migration rates up to 10 m/year; their shapes are often asymmetric; covered by mega-ripples.

Generally the sand bodies consist of well-sorted, medium-grained sand with fragmented shell debris. Core analyses reveal cross-bedding features and a coarsening-upward sequence due to winnowing of fines from the ridge/bank crest and deposition of fines in the troughs.

### 2.2.2 Limits of measurable bed level variations at shoreface

Preferably the mining of sand should be done seaward of the limit of significant sand transport processes and associated bed level changes. Hallermeier (1981) introduced the concept of offshore closure depth defining a limit beyond which no measurable bed level variations due to wave and current motion are assumed to occur (approximately 20 to 25 m based on outer limit of Hallermeier).

This limit may also be identified on the basis of field observations related to:

- **transition in sediment size**: along many micro-tidal coasts the transition from relatively coarse sand near the coast to relatively fine sand offshore occurs in depths of 10 to 20 m; along meso/macro-tidal coasts there may be another transition from finer to coarser sand in depths of about 20 m due to the presence of longshore tidal currents winnowing the fines from the sea bed; a review of data from many east coast Australian beaches indicates the presence of medium to coarse sands from 0 to 12 m depth, fine sand from 12 to 22 m depth, coarse-grained sediments from 22 to 45 m depth and fine sands and muds deeper than 45 m (Hilton and Hesp, 1996); a feature of many east coast beaches in New Zealand is a zone with fine sands in depths between 0 and 25 m and medium coarse sands in depths between 25 and 45 m (Hilton and Hesp, 1996);
- **transition in slope**: the nearshore bed consisting of coarser sand has a markedly steeper slope;
- **transition in bed forms**: periodic bed forms are generally absent in depths larger than about 25 to 30 m;
- **transition in observed bed level variation**: maximum observed bed level variations seaward of the 20 m depth line generally are less than 0.1 to 0.2 m; Kojima et al. (1986) placed graduated rods in the seabed (0.6 mm sand) and found bed level variations of 0.1 m in depths of 25 m over 3 months, 0.05 m in depths of 30 m and 0.03 m in depths of 40 m over 3 months with maximum wave height of about 5 m (period of 10 s); dredging pits in depths up to 30 m were gradually filled with sand.

Cross-shore transport processes and sediment sorting along the bed profile are often caused by rip currents. Rips are characterized by rip heads where the jet-like rip current at the seaward end breaks up into irregular to highly organised vortices and rip-transported sediment is dispersed. Rip currents are known to transport significant quantities of sediment seawards specifically in storm conditions when seaward flows may be significant up to depths of at least 12 to 18 m (Hilton and Hesp, 1996).

Indications of sediment particle movement along the shoreface in relation to water depth can be obtained from tracer studies. Crickmore et al. (1972) and Price et al. (1978) report of tracer studies using radioactive pebbles (19 to 38 mm) at depths of 9, 12, 15 and 18 m in the English Channel some 15 km’s east of Brighton (south coast of England). This operation was carried out in mid-September in 1969 and the pebble movement was tracked over a period of 20 months. Peak surface velocities were between 0.5 and 0.8 m/s during neap and spring tides. Wave observations from a light vessel were used to relate the rate of movement to the prevailing wave conditions (mild wave climate in English Channel due to limited
Various storm events with significant wave heights between 2 and 5 m occurred. The most striking feature of the mapped pebble distributions is the small degree of movement at all sites; even single tracer pebbles were very rarely encountered as far as 100 m from the centre of the original seeded area. The results clearly demonstrate an increase in pebble mobility with decreasing depth and also show the existence of a small net landward movement of pebbles of 10 m/yr at the 12 m depth contour and 25 m/y at the 9 m depth contour. No particle movement was observed at the depth of 18 m. The vertical mixing depth was found to be within 50 and 125 mm. Tests in a pulsating water tunnel showed that peak orbital velocities of 1.4 to 1.6 m/s are required to move the pebbles considered. These velocities do only occur at depth of 9 to 12 m during severe storm events.

Migniot and Viguier (1980) present information of tracer studies using radioactive sand tracers in the Gulf of Casgogne north of Biaritz (France) facing the Atlantic Ocean (severe wave climate). The experiments were carried out at depths between 6 and 22 m in the period between 15 September and 15 December 1975 (autumn and winter) in conditions with incident waves almost normal to the shore. The results show significant particle movement (fine to medium coarse sand of 0.1 to 0.8 mm) with transport rates of about 0.5 m$^3$/m over 3 months at a depth of 22 m up to transport rates of about 80 m$^3$/m over 3 months at depths of 6 to 8 m.

### 2.2.3 Sand transport rates at shoreface

Net transport rates (tide-averaged values) have been estimated for depths between 8 and 20 m in the North Sea (Van Rijn, 1995; 1997). The median size of the bed material on the lower shoreface (20 m depth) varies between 0.15 mm (near Den Helder) and 0.25 mm (near Hoek van Holland). On the upper shoreface (depth of 8 to 10 m) these values vary between 0.15 mm (Noordwijk) and 0.2 mm (Egmond). The tidal range is between 1 and 2 m. The peak tidal current velocities are about 0.7 m/s during flood to the north and 0.6 m/s during ebb to the south.

The wave climate (along the Holland coast) is rather constant; the dominant wave direction is south-west. Some values of the probability of occurrence (duration in % of time) for waves in deep water are:

- south-west($180^\circ$-$270^\circ$): 15% waves of 1-2 m, 4-5% between 2-3 m, 1-2% between 3-5 m;
- north-west($270^\circ$-$360^\circ$): 10% between 1-2 m, 4-5% between 2-3 m, 1-2% between 3-5 m.

The sediment transport rates (bed load plus suspended load transport) were computed by the UNIBEST-TC model (Bosboom et al., 1997) using schematized wave and current conditions. Tidal averaging was applied to obtain the tide-averaged transport rate for each wave direction and wave height class. The tide-averaged transport rate was multiplied by the percentage of occurrence of each specific wave condition, resulting in the weighted transport rate. The mean annual sediment transport rate was obtained by adding all individual weighted values. The results and error ranges (based on sensitivity computations varying input parameters) are given in Table 2.1.
Cross-shore profile at depth of 20 m | Net annual sand transport rates (m\(^3\)/m/year, incl. pores) | Longshore at depth of 20 m
--- | --- | ---
14, Callantsoog | 5 ± 10 | 75 ± 30
40, Egmond | 15 ± 10 | 60 ± 25
76, Noordwijk | 10 ± 10 | 35 ± 15
103, Scheveningen | 0 ± 10 | 25 ± 15

+ north/onshore; - south/offshore

Table 2.1 Best estimates of net annual sand transport rates at a depth of 20 m in profiles 14, 40, 76 and 103 along coast of Holland (all values incl. pores of 40%).

These computed transport rates show reasonable agreement with transport rates derived from available field data of the middle and lower shorefaces:
- dump site Hoek van Holland 1982,
- dump site Wijk aan Zee 1982,
- Simon Stevin pit 1981.

**Dump site Hoek van Holland 1982**

During the period 1982 to 1991 an artificial sand ridge was made by dumping sand over a length of about 3600 m normal to the shore (location Hoek van Holland) in an area with depths between 15 m and 23 m on the northern side of the navigation channel. In all, 3.5 million m\(^3\) of sand was dumped over the period 1982 to 1991 (Woudenberg, 1996; Walstra and Van Rijn, 1998; Walstra et al., 1999). The ridge dimensions are: length of about 3600 m; toe width between 250 m and 370 m; height between 1.3 m and 4 m; slopes between 1:50 and 1:100 on the south flank and slopes between 1:20 and 1:50 on the north flank; d\(_{50}\) between 0.15 mm and 0.45 mm. The landward end of the ridge is about 6300 m from the shoreline. Based on the analysis of detailed volume calculations (per unit length of the ridge), the increase of the net annual longshore sand transport from the ridge toe to the ridge crest was found to be 20±5 m\(^3\)/m/year (including pores).

**Dump site Wijk aan Zee 1982**

Another dump site of sand off the coast of Holland (location Wijk aan Zee, north of approach channel to port of Amsterdam) is located in relatively shallow water with depths between 13 and 15 m. An artificial shoal with a height of about 1.2 m was made in 1982 by dumping sand (about 1 million m\(^3\)). The shoal was sounded regularly over a period of 8 years without any additional dumpings (Rijkswaterstaat, 1992). Based on the analysis of the sounding data, the crest was found to migrate at a rate between 25 and 40 m/year in the direction of the dominant flood tidal current (in north-eastern direction) over a period of 8 years. The peak flood current is about 0.65 m/s; the peak ebb current is about 0.55 m/s, both parallel to the shore. The increase of the net annual longshore sand transport rate due to the presence of the shoal can be roughly estimated to vary between 40 and 50 m\(^3\)/m/year. The actual transport rates will be a factor of 2 to 3 larger (say 80 to 150 m\(^3\)/m/year), because the net annual longshore transport entering the sections has to be added.
**Mining pit Simon Stevin 1981**

The pit was dredged on 26/27 may 1981 (*Rijkswaterstaat, 1986*) northwards of a dump site (Loswal Noord near Hoek van Holland) for dredged material from the harbour of Rotterdam. The seabed was about 15.5 m below MSL; the pit had a depth of about 6.5 m with respect to the surrounding bed and side slopes between 1 to 5 and 1 to 15. The area of the pit was about 100x100 m$^2$. The local peak tidal velocities parallel to the coast are about 0.5 to 0.6 m/s. The local bed material was fine sand (median size between 0.1 and 0.2 mm). Analysis of regular soundings showed a natural deposition rate of about 45,000 m$^3$ (mixture of sand and mud) over the first 520 days immediately after dredging, which is equivalent to about 320 m$^3$/m per year. The deposition rates may be relatively high due to the fact that during the flood current the pit is situated some kilometres downstream of the Loswal Noord dump site.

Analysis of samples of the deposited material showed the presence of 40% to 60% of sand, yielding a deposition rate of sand of about 130 to 200 m$^3$/m/yr. Assuming that the pit trapped all incoming sand transport from both the flood and ebb directions, the gross sand transport rates will be about 130 to 200 m$^3$/m/yr. These values are considerably (factor 3) larger than the net values of Table 2.1, yielding net annual longshore transport rates between 35 and 60 m$^3$/m/year for profiles 76 and 40 km at a depth of 20 m.

**Sand transport measurements at Noordwijk, North Sea within EU-SANDPIT Project**

Sand transport measurements have been performed in Spring and Autumn of 2003 at the Noordwijk location (Dutch sector of North sea) by University of Utrecht using their HSM-tripod within the SANDPIT-project. Some results of the Spring campaign (*Grasmeijer and Tonnon, 2003*) are presented herein. The water depths were in the range of 13 to 15 m. The peak tidal velocities were in the range of 0.1 to 0.5 m/s. Significant wave heights were in the range of 2.2 to 2.7 m. The data reported here concerns ASTM-data; the ASTM measures velocities and sand concentrations of 5 levels simultaneously. The data was collected during a two-weeks measurement campaign in spring 2003. Measurements were done in burst-sampling mode of 34 minutes. Accurate, reliable ASTM-data was available only for burst numbers 1800-1833 and 2200-2225. Velocities for these burst numbers have been compared with EMF measurements and show very good resemblance. The measured data were clustered into 33 bins of different wave heights and longshore current velocities. The bin size for significant wave height was 0.25 m and for longshore velocity 0.2 m/s. As maximum significant wave height was 2.7 m and maximum longshore velocity was 0.5 m/s, this resulted in 11 wave classes and 3 velocity classes, together combining for 33 clusters. Clustering significantly reduces the amount of data and clearly illustrates the general trends in the data.

Figure 2.1 shows the (extrapolated and non-extrapolated) suspended transport rates as function of current velocity and wave height. These types of data of both the Spring and Autumn campaigns will be used for verification of sand transport models. The maximum transport rate is of the order of 0.1 kg/s/m or 5 m$^3$/m/day (incl. pores).
2.2.4 Mud transport at shoreface

The natural flux of fine sediments (size<0.05 mm) in the Dutch sector of the North Sea is concentrated in a relatively narrow coastal zone of about 20 km due to geostrophical effects. Field observations show that there is a pronounced cross-shore gradient in suspended sediment concentration, with the larger values occurring near the coast (MARE 2001). The total (gross) flux of fine sediments is about 20 $10^6$ ton/year or 50,000 ton/day (Skalden, 1998). Assuming a uniform cross-shore distribution of the longshore mud transport, this is equivalent to about 2.5 ton/day/m or 0.03 kg/m/s. Taking a mean discharge of about 3 m$^3$/m/s (depth of 10 m and current of 0.3 m/s), the mean sediment concentration is about 0.01 kg/m$^3$ or 10 mg/l.

The sand mining activities may affect the volume, transport and fate of fine grained sediments in the Dutch coastal zone in two ways:
- large amounts of fines can be mobilized and released in the environment during the sand mining activities,
- fine grained sediments may accumulate temporarily or permanently in mining pits, particularly in deep pits.

The sediments of the North Sea bed contain a few percentage of fines (between 1% and 3%) in the Dutch coastal zone. Suppose that the sand mining is carried out with a modern, large suction hopper dredger with a capacity of 20,000 m$^3$/hr in a sandpit with a diameter of 300 m. This would imply a sand production of 60,000 to 120,000 m$^3$/day, i.e. 0.1 to 0.2 $10^6$ ton/day, yielding 1000 to 6000 ton of fines per day. This amount of fines is mobilized by:
• breaching of the seabed during the suction activities,

• overflow of fines during the filling of the hopper.

The amount of fines released in the environment can be controlled by strict working procedures. However, if no regulations are set, it is estimated that 10% to 50% of the fines present in the seabed sediments can be mobilized. Hence, it is estimated that for a sand mining production of 60,000 to 120,000 m$^3$/day, an amount between 100 and 3000 ton per day of fines is released in the environment.

This amount should be compared to the natural flux of fine sediments in the Dutch coastal zone, which is currently estimated at about 20 $10^6$ ton/yr, or 50,000 ton/day. Considering the width of the sandpit of approximately 300 m and assuming a uniform cross-shore distribution, the natural fine sediment flux per 300 m width is estimated at about 900 ton/day. Hence it is concluded that the amount of fines mobilized (100 to 3000 ton) by the sand mining may be of the same order of magnitude as the local natural sediment flux, depending on the location of the mining pit from the shoreline and the dredging technique applied.

The overflow material from the dredging vessel may be: (i) released as clouds of sediment, or (ii) either be continuously mixed with the environmental water, or (iii) released as a density current over the seabed. The behaviour of the sediment in the vicinity of the mining activities, released through one of these three modes is considerably different. Clouds of sediment can behave as individual entities; within these clouds, segregation of coarse and fine sediment material may take place. This effect is also known as convective settling (Tacker and Lavelle, 1997).

Whether the overflow behaves as a plume that is rapidly mixed with the environment, or as a density current over the sea floor, it is governed by a bulk Richardson number and a velocity parameter (Winterwerp, 2002). In the latter case, the impact in the direct vicinity of the dredging vessel is the largest. The fine sediments mobilized during breaching are for the major part directly mixed over the water column, as the breaching process generates additional turbulence.

At present, it is not known whether all or part of the sediments, released during the sand mining process, will be reworked into the seabed, either temporarily, or permanently. Part of the released sediments will accumulate in the sandpit (order of 0.1 m per year for deep pits in the North Sea). Whether this accumulation is either temporarily or permanently, depends on whether local waves can stir up these sediments or not. This on its turn is dependent on the relative depth of the mining pit with respect to the undisturbed seabed, which is also a function of the location of the sand mining from the shoreline.

The sandpit can also collect sediments from the natural flux, through direct settling or supersaturation. In the latter case the transport capacity of the flow for fine sediment in the mining pit is exceeded, as a result of which a high-concentrated near-bed suspension is formed, resulting in a very efficient trapping of fine sediments in the pit (Winterwerp et al., 2002). These sediments may be re-eroded again by local wave activity. Boer et al. (2002) studied the deposition of mud in an offshore sandpit using a mathematical model (SUTRENCH). He found that the mud deposition in the summer period can vary between 0 and 0.2 m, depending on model settings. The erosion potential of soft mud in the middle of the pit due to wave activity in the winter period was as large as 1 m, depending on model settings.
2.3 Ecological processes

2.3.1 Overview of processes

Ecological processes are related to:

- primary production of biomass by algae in the water phase under the influence of nutrients and light; the biomass in the water column is a food source for zooplankton, fishes and bottom fauna;
- bottom fauna consisting of phytophthos (plants) and zoobenthos (living organisms); the zoobenthos can be subdivided into micro, meio and macrobenthos; macrobenthos consists of infauna (organisms living in the bottom) and epifauna (organisms living on the bottom); diversity of species strongly depends on water depth, temperature and sediment composition; recent studies show variations of individuals between 100 and 10,000 per m$^2$ (abundance) in the Dutch sector of the North Sea;
- watercolumn fauna; phytoplankton (plants) and zooplankton (living organisms), fishes and seamammals
- subaerial fauna; insects and birds.

An important aspect of the ecological process is the foodweb. The functioning of the ecosystem strongly depends on the functioning of the foodweb

Sand mining/dredging and dumping have various direct and indirect short term and long term effects on marine and coastal benthic communities of plants and animals. The ecological impacts depend on complex and dynamic interactions of abiotic and biotic factors including:

- composition and dynamics of the sediment,
- methods of dredging and dumping and the sediment spill,
- the occurrence and sensitivity of seagrass and macrozoobenthic communities and the rate of recovery of the communities affected.

An important problem of sand mining may be the release of fine sediments (silt and mud) in the environmental system during the dredging process. For example, roughly about 1% to 3% of the substratum of the North Sea consists of fine to very fine sediments. One of the consequences of massive sand mining will be the production of an enormous amount of fine sediments, which can be carried over large distances to the coasts and shores of the countries surrounding the North Sea, threatening the environmental system at those places.

In general, the diversity of zoobenthic communities in dynamic sandy bottoms is lower compared to more stable environments. The sensitivity and the rate of recovery are important factors in order to maintain the structure and function of benthic communities and sustainable exploitation of the sand resources. It is necessary to make an inventory of the ecological aspects resulting in a ‘state of the art’ description of the ecological aspects.

The attention needs to be focussed on the influence of mining/dredging/dumping on local turbidity patterns, local bathymetry and substratum, and local flora and fauna. This will require:

- description of the state of the natural environment (without proposed activities), its function in the natural system and the expected future development of the natural environment, with special emphasis on benthic communities, spawning and nursery grounds, fish, birds and marine mammals,
- description of the expected environmental effects of the proposed activities,
• identification of the least intrusive sand mining/dredging/dumping methods with respect to environmental effects.

Sand mining causes direct and indirect effects on the ecology of the seabed and water column. Main causes are the mining of the seabed, the production of silt in the water column, the increased deposition of silt on sediment and the disturbance of morphological and hydrodynamic processes. These causes have an impact on the ecology on different temporal and spatial scales. For instance, mining of the seabed causes direct mortality of bottom species. In contrast, enhanced silt concentration in the waterphase can cause long term (months) and large scale impacts on primary production by reduction of the light climate. The main ecological impacts are listed below.

**Bottom**

• loss of bottom-habitats (micro, meio and macrobenthos) at the mining location; direct mortality of bottom dwelling species;
• burial/smothing of bottom-habitats due to increased siltation rates;
• morphological and hydrodynamic changes with impacts on the occurrence and quality of habitats of bottom species;

**Waterphase**

• reduction of primary production by increased turbidity due to production of silt during sand mining and transportation; left-over nutrients can cause increased production in areas further away from the site;
• alteration of chemical and physical characteristics in sand mining pits such as reduced current speeds, stratification and changed oxygen and nutrient availability; this could have an effect on the primary production;

**Foodweb**

• various direct and indirect impacts on mobile species such as fish, birds and mammals due to loss of feeding and spawning areas, increased turbidity, loss of food production, disturbance by noise and transport activities;

**Other**

• fishery activities can be influenced by direct loss of fishing grounds and reduction of fish production.

During sand mining, the species living on or in the seabed will be killed. This impact may be temporary, because after mining, the ecology of the seabed will be restored (if governing factors do not change permanently). Some bottom species will recuperate within some years due to their short life cycles and their large larval production. Opposite, some species can get very old. It will therefore take a very long time to re-establish these populations, once lost. The amount of impact therefore is dependent on the typical habitats that are lost. If it takes place in already disturbed areas (for instance intensively trawled areas), the impact to bottom species could be relatively small. However, the impact to fishing activities is then expected to be larger.
The sensitivity of species to burial or smothering is dependent on the species and its ability to move or grow through the sediment. Species that are attached to a substrate, such as oysters, mussels and barnacles will be more susceptible to smothering or burial. Other mobile species will be able to move upward to compensate for burial. Macro-algae or macrophytes will try to grow back to the surface. The maximum layer thickness of added sediment that can be coped with is called the ‘fatal depth’. This depth is dependent on both the species and sediment characteristics. This depth seems correlated to the (dis)similarity of the characteristics of the deposited sediment in relation to the original sediment. It was found that species in a sandy sediment are more sensitive to burial with silty material than species in a silty sediment.

By spatial spreading of free floating larvae or eggs, a swift recolonization of the disturbed area is possible. This so called ‘pelagic’ state of many bottom species can cover weeks to months, enabling the spreading of a species over a large area. Many species reproduce in two periods each year, in spring and in the autumn.

After settling of larvae, some species achieve high densities, high growth rates and high biomass in one year. However, most bottom species live three years to ten years and are slow growing. Disturbance of populations of these species will therefore take many years to recover.

Another impact that can be found is the negative effect of increased suspended matter concentrations on the functioning of the gills of the fish. The sensitivity to this effect is species dependent. It is expected that pelagic species are more sensitive than bottom dwelling species such as flat fish. No observations are known of fish mortality near dredging works. Fish, of course, will try to evade bad environmental conditions. For fish, birds and mammals it is assumed that turbidity, noise and transport activities in the area can disturb natural behaviour. A foodweb impact can be that schools of prey-fish will evade the disturbed area and therefore reduce feeding opportunities for predator-species.

**Oxygen cycle**

The quality of the ecological processes in the marine environment strongly depends on the biological and chemical properties of the water phase. One of the most important chemical parameters in the water column in deep mining pits is the dissolved oxygen level.

The dissolved oxygen cycle consists of the following basic terms:

<table>
<thead>
<tr>
<th>Positive terms</th>
<th>Negative terms</th>
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</thead>
<tbody>
<tr>
<td>• primary production (photosynthesis),</td>
<td>• respiration by organisms (decay of organic material),</td>
</tr>
<tr>
<td>• re-aeration over the atmosphere-water interface (in case of undersaturation),</td>
<td>• re-aeration over the atmosphere-water interface (in case of oversaturation),</td>
</tr>
<tr>
<td></td>
<td>• oxidation of reduced substances such as ammonium (nitrification), sulphides and methane.</td>
</tr>
</tbody>
</table>

In equilibrium with the atmosphere the saturated oxygen concentration ranges from 6 to 14 mg/l. The lower value can be found in warm, marine waters; the higher value in cold, fresh water. Oxygen is produced through photosynthesis by algae and plants resulting in an oversaturation as compared to the equilibrium or ‘saturation’ concentration. Micro-
organisms use oxygen for the mineralization of organic matter. Reduced substances such as sulphide and ammonium, produced by this mineralization also consume oxygen. This results in undersaturation as compared to the saturation concentration. Reaeration always strives for the saturation concentration. If the water is oversaturated with oxygen, it will escape to the atmosphere; in case of undersaturation, oxygen will be imported from the atmosphere.

As long as the water column is unstratified or well-mixed, oxygen depletion will be very unlikely. After all, oxygen that is consumed can be replenished easily by re-aeration from the atmosphere and oxygen produced by primary producers in the upper water layers. In general, oxygen depletion of the water column can only occur under stratified conditions. Possibly the best-known example is the Black Sea, where a permanent pycnocline exists at a depth of approximately 200 m. The hypolimnion (lowest cold water layer) is permanently anoxic (dissolved oxygen concentration is 0 mg/l). In other water bodies stratification is only seasonal. For example, in subtropical regions during the monsoon season the high riverine discharge of fresh water results in a low saline surface layer on top of a high saline bottom layer (e.g. the Pearl River in China). In fresh water lakes, stratification is only caused by temperature effects. The surface layer is heated during summer, while the bottom layer remains cool. The water column is destratified in winter time, when the surface water cools again. Boers (2004) concluded that oxygen-depletion is unlikely to occur off the Holland coast due to the fact that haline stratification only occurs in a relative small region due to the low Rhine discharge. Moreover, stratification is only present during a part of the tidal cycle, during the remaining period there is a free vertical exchange of oxygen by turbulence through the entire water column. The change of oxygen-depletion is further reduced by an onshore drift of about 1.5 cm/s which transports oxygen from the deeper parts of the North Sea to the coastal zone.

In all cases the mechanism for oxygen depletion is equal. Since stratification only occurs in deep water, shallow areas are not considered and photosynthesis by plants can be considered as minor except may be in very clear water. Photosynthesis by algae occurs near the water surface where light is still available. Algae convert light (energy), carbondioxide and other nutrients to organic matter, thereby releasing dissolved oxygen. Part of the organic matter produced by algae sinks towards the sediment bed. On its way down organic matter decays in a reversal of the photosynthesis reaction: oxygen is consumed. When the organic matter has settled through the pycnocline, it will still decay, but oxygen can not be replenished from the atmosphere as the stratification prevents the exchange over the pycnocline. The dissolved oxygen concentration in the hypolimnion will start to decrease. If the amount of organic matter reaching the hypolimnion and stratification is large enough, oxygen can be depleted completely. Oxygen consumption will continue after the organic matter has settled to the sediment bed, which is referred to as the Sediment Oxygen Demand (SOD).

Apart from primary production external sources form a second major source for organic matter. External sources are rivers and streams or sewage discharges.

Summarizing, the occurrence of oxygen depletion in deep pits depends on the presence of stratification. If stratification occurs, important questions are: what is the influx of organic matter into the pit?; what is the Sediment Oxygen Demand and is there an external source of organic matter nearby?

The dissolved oxygen concentration in a pit depends on the combination of the components described above. The processes can be reasonably well simulated by 3D-numerical models.
Pollutants

Pollutants are carried by the fine-grained sediment fractions (silt, clay, mud; particles smaller than 0.05 mm) carried by the fluid phase, but also, in dissolved form by the fluid phase (surface water, pore water). Surface waters receive a substantial part of their dissolved load from atmospheric fall-out (blown soil and dust, biological emissions from living vegetation, burning of organic matter, volcanic emissions) and anthropogenic emissions. Biological processes in the aquatic system will also affect the dissolved load (uptake by aquatic organisms). Depressions in the seabed such as pits, channels and trenches generally are sinks for suspended sediments and may therefore also act as sinks for pollutants. The deposited sediments may be stirred up by wave action during storm periods and transported by tide- and wind-induced drift currents.

2.3.2 Results of ecological field studies

Results of field studies into the ecological impact of nearshore extraction pits along the coast of Florida (1982) show that the faunal recovery in extraction pits (in depths of 6 to 10 m) occurred within a year after dredging. The benthic fauna within the extraction pits showed no lasting detrimental effects on numbers of species, faunal densities, or species diversity from dredging that occurred 5 years previously. The data from extraction pit stations sometimes showed significantly greater numbers of species and individuals than from control stations; species diversity values were also unusually higher at the extraction stations. The overall conclusion was that dredging caused an immediate decline in the bottom community followed by a rapid postdredging recovery that was virtually completed after a year. The dredging had no adverse long-term effect on bottom fauna. Favourable was that dredging occurred in relatively shallow water where sand transport was sufficiently large to cause rapid infill of the pits. No biologically detrimental quantities of silt and clay particles accumulated in the most nearshore pits. However, thick deposits (>3 m) of gelatinous, organic-rich sediments were found in some offshore pits resulting in low dissolved oxygen concentrations and low densities and diversities of benthic fauna within the extraction pit compared to surrounding, relatively undisturbed bottom.

Results of studies performed in 1992 along the Norfolk coast in England show that in the first 12 months following dredging at an offshore location, recolonisation in terms of animal types was rapid, but abundance and biomass remained significantly depressed. However, some 3 years following dredging, both diversity and biomass of animals were indistinguishable from those at an adjacent reference site, although the abundance had stabilised at a lower level than at the reference site.

The ecological impact of an offshore extraction pit at a depth of about 20 m north of Terschelling (North Sea) was studied in The Netherlands. A total volume of 2 million m$^3$ of fine sand (0.2 mm) was excavated over an area of a few km$^2$. The maximum layer thickness of the excavated area was 2 m. Based on the analysis of bed samples, it was concluded that the recovery time scale of the bed fauna (fauna density and structure, biomass) was about 2 to 6 years. Similar field research was carried out in the Frisian backbarrier basin (Waddenzee) after completion of mining activities. The recovery time scales were 2 to 4 yours after mining of sand in the main flood and ebb channels and up to 15 years after mining of sand on a tidal flat due to the trapping of mud.

More detailed results of various studies are presented hereafter:

- coastal waters of Florida, USA,
- coastal waters of United Kingdom,
- coastal waters of The Netherlands, North Sea.
Florida, USA
Saloman (1974) studied the benthic fauna in an extraction pit created in 1971 off Treasure Island (Pinellas County, west coast of Florida, USA). He found low densities and diversities of benthic fauna within the extraction pit compared to surrounding, relatively undisturbed bottom. He attributed these differences to thick deposits (>3 m) of gelatinous, organic-rich sediments that had accumulated in the extraction pit resulting in low dissolved oxygen concentrations.

Turberville and Marsh (1982) have evaluated the impact of an offshore extraction pit on the benthic fauna off Hillsboro beach, east coast of Florida, USA.
Dredging dates: August and September 1972; sand was used for local beach nourishment (Hillsboro beach).
Location of extraction pit: two elongated extraction pits with a total volume of about 275,000 m³ at a depth of about 9 to 10 m to MSL; in a sandy area between two reef lines off the east coast of Florida, USA; first reef is approx. 100 m from shore; second reef is approx. 700 m from shore.
Pit dimensions: approx. 200 m long; 75 m wide; inshore edge slopes from a depth of 10 m outside the pit to a depth of 13 to 15 m inside; bottom of pit is flat; pits are still well-defined 8 years after excavation; no deposits of fines (muds) were observed in the pit.
Tidal range and currents: tidal range is about 0.5 to 1 m; tidal currents are predominantly in southerly direction.
Sampling methods: samples were taken by divers from two stations outside (north of) the pit at the same depth contour (two control stations) and from two stations in the northernmost pit; 24 core samples containing the top 11 cm of the sediment bed were collected at each station on 16 June 1977; 21 September 1977; 16 December 1977; 26 March 1978.
Sediments: fine to coarse sands with mean grain sizes between 0.25 and 0.5 mm; both extraction stations had slightly larger mean grain sizes than the control stations; the fractions in the very coarse sand (1 to 2 mm) category were significantly greater at the extraction stations; the organic content was low (<2%).
Fauna: approx. 6000 individuals comprising 224 species were observed in the four sampling stations; dominant species were polychaete annelids (33% of the individuals and 86 species) and bivalve molluscs (46% of the individuals and 33 species); six species comprised about 50% of all individuals (four species of bivalve molluscs; one polychaete and one tanaidacean); extrapolated fauna densities ranged from about 900 individuals per m² to approx. 13,000 per m²; declines in diversity were evident at control stations 1 and 2 during the winter, when values dropped to less than half their values at all other sampling dates.
Conclusions:
- data combined from extraction stations showed significantly greater numbers of species and individuals than from control stations; species diversity values were also unusually higher at the extraction stations;
- benthic fauna within the extraction pits showed no lasting detrimental effects on numbers of species; faunal densities, or species diversity from dredging that occurred 5 years previously.

Salomon et al. (1982) have evaluated the impact of an offshore extraction pit on the benthic fauna off Panama City beach, northwestern Gulf coast of Florida, USA.
Dredging dates: July to August 1976; sand was used for local beach nourishment (Panama City Beach).
**Location of extraction pit:** numerous small-scale extraction pits with a total volume of about 300,000 m$^3$ at offshore locations of 300 to 900 m in depths of about 6 to 9 m were dredged to nourish sand at a 23 sites along a coastal stretch of 35 km.

**Tidal range and currents:** diurnal tidal range is about 0.6 m; tidal currents are maximum 1 m/s; waves generally are 0.5 to 1 m.

**Sampling methods:** samples were taken by divers from stations in about 9 m of water (surface samples of 10 cm for sediments and box core samples of 23 cm for the bed fauna); sampling before dredging was carried out (called baseline samples); after dredging concurrent sampling was carried out regularly inside the pit (called experimental samples) and outside the pits (called control samples) until November 1977; the samples were collected to record differences in species diversity and abundance for evaluation of short-term recovery (after 1 year).

**Sediments:** sugarlike beach sands with mean sizes between 0.1 and 0.2 mm; a series of parallel sand bars protects the beach offshore; beyond the bars the seabed slopes rather quickly to depth of 15 m at 1.5 km from shore; a comparison of sediments from inside and outside the pits showed the accumulation of loosely packed, darker and siltier sediments in the pits shortly after dredging; after a year, the surface samples from the pits were very similar to the control samples outside the pits.

**Fauna:** the data from baseline samples indicate that species richness followed an irregular seasonal pattern; the number of species per sample had an average of 49 and ranged between 15 (November) and 120 (July); the average of control samples was 74 and ranged between 53 (February) and 132 (July); intermediate values were recorded for the samples from within the pits (average of 60); in baseline samples, numbers of individuals per m$^2$ (abundance) averaged 3900 and ranged between 1500 (April) to 7000 (July); the average of control samples was 3100 with a range between 1400 (July) and 5500 (August); samples from the pits had an average of 2200 with a range between 325 (immediately after dredging) to 4100 after a period of 1 year following dredging.

**Conclusions:**
- the benthos off Panama City Beach exhibited an annual cycle in which species diversity and abundance were greater in warm summer months than in cold winter months;
- faunal recovery in extraction pits occurred within 1 year after dredging in at least half of the six pits sampled.

The overall conclusion was that dredging caused an immediate decline in the bottom community followed by a rapid postdredging recovery that was virtually completed after 1 year. This dredging had no adverse long-term effect on bottom fauna. Favourable was that dredging occurred in relatively shallow water where sand transport was sufficiently large to cause rapid infill of the pits. After one year the pits had filled to within 1 m of the surrounding bed. No biologically detrimental quantities of silt and clay particles accumulated in the pits.

**United Kingdom**

**Crown Estate (1999)** presented results of studies performed in 1992 along the Norfolk coast in England, which showed that in the first 12 months following dredging at an offshore location, recolonisation in terms of animal types was rapid, but abundance and biomass remained significantly depressed. However, some 3 years following dredging, both diversity and biomass of animals were indistinguishable from those at an adjacent reference site, although the abundance had stabilised at a lower level than at the reference site

**Newell et al. (2004)** presented survey results of benthic macrofauna in the vicinity of a coastal marine aggregate dredging site off the south coast of UK carried out in 1999. Part of the site was intensively dredged by vessels at anchor whilst other parts were less intensively dredged by trailer hopper dredging. Impacts included a suppression of species variety,
population density and biomass, as well as differences in species composition compared with the surrounding deposits. In contrast, trailer dredging had no impact on community composition of macrofauna within the dredged site. No suppression of benthic community structure was recorded beyond 100 m from the dredged site. Species variety, population density, biomass and body size of macrofauna were enhanced for as much as 2 kilometres in each direction along the axis of the tidal currents. The rate of restoration of biomass following dredging (within 175 days) was slower than that recorded for species diversity and population density (within 100 days).

Netherlands
Rijkswaterstaat (1997, 1999) has evaluated the impact of an offshore extraction pit on the benthic fauna off the barrier island of Terschelling (North Sea), The Netherlands.

Dredging dates: April to November, 1993; sand was used for local shoreface nourishment.

Location of extraction pit: approximately 8 km north of Terschelling at depths between 20 and 23 m (to MSL); maximum pit depth is about 1.5 m over an area of about 1.4 km²; some sedimentation took place in the northwestern corner of the site; echosoundings in October 1997 showed no major bed level changes.

Pit dimensions: triangular extraction pit with a maximum depth of about 1.5 m; 2.5 million m³ of sand was removed by hopper dredgers.

Tidal range and currents: tidal range is about 2 to 3 m; tidal currents in easterly direction are somewhat larger than those in westerly direction.

Sampling methods: a total of 30 samples was taken in March 1993 (pre-dredging survey) and October 1994 randomly distributed over the extraction area; a total of 34 samples was taken in October 1995; a total of 30 samples was taken in September/October 1997; all samples were taken by a Reineck boxcorer (0.078 m²); samples from a subarea near the corner of the extraction site, where hardly any dredging had taken place, were defined as samples from an undisturbed reference area.

Sediments: fine sands with mean grain sizes between 0.18 and 0.23 mm.

Fauna: the natural site is characterized by a macrofauna density between 2,000 and 30,000 individuals per m²; biomass between 10 and 20 gram per m²; the number species increased strongly from an average of 16 species per sample in March 1993 to 27 species in October 1994; and decreased again to 16 in October 1995; about 21 species per sample were present in 1997; samples from the reference area showed similar values; the diversity of the benthic community in October 1994 and 1995 showed a significant increase compared with pre-dredging values of March 1993; a general decline in total macrofauna abundance in terms of numerical densities (mainly polychaetes and crustaceans) was found to occur over time (2 years); the total numerical density of molluscs (mainly bivalves) showed little variation over time; the total biomass of the benthic fauna showed a decreasing trend from the March 1993 survey to the October 1995 survey; the biomass of the molluscs also decreased; species numbers and diversity were larger in 1997 compared with pre-dredging values of March 1993.

Conclusions:
- the short term effects (1 year) of sand extraction on the benthic fauna are most evident for long-living species (bivalve molluscs and echinoderms); the adults are affected causing a significant reduction in numbers and biomass of these species; a significant change of the benthic community structure was observed due to colonization effects (within group of polychaetes);
- on the longer term (2 years), the numbers of bivalve molluscs and echinoderms recovered; adult specimens remained rare however; after 2 years the structure of the benthic community was approximately the same as that before dredging; differences existed in the abundance of long-living species;
- the effects of sand extraction on the benthic community were hardly visible after a period of 4 years; the community structure in 1997 had not fully returned to its pre-dredging structure, but this may also be caused by natural fluctuations; recovery of the population structure of long-living species will take more than 4 years;
- extraction of a few million m$^3$ of sand seaward of the 20 m depth contour is not likely to interfere significantly with local benthos and their consumers;
- the sand from the extraction site was used for shoreface nourishment between 5 m and 7 m depth contours; analysis of samples at that site showed a short term reduction (1 year) of especially bivalve abundance due to the disappearance of the older specimen from the population; recovery of the seabed morphology and benthic fauna took place to large extent within a period of about two years; recovery of total biomass was not completed in this period as the growth of long-living species as molluscs and echinoderms requires more time.

Based on all available information, Rijkwaterstaat (1999) has presented a qualitative evaluation of the effects of various sand mining scenarios on the ecologic processes (see Table 2.2, Table 2.3 and Table 2.4). Three scenarios were distinguished:
- mining in navigation channels (extension of width); the existing channels can be widened by about 1 km;
- mining at bed surface (layer of maximum 2 m) in depth larger than 20 m;
- mining in deep pits.

<table>
<thead>
<tr>
<th>Abiotic effect</th>
<th>Biotic effect</th>
<th>Ecologic effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Removal of bed material</td>
<td>Destruction of bottom fauna; Modification of habitat</td>
<td>unknown</td>
</tr>
<tr>
<td>Modification of flow patterns</td>
<td>Modification of supply of organism and nutrients</td>
<td>moderate to large</td>
</tr>
<tr>
<td>Stratification</td>
<td>Increase of mortality rates; Decrease of recovery rates</td>
<td>small</td>
</tr>
<tr>
<td>Increase of turbidity level</td>
<td>Decrease of light penetration; Increase of nutrients; Modification of primary production</td>
<td>small to moderate</td>
</tr>
<tr>
<td>Modification of sediment composition</td>
<td>Modification of biodiversity; Modification of habitat</td>
<td>moderate</td>
</tr>
</tbody>
</table>

Table 2.2 Mining in navigation channel (extension of width).

<table>
<thead>
<tr>
<th>Abiotic effect</th>
<th>Biotic effect</th>
<th>Ecologic effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Removal of bed material</td>
<td>Destruction of bottom fauna; Modification of habitat</td>
<td>large</td>
</tr>
<tr>
<td>Modification of flow patterns</td>
<td>Modification of supply of organism and nutrients</td>
<td>small</td>
</tr>
<tr>
<td>Stratification</td>
<td>Increase of mortality rates; Decrease of recovery rates</td>
<td>small</td>
</tr>
<tr>
<td>Increase of turbidity level</td>
<td>Decrease of light penetration; Increase of nutrients; Modification of primary production</td>
<td>moderate</td>
</tr>
<tr>
<td>Modification of sediment composition</td>
<td>Modification of biodiversity; Modification of habitat</td>
<td>small</td>
</tr>
</tbody>
</table>

Table 2.3 Mining at bed surface (layer of maximum 2 m) in depth larger than 20 m; in one large area or multiple smaller areas.
### Table 2.4 Mining in deep pits.

<table>
<thead>
<tr>
<th>Abiotic effect</th>
<th>Biotic effect</th>
<th>Ecologic effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Removal of bed material</td>
<td>Destruction of bottom fauna</td>
<td>moderate</td>
</tr>
<tr>
<td>Modification of flow patterns</td>
<td>Modification of supply of organism and nutrients</td>
<td>small</td>
</tr>
<tr>
<td>Stratification</td>
<td>Increase of mortality rates</td>
<td>moderate to large</td>
</tr>
<tr>
<td>Increase of turbidity level</td>
<td>Decrease of light penetration; Increase of nutrients</td>
<td>moderate</td>
</tr>
<tr>
<td>Modification of sediment composition (deposition of mud)</td>
<td>Modification of biodiversity; Modification of habitat</td>
<td>small to moderate</td>
</tr>
</tbody>
</table>

#### 2.4 Morphological behaviour of mining pits

The morphological behaviour of mining pits is reviewed by considering the following items:
- trapping of sediments in the pit;
- effect of a pit on the coast;
- results of data sets of mining areas;
- results of mathematical model studies of mining areas.

#### 2.4.1 Trapping of sediments

The sedimentation, erosion and migration of a mining or extraction pit (channel or trench) in a coastal environment strongly depend on the sediment supply, the hydraulic conditions and the orientation of the pit.

When a current passes a pit (perpendicular or oblique), the current velocities decrease due to the increase of the water depths in the pit resulting in a decrease of the sediment transport capacity. As a consequence the bed-load particles and a certain amount of the suspended sediment particles will be deposited in the pit. The settling of sediment particles is the dominant process in the downsloping section (deceleration) and in the middle section of the pit. The most relevant processes are: convection of sediment particles by the horizontal and vertical fluid velocities, mixing of sediment particles by turbulent and orbital motions, settling of the particles due to gravity and pick-up of the particles from the bed by current and wave-induced bed-shear stresses. The effect of the waves is that of an intensified stirring action in the near-bed region resulting in larger sediment concentrations, while the current is responsible for the transportation of the sediment. In case of flow parallel or almost parallel with the channel axis, the side slopes of the channel are flattened and smoothed due to gravitational effects. When a sediment particle resting on a side slope is set into motion by waves or currents, the resulting movement of the particle will, due to gravity, have a component in downward direction. By this mechanism sediment material will always be transported to the deeper part of the channel yielding reduced depths and smoothed side slopes. Slope instability may occur in case of relatively steep slopes immediately after (capital) dredging, especially in deep mining pits.

Wave action over a muddy bed may generate a high-concentration fluid mud layer close to the bed. The sediment concentrations in this layer may be of the order of 100 to 300 kg/m$^3$. The sediment concentrations above this layer generally are an order of magnitude smaller. Tide-driven, wave-driven, wind-driven or gravity-driven (on slopes) currents are able to
transport the fluid mud layers towards the channel resulting in excessive deposition on short term time scales (storms, monsoon waves).

The sedimentation in mining pits basically consists of two elements:
- sediment transport (mud, silt and sand) carried by the approaching flow to the pit/channel, depending on flow, wave and sediment properties;
- trapping of sediment in the pit, depending on pit dimensions, channel orientation and sediment characteristics.

2.4.2 Effect on shoreline

The effects of a nearshore pit or channel on the shoreline can be described as:
- **beach drawdown (sink effect)**; this usually occurs during storms due to the action of high steep waves generating breaking wave conditions and hence a relatively strong near-bed, offshore-directed currents (undertow); beach material is eroded from the upper shoreface and moved seawards; during periods of calmer weather the material is returned to the beach by shoaling, non-breaking waves (sea and swell waves); if the pit is situated near the shoreline then this dynamic equilibrium is disturbed and sediment may be trapped in the pit (pit acts as sink) and erosion of the foreshore may result (see Figure 1.2 Top);
- **interception of onshore sand transport**; if the beach is being nourished by sediments coming from the shelf by onshore-directed transport processes (wave action) then the pit will trap a proportion of this sediment and interrupt the supply of sediment to the shore (see Figure 1.2 Top);
- **modification of offshore sand banks**; if the dredging of a pit leads to permanent or temporary lowering of the sand bank crests present in the nearshore zone then the protection level of the shoreline against wave attack is reduced; the offshore sand banks help to protect the shoreline against wave attack by either dissipating wave energy as a result of bed friction, partial breaking of the waves and by reflection.
- **generation of alongshore transport gradients**; the presence of a pit will lead to local changes in the wave refraction patterns and associated wave height patterns at the edge of the surf zone; this will result in alongshore variations (gradients) of the littoral drift and hence in shoreline changes (Figure 1.2 Bottom).

The effect of mining pits on the shoreline strongly depends on the distance to the shore. Nearshore mining pits will immediately have a negative effect, but offshore mining pits generally have not much direct effect. Their negative effect on the shoreline may come out on the long term after the pit has migrated to the shore. The migration rates vary roughly between 0.2 m/year at the 20 m depth contour to about 1.5 m/year at the 10 m depth contour.

2.4.3 Results of data sets of mining pits

Herein, the attention is focussed on extraction/mining pits. The number of data sets available for hindcast studies of the morphological behaviour of mining pits in combined current and wave conditions is relatively small. In most cases the boundary conditions (current and wave regimes) are missing.

**Extraction pits in laboratory conditions**

Laboratory data of trapezoidal extraction pits have been presented by Migniot and Viguier (1980). They carried out scale tests with extraction pits at depths between 6 and 23 m in a wave flume (pit width of 80 m at bottom and 140 m at top; depth of 5 m) and in a wave...
basin (pit width of 80 m at bottom and 200 m at top; pit length of 800 m; depth of 6 m). Plastic sediment particles with a diameter of 0.255 mm and a density of 1380 kg/m³ were used to scale the natural sand particles of 0.06 to 0.3 mm as present in the Gulf of Casgogne north of Biaritz (France). The horizontal scale of the model was set to 1 to 200 and the vertical scale was set to 1 to 75. The wave height at the offshore boundary (about 40 m depth) was varied between $H_{1/10}=1.9$ and 7.5 m ($H_{1/10}=1.2H_{1/3}$). The maximum incident wave angle was 15° in the wave basin. Wave action was simulated over a period of 2 years. The wave basin tests showed the following results:

- pit at 6 m depth: deposition in middle of pit= 6 m;
- pit at 11 m depth: deposition in middle of pit= 3.5 m;
- pit at 16 m depth: deposition in middle of pit= 1.3 m;
- pit at 21 m depth: deposition in middle of pit= 0.3 m (waves normal to shore); 0.35 m (oblique angle of 15°).

The pits were filled from the landside by storm wave-induced near-bed currents and from the seaside by wave asymmetry transport. The former dominated in shallow depths (<15 m). The minimum wave height causing depositional processes was about $H_{1/10}=0.25$ h with h= local water depth.

It is concluded that the annual deposition of sediment in extraction pits in depths larger than 20 m with occasional storm waves up to 9 m is not more than about 5% of the initial pit volume.

**Extraction pits in field conditions outside The Netherlands**

**USA**

Field data of the morphological behaviour of nearshore extraction pits in the USA (period 1955 to 1965) are given in Table 2.3. As the boundary conditions (current and wave climate) are not sufficiently known, the data sets can not be used for hindcast studies. These pits were excavated in relatively shallow waters (depth of 1 to 6 m) in the lee of barrier islands (3 pits in the Long Island Sound and 1 pit in the Mississippi Sound) to obtain sand for nourishment of beaches on the mainland. The extraction pits were excavated just beyond the foot of the beach face at which the sand was dumped for nourishment purposes. As the extraction pits are rather close to the beach, they will act as a sink for the sediments transported offshore by wave-induced near-bed return currents and the trapped sediments can be used again for beach nourishment in the future.

The annual deposition in the extraction pits in the first years (3 to 5 years) after dredging was not more than about 3% of the capital dredging volume, indicating the presence of a relatively mild wave climate.

The design of extraction pits close to the beach (at the toe of the beach face) is a relatively simple and cheap method of beach nourishment, which can however only be used in conditions with a mild wave climate (sheltered beaches) and hence a small longshore transport rate. In open sea conditions the presence of a relatively deep extraction pit close to the beach will lead to higher waves at more inshore locations and hence to an increase of beach and dune erosion.

Combe and Soileau (1987) describe the effects of nearshore mining along the micro-tidal coast of Grand Isle, Louisiana, USA. An artificial dune was constructed in 1983 to replace the natural dune destroyed during a storm event on the barrier island of Grand Isle in the Gulf of Mexico. The sand material was taken from a extraction pit (length= 3 km, width= 0.5 km) situated about 1 km offshore in front of the midway point of the island. The
estimated water depth is about 10 m. More material was taken from both end sections of the extraction pit, yielding a depth of about 6 m below the seabed and about 3 m in the center of the pit. In all, about 2.5 million m$^3$ of sand was dredged. Two cusparse bars welded to the shore were formed opposite to the ends of the extraction pit during a period of 6 to 12 months after completion of the dredging activities. Significant erosion during storm events was observed on the flanks of the bars and in the middle between the cusparse bars. The erosion embayment had reached the toe of the dunes after a series of severe storms hitting the coast. This example shows that nearshore extraction pits of sufficient size may change the nearshore wave climate by refraction and diffraction effects, producing alongshore gradients of the littoral drift and hence deposition/erosion forms. Dune erosion and breaching may occur in the erosion embayment between the bars. The extraction pit was filled by about 1 million m$^3$ of sand (50% of capital volume) during two years after dredging.

Cialone and Stauble (1998) discuss the removal of sand material from ebb tidal shoals near tidal inlets as a source for beach nourishment. This practice is referred to as shoal mining. Ebb shoal sediment is reasonably compatible with native beach material. The results of eight ebb shoal mining projects within the last 15 years (Gulf and Atlantic coasts of Florida; New York and New Jersey coasts) are presented. The majority of the sand taken from the ebb shoals was placed on downdrift beaches. In two projects the sand was used for updrift beach fills. The scale of the projects ranged from 5% to 25% removed from the total ebb shoal volume. Only one project encompassed the entire ebb shoal area while the other seven projects were restricted to specific extraction areas within the ebb shoal complex. The analysis results show that at some inlets, the adjacent shorelines maintained a stable downdrift position due to the placement of mined material on the downdrift beach. Other inlets exhibited an increased downdrift erosion rate following the mining of an ebb shoal. Final conclusions on the maximum quantity (and the optimum location) that can be dredged safely from an ebb shoal can not yet be given.

Japan
Field data of the morphological behaviour of nearshore extraction pits in Japan (period 1980 to 1995) are given in Table 2.4. As the boundary conditions (current and wave climate) are not sufficiently known, the data sets can not be used for hindcast studies.

Uda et al. (1995) describe the morphological behaviour of extraction pits in Tosa Bay off the Niyodo river mouth bar (Japan). The extraction pits act as sinks for the sediment supplied (intermittently during floods) by the river flow. As a consequence the supply of sand to the adjacent coasts is partly cut off resulting in severe erosion of the local beaches and bars by wave-induced processes.

Kojima et al. (1986) describe the morphological behaviour of extraction pits during storm events in the northern part of Kyushu, Japan. They also studied the behaviour of the shoreface bed at various depths by using tracers and graduated rods placed in the bed. The shoreface has a slope of about 1 to 100 down to the 15 m depth contour and a slope of 1 to 200 between the 15 m and the 25 m depth contours.

The observed extraction pits showed relatively large infill rates in depths up to 25 m during the winter months with typhoon waves up to 5 m. The pit H1 in a depth of about 21 m at site 2 was almost completely filled after 5 months (infill rate of 250 m$^3$/m over 5 months) on the landward side of the pit, suggesting sedimentation due to offshore-directed processes (offshore-directed near-bed return currents along the relatively steep shoreface). Shoreline recession of about 10 m was observed in the period between 1975 and 1985 when offshore sand mining at depths between 13 and 21 m was executed. The extraction pits H2 and H7 in depths of 15 to 20 m also showed considerable bed profile changes during the winter
months. The extraction pit H3 in depths of 35 to 40 m showed only minor bed profile changes and remained its shape. Kojima et al. conclude that the excavation of extraction pits in depths smaller than about 30 m may lead to increased shoreline erosion due to infill of the pits with sediments coming from the landside and causing a steeper shoreface slope.

**New Zealand**

Hesp and Hilton (1996) discuss the effects of nearshore mining along the Pakiri-Mangawhai coast of New Zealand. Mining takes place during periods of low swell wave activity and offshore winds, using suction pumps mounted on dump barges. The immediate impact of these types of extractions is the excavation of an extraction pit approximately two metres deep and tens of metres in length and width, which is rapidly obliterated during subsequent periods of swell and/or sea wave activity. In 1993 permits were granted to extract a total of about 100,000 m$^3$/yr of sand for a 10 year period from the shallow nearshore zone (depths of 3 to 8 m) bordering the sandy Pakiri-Mangawhai coast. The environmental impact assessment submitted in support of the applications by the mining companies concluded that: 1) the quantities of sand to be extracted would be small in comparison with the total volume of sand in the beach system, 2) the beach system is open and sands extracted are replaced as a result of onshore transport of inner shelf sand by swell waves, 3) the beach system has accreted in recent periods in the presence of mining and 4) there is no evidence of impact of past coastal mining.

Analysis of beach profiles after 1978 shows that the beach is gradually accreting (about 20 m at shoreline over 10 to 15 years) in the presence of mining activities in the nearshore zone. This means that the volume of onshore sand transport by the swell type waves is larger than the extraction volume.
<table>
<thead>
<tr>
<th>General site characteristics</th>
<th>Dimens</th>
<th>Local water depth (m); Offshore distance (km)</th>
<th>sand size</th>
<th>Morphological behaviour</th>
</tr>
</thead>
<tbody>
<tr>
<td>Westhaven beach, Connecticut, USA (USACE, 1961)</td>
<td>situated in Long Island Sound in lee of L.I. barrier island; width of sound=30 km; semi-diurnal tide of 2 to 2.5 m; mild wave climate</td>
<td>length=600 m, width=150 m depth=5 m; Volume= 0.4 $10^6$ m$^3$</td>
<td>depth=1.5 to 2m (to mlw); at 300 m from shoreline</td>
<td>0.22 to 0.9 mm used for beach fill</td>
</tr>
<tr>
<td>Seaside Park, Connecticut, USA (USACE, 1965)</td>
<td>situated in Long Island Sound in lee of L.I. barrier island; width of sound=30 km; semi-diurnal tide of 2 to 2.5 m; mild wave climate</td>
<td>l=1100 m, w=110 m d=5m; V= 0.6 $10^6$ m$^3$</td>
<td>depth=1.5 to 2m (to mlw); at 300 to 400 m from shoreline</td>
<td>0.12 to 1.1 mm used for beach fill</td>
</tr>
<tr>
<td>Sherwood Island State Park, Connecticut, USA (USACE, 1967)</td>
<td>situated in Long Island Sound in lee of L.I. barrier island; width of sound=30 km; semi-diurnal tide of 2 to 2.5 m; mild wave climate</td>
<td>3 extraction areas close together, l=250 m, w=250 m d=6 m; V$_{total}$= 0.45 $10^3$ m$^3$</td>
<td>depth=6 m (to mlw); at 400 to 500 m from shoreline</td>
<td>0.2 to 0.6 mm used for beach fill</td>
</tr>
<tr>
<td>Harrison County, Mississippi, USA (USACE, 1958)</td>
<td>situated in Mississippi Sound in lee of low barrier island; width of sound=20 to 30 km; diurnal tide=0.5 m; mild wave climate; extremes during hurricanes</td>
<td>l=1 long, narrow extraction channel, l=15 km, w=50 to 100 m d=3 to 4 m; V$_{total}$= 4.5 $10^5$ m$^3$</td>
<td>depth=1 to 1.5 m (to mlw); at 500 m from shoreline</td>
<td>0.15 to 0.3 mm used for beach fill</td>
</tr>
<tr>
<td>Revere Beach, Massachusetts, USA (Watts, 1963)</td>
<td>situated about 10 km north of Boston; exposed to waves from open ocean; tide=2.7 m</td>
<td>l= 500 m, w=100 m d=3 to 4 m; V$_{total}$= 0.15 $10^3$ m$^3$</td>
<td>depth=2 m (to mlw); at 300 m from shoreline</td>
<td>0.28 mm used for beach fill</td>
</tr>
<tr>
<td>Grand Isle barrier island, Louisiana, USA (Combe and Soileau, 1987)</td>
<td>situated on a barrier island in the Gulf of Mexico; moderate wave climate with hurricane waves</td>
<td>long extraction pit l= 3000 m; w=500 m, d=3 to 6 m, V=2.5 $10^6$ m$^3$;</td>
<td>1 km from shoreline</td>
<td>sand</td>
</tr>
</tbody>
</table>
Table 2.5 Extraction pits in the USA.

<table>
<thead>
<tr>
<th>Extraction pit Cases</th>
<th>General site characteristics</th>
<th>Dimensions (l=length w=width d=depth V=volume)</th>
<th>Local water depth (m); Offshore distance (km)</th>
<th>sand size</th>
<th>Morphological behaviour</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tosa Bay off the Niyodo river mouth bar, Japan (Uda et al., 1995)</td>
<td>situated on Pacific Ocean; severe wave climate; Hs of 3 to 4 m during typhoons</td>
<td>extraction pits just seaward of bars in mouth of river; pit depth of 5 to 7 m</td>
<td>depth of 5 to 7 m; 150 to 200 from shoreline at bars</td>
<td>1 to 30 mm above -5 m depth line; 0.1 to 1 mm seaward of this depth line</td>
<td>- annual mining of 0.3 to 0.4 $10^6$ m$^3$ since 1978; - annual supply of sand by river=0.11 $10^6$ m$^3$ (intermittent during floods); - extraction pits acts as sink for sand supplied by river; surrounding coast shows severe wave-induced erosion due to lack of supply of sand from river; bars are eroded (recession of 150 m)</td>
</tr>
<tr>
<td>Northern part of Kyushu Island, Japan (Kojima et al., 1986)</td>
<td>coastline consists of series of concave beaches separated by rocky headlands; Onga river mouth at 5 km from site 2; severe wave climate with typhoon waves up to 5 m</td>
<td>pit H-1 l= 2 km; w= 200 m; d= 2 to 6 m V= 1 to 2 $10^6$ m$^3$</td>
<td>depth of 21 m; 3 km from shore</td>
<td>0.5 to 0.8 mm at depth between 20 and 25 m</td>
<td>- pit H1 was dredged in Oct. 1983 - infill of about 250 m$^3$/m over 5 winter months due to storm waves (typhoons) on the landward side of the pit; - tracer studies over 2 months show movement of sediments up to depths of 40 m; - bed level changes along graduated rods in the bed showed variations over 3 winter months of 0.1 m in depths of 25 m, 0.05 m in depths of 30 m and 0.03 m in depths of 40 m</td>
</tr>
</tbody>
</table>


Table 2.6 Extraction pits in Japan.

France
Detailed knowledge of the long-term bed evolution (20 years) of a sand mining pit in coastal waters can be obtained from the CNEXO-PIT in France. The CNEXO sandpit is 2.5 km long and 400 m wide inside the Seine Estuary, France (CETMEF, 2004). The local water depth is 17 to 18 m. Its direction is southwest-northeast. It was excavated in a region where the depths vary between 16 m and 17.5 m with a slight slope towards the north. A sediment
study of the east part of the Seine bay was carried out in 1967 and showed that the CNEXO pit was excavated in a region where the bottom material was made of fine quartz sands with a median diameter between 0.25 mm and 0.50 mm. These sands at the surface of the bottom contain from 20% to 30% of limestone but less than 2% of silt.

The dredging of the Cnexo sandpit was carried out from 1974 to 1980 through 13 campaigns of sediment extraction that removed more than 2,800,000 m$^3$ of materials. From 1974 to 1977, only the northeast part of the domain was dredged over a length of 1500 m approximately. At the end of this first stage, this “old” dredging is 200 m wide and the depth varies between 3 and 5 m. From 1977 to 1980, the southwest part of the domain was also dredged and this dredging was deeper and also thinner. At the end of the “new” dredging in 1980, the whole dredging is about 3 km long and between 130 m to 300 m wide.

Three different bathymetries for years 1981, 1996 and 2002 are available (see Figure 2.2, Figure 2.3, Figure 2.4 and Figure 2.5). The two most recent bathymetries (1996 and 2002) were made by Le Havre Harbour using exactly the same Global Positioning System (horizontal accuracy of about 1 m and vertical accuracy of about 0.2 m). The bathymetry of 1981 is less accurate, as it is based on digitalization of an old map. This leads to a small shifting of the sandpit compared to 1996 and 2002 bathymetries. Therefore, the 1981-bathymetry was shifted so that it fits the 1996 and 2002 pit's characteristics (horizontal accuracy of about 10 to 15 m and vertical accuracy of about 0.3 m).

Figure 2.2 Cnexo Bathymetry.
CETMEF performed various analyses of these three bathymetries to estimate the morphodynamic evolution. Based on the bed evolutions shown in three cross-sections S1, S2 and S3, it can be observed that there is relatively large deposition in the southern part of CNEXO pit between 1981 and 1996, which continued between 1996 and 2002 at a smaller rate. The middle and northern cross-sections show almost no deposition (S2 and S3).
The deposition volumes in the CNEXO pit are:

- **615,000 m$^3$** (or 41 000 m$^3$/year), which is about 22% of total volume of 2.8 million m$^3$ for the period from 1981 to 1996;
- **90,000 m$^3$** (or 15 000 m$^3$/year), which is about 3% of total volume of 2.8 million m$^3$ for the period from 1996 to 2002.

Thus, the annual infill rate is of the order of 1% of the total pit volume in the initial period of about 20 years. Information of the sediment composition is given in Table 2.7 based on the average of four samples inside the pit and six samples in the vicinity of the pit. The deposition material is relatively coarse sand of 0.39 mm. The percentage of fines smaller than 50 microns is rather small (<3%).

<table>
<thead>
<tr>
<th></th>
<th>Inside Sand Pit</th>
<th>Vicinity of Pit</th>
</tr>
</thead>
<tbody>
<tr>
<td>% gravels (&gt;2 mm)</td>
<td>9.4</td>
<td>1.4</td>
</tr>
<tr>
<td>% coarse sand (0.5-2 mm)</td>
<td>14.3</td>
<td>11.9*</td>
</tr>
<tr>
<td>% medium sand (200-500 mm)</td>
<td>54.1</td>
<td>68.9</td>
</tr>
<tr>
<td>% fine sand (50-200 mm)</td>
<td>21.6</td>
<td>16.4</td>
</tr>
<tr>
<td>% silt (&lt; 50 mm)</td>
<td>2.9</td>
<td>0.6</td>
</tr>
<tr>
<td>Median diameter (mm)</td>
<td>0.393</td>
<td>0.388</td>
</tr>
</tbody>
</table>

Table 2.7 Sediment composition data of CNEXO Pit.

The tidal conditions at the pit site can be summarized, as follows:
- mean tidal range of about 5 to 6 m; spring tidal range of about 7 m;
- maximum depth-averaged velocities in the range of 0.3 to 0.45 m/s during mean tide.

Information of the wave field can be obtained from two wave buoys located near the CNEXO site. with data records in the period of July 1996 to February 2003. Wave directions near the CNEXO site are not yet available. The wave height distribution near the pit can be summarized, as follows:
- $H_s=0.36$ m, $T_p=4.4$ s, percentage=77.6;
- $H_s=1.37$ m, $T_p=5.4$ s, percentage=17.9;
- $H_s=2.35$ m, $T_p=6.5$ s, percentage=4.0;
- $H_s=3.29$ m, $T_p=7.5$ s, percentage=0.5.

**Extraction pits in field conditions in The Netherlands**

*Scheveningen Trench Case*
A trial trench was dredged in the North Sea bed (sand between 0.2 and 0.3 mm) near Scheveningen in March 1964 to obtain information of deposition rates with respect to the construction of a future sewer-pipeline trench (Svasek, 1964). The trial trench was dredged perpendicular to the shoreline between 1 km (local depth of about 7 m below MSL) and 1.7 km (local depth of 10.5 m) from the RSP-baseline on the beach. The length of the trench along the main axis of the trench was about 700 m; the bottom width of the trench was about 10 m; the side slopes of the trench were about 1 to 7 and the trench depth below the surrounding sea bed was about 2 m. In all, about 30,000 m$^3$ was dredged. The local peak flood and ebb currents are estimated to be in the range of 0.6 to 0.5 m/s parallel to the shoreline (perpendicular to the trench axis). Details of the hydrodynamic and sediment conditions are given in Table 2.8. The trench was sounded regularly in the period between 7 March and 27 August 1964. Analysis of the bed profiles shows:
- almost symmetrical filling of the trench; net migration was not observed;
- deposition of about 30 to 35 m$^3$/m over 173 days (7 March-27 Aug. 1964) or about 70 to 75 m$^3$/m per year (for currents with moderate waves, summer conditions); annual infill rate is about 100%;
- assuming that all incoming sediment is trapped in the trench, the gross transport rates (sum of net flood and ebb transport) will be about 70 to 75 m$^3$/m/yr for tidal currents with moderate waves (spring and summer weather).

Measured bed profiles for a typical cross-section are shown in Figure 2.6. This case is also used in Chapter 4 for the validation of Delft3D-Online.

![Figure 2.6 Sedimentation in trial trench near Scheveningen in North Sea.](image)

<table>
<thead>
<tr>
<th>Trial trench near Scheveningen in North Sea</th>
<th>Inlet conditions</th>
<th>Channel dimensions</th>
<th>Sedimentation values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water depth to MSL $h_0$ (m)</td>
<td>7 to 11</td>
<td>Water depth in channel $h_1$ (m)</td>
<td>11 to 12</td>
</tr>
<tr>
<td>Approach angle $\alpha_o$ (degrees)</td>
<td>90</td>
<td>Bottom width (m); top width (m); slope</td>
<td>10 to 20; 30 to 40; between 1 to 5 and 1 to 7</td>
</tr>
<tr>
<td>Tidal range (m)</td>
<td>1.5 to 2</td>
<td>Sedimentation area (cross-channel, dry bulk volume in m$^3$/m, including pores)</td>
<td>30 to 35 during 173 days</td>
</tr>
<tr>
<td>Peak flow velocity (ebb) to south (m/s)</td>
<td>0.5</td>
<td>Sediment size $d_{50}$, $d_{90}$ (fine sand in mm)</td>
<td>0.2; 0.3</td>
</tr>
<tr>
<td>Peak flow velocity (flood) to north (m/s)</td>
<td>0.6</td>
<td>Gross sediment transport (estimated in m$^3$/m, bulk volume incl. pores)</td>
<td>40 to 55</td>
</tr>
<tr>
<td>Measured wave height $H_s$ (m) during 173 days peak period (s)</td>
<td>3 m during 1 day; 2.5 m during 7 days; 1.75 m during 14 days; 1.25 m during 30 days; 0.75 m during 50 days; 0 m during 71 days 5 to 8 s</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2.8 Basic data of sedimentation in trial trench near Scheveningen in North Sea.
**PUTMOR Case**
The PUTMOR pit is described in Section 3.2. As the measured morphological development only consider a relatively short period of about 1 year with considerable uncertainties, an unambiguous conclusion regarding the morphological evolution on the long term can not be drawn.

**Extraction from sand waves/shoals**

**The Netherlands**
*Rijkswaterstaat (1981)* in The Netherlands studied the regeneration of a sand wave in the North Sea after removal of the crest of the sand wave in a water depth of about 20 to 25 m by dredging. The crest of one sand wave within a large-scale sand wave field was removed in 1974 by about 1.5 m over a length of about 1 km (total dredging volume of about 350,000 m$^3$). The sand wave field consisted of waves with a height of about 5 to 6 m and spacings of 400 to 500 m at about 30 km from the coast and about 3 km north of the navigation channel to the Port of Rotterdam. The sand wave crests are superimposed by active megaripples with a height of about 0.5 to 1 m and length of about 20 to 30 m. The maximum tidal current velocities during ebb and flood in this area are about 0.4 to 0.6 m/s. Storm waves with a height of about 3 to 4 m occur during the winter season during 3% of the time. The mean sediment size is about 0.2 to 0.3 mm. The morphological behaviour of the dredged sand wave crest was followed over a period of 6 years up to 1980. Analysis of the sounding data from the period of 1976 to 1980 shows that a mean sand wave height of about 4.5±1.0 m is present along the dredged section of the sand wave and about 6.0±0.5 m on both sides of the dredged area (in the direction of the crest) over the period of 4 years. The difference in wave height inside and outside the dredged crest section was still the same (about 1.5 m) after 6 years. A regeneration trend with a clear increase of the sand wave height in time could not be detected within the dredged section. The sand waves were quite stable, although significant vertical and horizontal fluctuations were observed in the crest regions due to the movements of the megaripples. The vertical fluctuations at the crests were in the range of 0.5 to 1.5 m; the horizontal fluctuations were in the range of 15 to 30 m.

**Japan**
*Katoh et al. (1998)* studied the generation and migration of sand waves over a shoal inside a navigation channel (Bisanseito channel, Japan). The sand waves had a height of about 5 m and a length of about 100 m and were most pronounced and mobile in depths of about 15 to 25 m. The crestlines of the sand waves are essentially normal to the direction of the predominant tidal currents. The bed consisted of sand in the range of 0.5 to 2 mm. The sand wave crests were removed in the period 1981-1983 by dredging to obtain a larger depth for navigation (dredged volume of about 2 million m$^3$). During a period of 10 years after dredging the sand wave pattern was restored similar to the initial situation. Based on analysis of regular sounding data, the following observations were derived:

- gradual reduction of the mean depth (spatially averaged) in the most shallow area of the shoal (depths of 15 to 20 m) by about 0.7 m over 10 years over an area of about five wave lengths due to sand transport towards the shallow part of the shoal;
- gradual increase of the sand wave height by about 3 m over a period of 10 years (reduction of minimum depth);
- sand wave migration (about 5 m/yr in depths of 25 to 30 m up to 15 m/yr in depths of 15 to 25 m) from both sides of the shoal towards the most shallow part of the shoal in the direction of the predominant currents.
These results show that sand waves in deep water (15 to 25 m) can recover to their original shape and size over a period of say 10 to 20 years in dynamic conditions (relatively strong currents plus waves) with sufficient supply of sand.

Conclusions

Extraction from pits

The available information on the coastal impact of mining pits (extraction pits for beach nourishments) can be summarized, using the following zonation:

- **inshore at foot of beachface (2 to 5 m depth contour);**
  - cheap and attractive method for sheltered beaches (mild wave regimes; small littoral drift);
  - can not be used for open, exposed beaches; infill from beachside and seaside and from shore-parallel directions (annual infill rate is not more than about 3% of initial pit volume for sheltered beaches);
  - infill rates are between 5 and 15 m$^3$/m/yr, depending on wave climate; filling time scale is 10 to 30 years; local recirculation of sand; no new extraction sand is added to beach system;

- **upper shoreface (5 to 15 m depth contour);**
  - relatively strong impact on inshore wave climate due to modified refraction and diffraction effects;
  - relatively strong modification of gradients of littoral drift in lee of pit resulting in significant shoreline changes (growth of beach salients, see Combe and Soileau, 1987);
  - relatively rapid infill of extraction pit with sediments from landside (beach zone) and from shore-parallel directions; annual infill rates are in the range of 20% (depths of 10 to 15 m) to 100% (depths of 5 to 10 m) of initial pit volume; the filling time scale is 5 to 10 years;
  - local recirculation of sediment; no new extraction sand is added to nearshore system;

- **middle shoreface (15 to 25 m depth contour);**
  - negligible impact on nearshore wave climate (see Motyka and Willis, 1974);
  - negligible effect on nearshore littoral drift;
  - no measurable shoreline changes;
  - new extraction sand is added to nearshore morphological system (nourishment);
  - infill of extraction pit mainly from shore-parallel directions and from landside with sediments eroded from upper shoreface by near-bed offshore-directed currents during storm events (see Migniot and Viguier, 1980; Kojima et al., 1986); annual infill rate is about 1% of initial pit volume; the filling time scale is 100 years;
  - trapping of mud in pits (negative ecological effect);
  - particle tracer studies show small but measurable transport rates, mainly due to storm waves;
  - long-term deficit of sand for upper shoreface;

- **lower shoreface (beyond -25 m depth contour);**
  - no impact on nearshore wave climate;
  - no effect on nearshore littoral drift;
  - no measurable shoreline changes;
  - new extraction sand is added to nearshore morphological system (nourishment);
  - minor infill of sand in extraction pit; only during super storms;
  - trapping of mud in pits (negative ecological effect);
  - particle tracer studies show minor bed level variations (of order of 0.03 m over winter period) during storms.
Extraction pits in the middle and lower shoreface should be designed with their longest axis normal to the shore to minimize the trapping of sand from the nearshore zone during storm events (to minimize the impact on coast). The estimated time scales for the middle and lower shoreface are extremely uncertain due to lack of sand transport data at these locations.

*Extraction from sand waves/shoals*

As the field data information of extraction pits in sand wave/shoal areas is extremely limited, general conclusions can not be given. Removal of the crest of a sand wave in the Dutch sector (water depth of 20 to 25 m) of the North Sea, shows almost no regeneration of the sand wave crest over a period of about 6 years. Field data results from Japan shows that sand waves in deep water (15 to 25 m) can recover to their original shape and size over a period of say 10 to 20 years in dynamic conditions (relatively strong currents plus waves) with sufficient supply of sand.
3 Results from morphological model studies

3.1 Introduction

In this Chapter an update is given of the literature review of Van Rijn and Walstra (2002) on the results of mathematical modelling studies related to offshore sand mining. Several model studies have been performed related to the behaviour of sand mining/extraction pits in laboratory and field conditions:

1) Morphology of mining pits and mining from IJ-channel, The Netherlands;
2) Morphology of mining from EURO-MAAS channel, The Netherlands;
3) Morphology of large scale mining pits near EURO-MAAS channel, The Netherlands;
4) Flow in large scale mining pits, The Netherlands;
5) Morphology (2DV) of mining pits, The Netherlands;
6) Morphology (2DV) of mining pits, The Netherlands;
7) Flow and morphology (2DH) in large scale mining pits, The Netherlands;
8) Morphology (2DH) of large-scale mining pit using stability analysis, The Netherlands;
9) Shoreline changes due to modification of wave refraction patterns over extraction pits;
10) Sand extraction in central Gulf of St. Lawrence, Canada;
11) Extraction site offshore of Ocean City, Maryland, USA;
12) Extraction site offshore of Harwich, UK;
13) Extraction site at Sandbridge shoal, Virginia, USA;
14) Extraction sites offshore of Alabama, USA;
15) Extraction sites offshore of New Jersey, USA;
16) Extraction sites offshore of Maryland and Delaware, USA;
17) Extraction site offshore of South-Central Louisiana, USA;
18) Extraction sites on the U.S. Gulf and Atlantic Continental Shelves;
19) Shoreline response to offshore sand extraction at three U.S.A. sites;
20) Impacts of dredging on shoreline change, Turkey;
21) PUTMOR Case, The Netherlands

Here we can only give a brief overview, a detailed study which includes most of the Dutch sites listed was carried out by Hoogewoning and Boers (2001).

3.2 Results of model studies of mining pits available in Literature

1. Morphology of mining pits and mining from IJ-channel, The Netherlands

This study (Rijkswaterstaat, 1990) was focussed on the mining of seasand in deeper water and its effects on the shoreline of the Dutch coast. Two aspects were studied:

- effects of sand mining from pits at various depths (between 10 and 20 m) on the shoreline at four alongshore locations (Scheveningen, Bergen, Texel and Ameland),
• effects of sand mining from the IJ-channel (near IJmuiden) on the shoreline.

The **UNIBEST** model of Delft Hydraulics was used to estimate the cross-shore morphological bed evolution; the **LOMOR** model of Delft Hydraulics was used to estimate the longshore morphological bed evolution. The pit dimensions are given in Table 3.1. Based on the model computations, it was concluded that:

- the flow pattern outside the pit is modified over a distance of maximum twice the pit width and length;
- the flow velocity in the pit is reduced by about 10% for a pit depth of 5 m and by 5% for a pit depth of 2 m;
- the cross-shore morphological changes are relatively small; the migration rates are mainly affected by the local water depth and not by the pit dimensions (depth, width, length); the landward side slope of the pit shows net onshore migration of the order of 0.2 m/year at the 20 m NAP depth contour, 0.5 m/year at the 16 m NAP depth contour and 1.5 m/year at the 10 m NAP depth contour; the pit will be filled up in about 100 years; the maximum migration in that period will be about 1500 m at the 10 m depth contour; the effect on the shoreline depends on the distance of the pit to the shoreline, yielding time scales of centuries;
- the longshore morphological changes are relatively small; the side slopes are flattened over a length equal to the pit length (a few km’s); the pit will be filled up in about 100 years; the longshore migration length in that period is of the order of the pit length (say 5 km).
- the uncertainty ranges are relatively large (factor 5) due to lack of field data for verification.

<table>
<thead>
<tr>
<th>Depth contour to NAP (m)</th>
<th>Cross-shore width of pit (m)</th>
<th>Alongshore length of pit (m)</th>
<th>Depth of pit (m)</th>
<th>Volume of pit ($10^6$ m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>100</td>
<td>2000</td>
<td>1</td>
<td>0.2</td>
</tr>
<tr>
<td>10</td>
<td>500</td>
<td>2000</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>16</td>
<td>100</td>
<td>2000</td>
<td>1</td>
<td>0.2</td>
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<tr>
<td>16</td>
<td>500</td>
<td>2000</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>16</td>
<td>1000</td>
<td>2000</td>
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</tr>
<tr>
<td>16</td>
<td>1000</td>
<td>5000</td>
<td>2</td>
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<tr>
<td>20</td>
<td>1000</td>
<td>2000</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>20</td>
<td>1000</td>
<td>5000</td>
<td>2</td>
<td>10</td>
</tr>
</tbody>
</table>

Table 3.1 Pit dimensions.

Mining of sand from the IJ-channel (navigation channel to Port of Amsterdam) by widening and/or deepening of the channel has no significant effect on the far-field shoreline. The local shoreline close to the breakwaters surrounding the entrance may be modified slightly due to changes of the local wave-current conditions. A summary of this study is given by Van Alphen et al. (1990).

### 2. Morphology of mining from Euro-Maas channel, The Netherlands

Mining of seasand from the EURO-MAAS channel (approach navigation channel to Port of Rotterdam) was studied by Delft Hydraulics (1992). The options considered were: widening (from 600 m in present situation to maximum 2700 m in future situation) and deepening (maximum 20% of the present depth) of the cross-section of the channel; the
cross-section modifications were assumed to be situated between 5 and 20 km from the shoreline.

The study comprised the following elements:

- analysis and description of the physical system (tides, currents, waves, sediments, transport rates);
- determination of alternative cross-sections for mining of sand;
- estimation of morphological effects:
  - deposition in channel due to reduction of sand transport capacity (maximum 0.2 m/year);
  - flattening of side slopes in longshore direction (maximum 2 km);
  - migration of slopes in cross-shore direction (maximum 1 km);
- estimation of trapping of mud in channel (maximum 5% of the amount of mud passing the channel).

Overall, the morphological changes are found to be limited to an area of one or two kilometres on both sides of the widened channel. The effects on the local wave and current patterns are so small, that appreciable effects on the shoreline are not to be expected. The uncertainty ranges are relatively large due to lack of accurate field data.

3. **Morphology of large scale mining pits near EURO-MAAS channel, The Netherlands**

**Walstra et al. (1997)** studied the overall long-term morphological impact on the Dutch coast of the port extension (Maasvlakte-2) and associated sand mining areas in the North Sea.

The study consisted of the following elements:

- determination of morphological tide to represent the neap-spring tidal cycle using **DELFt 2DH** model runs;
- determination of representative wave conditions using **SUTREnch-2DV** model runs (annual wave climate);
- initial sand transport computations using **DELFt-2DH** model for schematised tide and wave conditions to determine annual mean residual transport rates;
- long-term morphological computations (50 years) using **DELFt-2DH RAM** model based on annual mean residual transport rates;
- long-term morphological computations (300 years) using diffusion-type long-term model based on the quasi-equilibrium bathymetries produced by **RAM** model.

Two alternative sand mining scenarios have been studied:

- wide and shallow mining pit (approx. 7x20 km², depth of 2 m) north of EURO-MAAS channel;
- narrow and deep mining pit (approx. 3x7 km²; depth of 10 to 15 m) north of EURO-MAAS channel.

Based on the long-term morphological model results, the migration velocity of the mining pits was found to be 10 to 15 m/year. The morphological changes remain within the local surrounding of the mining pits. On the time scale of 100 years the overall migration of the mining pit will be of the order of 1 to 2 km, which is smaller than the width (about 3 km) of the deep mining pit. The effect of the mining pit scenarios on the nearshore coastal zone is found to be negligibly small. The morphological effect of the construction of the port
extension (land reclamation) on the nearshore coastal zone is found to be substantially larger than the effects of the sand mining pits.

4. **Flow in large scale mining pits, The Netherlands**

*Svasek (1998)* has studied the flow in mining pits (rectangular planform) situated in the Dutch sector of the North Sea. The base case is a shore-parallel pit with a length of L = 20 km, a width of W = 2 km and a depth in the pit of \( h_1 = 30 \) m; the water depth outside the pit is \( h_0 = 20 \) m. The Chézy value is set to 50 m\(^{0.5}\)/s.

The study comprised the following elements:
- theoretical analysis of the flow phenomena involved for stationary and non-stationary (tidal) flow focussing of far-field effects and in/outflow effects (flow contraction);
- model computations using a 2DH approach;
  - stationary flow with \( u_0 = 1 \) m/s;
  - tidal flow with \( u_0 \) varying between -0.6 and +0.6 m/s; water level between -1 and +1 m;
  - channel lengths between 2 and 20 km, channel width between 2 and 20 km;
  - water depth in channel between 22 and 40 m;
  - approach angles (between flow direction and main axis) of 0\(^\circ\), 30\(^\circ\) and 60\(^\circ\).

The most important conclusions of the numerical flow computations are:

**Stationary flow**
- the maximum flow velocity in the middle of the pit increases (10% to 20%) with increasing L/W ratio, in case of constant pit depth;
- the maximum flow velocity in the middle of the pit increases (10% to 20%) with decreasing \( W/h_1 \) ratio, in case of a constant pit length,
- the maximum flow velocity in the middle section (longitudinal) of the pit increases with decreasing Chézy value (more rough bed) due to decrease of the adjustment length (dominant effect),
- the maximum flow velocity in the middle section of the pit is smaller than the upstream velocity for a pit length smaller than two times the pit width (L<2W);
- the flow in a long and small (narrow) pit can be reasonably well represented by the far-field expressions for stationary flow.

**Tidal flow**
- the maximum flow velocity in the pit has a small time lag of about 15 minutes with respect to the maximum flow velocity upstream of the pit; the time lag decreases with increasing \( W/h_1 \) ratio;
- the residual (time-averaged over the tidal period) velocities are largest (order of 10% of main flow) near the inflow and outflow areas of the pit; the residual velocities are directed towards the outside area;
- the maximum flow velocity in the pit decreases for approach angles of 30\(^\circ\) and 60\(^\circ\); the residual velocities at the inflow and outflow sections are largest for an angle of 60\(^\circ\).

5. **Morphology (2DV) of mining pits, The Netherlands**

*Hoitink (1997, 1998)* has studied the longshore and cross-shore morphology of mining pits situated in the Dutch sector of the North Sea.

The study comprised the following elements:
- analysis of the hydrodynamics and bathymetry of the EURO-MAAS Channel (approach channel to Port of Rotterdam);
- application of SUTRENCH model to various sections of the EURO-MAAS Channel;
  - calibration of model based on observed bed profile changes of the channel (bottom width of approx. 600 m, maximum width of approx. 1000 m, channel depth of approx. 7 m) based on a simulation over 5 years;
  - application of model to deepened and widened channel sections based on simulations over 50 years.
- application of UNIBEST- model to estimate the cross-shore development of mining pits (depth of 2 m) in water depth of 20 m (depth contour -20 m NAP) due to waves up to $H_{rms}=2.25$ m and tidal flow up to 0.65 m/s.

The SUTRENCH runs (sand of about 0.2 mm; bed roughness in range of 0.001 to 0.5 m) show that the net displacement of the centre of the side slopes is of the order of 500 m, while the total area of influence in the direction of the tidal flow is approximately 10 km on a time scale of 50 years. The UNIBEST runs show cross-shore migration rates of the pit (with depth of 2 m) of maximum 2 m/year.

6. Morphology (2DV) of mining pits, The Netherlands

The 2DV development of sand mining pits in the North Sea (perpendicular to the flow) was studied by Walstra and Van Rijn (1998) using the SUTRENCH model (Walstra et al., 1999). The model was first tested by comparing computed and measured results for two cases concerning combined current and wave conditions: (i) small-scale channel perpendicular to flow and oblique to waves in laboratory wave-current basin and (ii) morphological development (over period 22 March to 14 April 1982) of pipeline trench in Danish littoral zone. After testing, the model was applied to determine the most important model and input parameters (sensitivity study). Finally, the long-term morphological evolution of various pit cases was determined.

The representative tidal flow characteristics (19 quasi-steady flow blocks) are:
- **Flood:** maximum water level of 1.4 m above MSL (NAP); peak flow of 0.9 m/s to north; duration of 6 hrs;
- **Ebb:** maximum water level of -0.5 m below MSL (NAP); peak flow of -0.7 m/s to south; duration of 6.5 hrs.

The representative wave characteristics are:
- Significant wave height: $H_s = 2.25$ m during 84% of the time,
- Peak wave period: $T_p = 6.6$ s,
- Wave direction: 315 degrees with respect to north.

The representative sediment characteristics are:
- Bed material: $d_{50} = 0.21$ mm, $d_{90} = 0.31$ mm,
- Fall velocity of suspended sediment: $w_f = 0.0275$ m/s,
- Bed roughness: $k_{r,c} = 0.05$ m, $k_{r,w} = 0.01$ m,
- Reference level: $a = 0.05$ m,
- Correction factor for reference concentration: $\gamma = 0.7$.

Given the input data for tidal flow, waves and sediment, the reference concentrations at the bed boundary were calibrated (correction factor of 0.7) to obtain a net annual sand transport rate at the inlet boundary of about 50 m$^3$/m/year to the north. This latter value is the characteristic net annual transport rate for North Sea conditions at a depth of about 20 m.
The channel depth (below surrounding bed surface) was varied in the range between 2 and 14 m; the width was varied between 300 and 2400 m; the side slopes were 1 to 12.5 and 1 to 50. The upstream water depth to MSL was varied between 15 and 25 m.

Summarising:
- water depth outside pit between 15 and 25 m (20 m in base run);
- tidal flow with depth-averaged flood velocity of 0.9 m/s and ebb velocity of 0.7 m/s;
- representative wave height of $H_s = 2.25$ m (varied between 1.125 and 3.375 m), wave period of 6.6 s, wave direction of 315°;
- wave-related bed roughness between 0.005 and 0.05 m;
- current-related bed roughness between 0.025 and 0.075 m;
- sediment size $d_{50}$ between 0.1 and 0.3 mm, $d_{90}$ between 0.2 and 0.45 mm;
- net annual sand transport at upstream boundary (inlet, $x=0$ m) of about $50 \times 10^3$/m year;
- pit width between 300 and 2400 m, depth between 3.5 and 14 m, slopes between 1:12.5 (8%) and 1:50 (2%).

**Model appraisal**

The results for the laboratory basin experiment show good agreement with the measurements. The migration of the trench is modelled accurately, the morphological development of the trench slopes is not modelled accurately. The upstream slope is generally predicted too steep whereas the erosion of the downstream slope is underpredicted. From the basin experiment it is found that the trench slope development is influenced by varying the roughness heights. Varying the sediment fall velocity mainly influences the sedimentation (and migration) of the trench. An optimal fit to the upstream boundary velocity and concentration profiles resulted in a good representation of the measured trench development. An accurate hindcast of the Danish field experiment was not possible due to the fact that current data sets were not available for the simulated period. The migration and sedimentation of the trench over a period of 3 weeks show reasonable agreement with the observed morphological developments by using reasonable estimates for the tide-and wind-induced currents.

Overall it is concluded that the deposition in trenches and channels can be simulated quite well, provided that the incoming sediment transport is known.

**Influence of dominating parameters on morphological evolution of pit**

A sensitivity study using the SUTRENCH 2DV model has been performed, focussing on deposition and migration of the EURO-MAAS channel. Based on model runs varying process and model input parameters, it is found that the tide and wave climate should be accurately schematised to obtain reliable and accurate morphological results. Small variations of the current velocity have a relatively large effect, because the transport rates in deep water are relatively small (close to the initiation of motion). Furthermore the model is found to be very sensitive to variations of the sediment characteristics, calibration and validation of the transport functions for fine sediment is necessary. The sensitivity of SUTRENCH results to variations in the wave-related mixing parameters illustrates the need to validate the model for deep water conditions as the referred parameters have only been validated for shallow water conditions.
**Long term (50 years) morphological evolution of various mining pits**

The water depth outside the mining pit has the largest influence on the morphological evolution of the pit owing to the effect of the water depth on the sand transport capacity.

The pit geometry and dimensions have much less effect on the morphological evolution of the pit. The maximum initial total trapping efficiency of the pit is about 75% for the simulation with a reduced water depth. The minimum trapping efficiency is about 35% for the shallow pit with a depth of 2 m. The maximum migration of the pit in longshore direction over 50 years is 800 m for the decreased water depth case. The minimum migration is about 250 m for the increased water depth case. The relative volume decrease of the pit after 50 years is highest for the reduced water depth case, minimum relative sedimentation occurs for the pit with a width of 2400 m. A deep pit of 14 m (twice as deep as base run) has a time scale of 800 years (extrapolation to zero trapping efficiency) whereas a wide pit of 2400 m (four times as wide as base run) only has a time scale of about 500 to 600 years.

The morphological development is mainly influenced by the lag of the settling and picking up of the suspended sediment. In cases with sediment deposited on the pit bottom before the toe of the upstream slope, both slopes will develop almost independently from each other. This so-called morphological interaction between the pit slopes mainly occurs for the wide and deep pits. In case of reduced width or depth an increasing interaction between both slopes can be seen which results in an increasing sedimentation at the toe of the upstream slope. Wide pits have a relative short morphological time scale whereas deep pits have a relative long morphological time scale but also a relative small migration rate, which is favourable in relation to effect on the coastline.

The longshore morphological evolution of the pits is assumed to be driven by longshore currents (pit axis perpendicular to longshore current). In the cross-shore direction tidal currents are of a smaller order, resulting in smaller migration rates of the pits. The transport capacity of waves however increases if the water depth decreases. A decrease of 25 % in water depth (from 20 to 15 m) results in an increase of the migration rate of almost a factor 2. The morphological time scale is also halved. It illustrates that the dynamic behaviour of a pit changes dramatically if it is located in or migrates to shallower waters.
Figure 3.1 Influence of channel dimensions on sedimentation and horizontal displacement of channel after 50 years. Top: Ratio of channel depth (deepest point) and initial channel depth as function of time, Bottom: Ratio of horizontal displacement of centre of gravity of channel and upstream water depth as function of time.

The results are summarised in Figure 3.1, focussing on: (i) horizontal displacement of centre of gravity of channel (relative to upstream water depth of 20 m) after 50 years and (ii) ratio of channel depth (below the surrounding bed) at deepest point after 50 years and initial channel depth.

The following features can be observed:

- a shallow channel of 2 m is characterised by a relatively large horizontal displacement \((35 h_0\) with \(h_0\) = upstream water depth) and relatively large sedimentation (channel depth is reduced by about 70%) after 50 years;

- a deep channel of 14 m is characterised by a relatively small horizontal displacement \((12 h_0\) and sedimentation (channel depth is reduced by about 5%) after 50 years;
a wide channel (1200 and 2400 m) is characterised by sedimentation on the upstream side slope and erosion on the downstream slope; the sedimentation in the middle of the channel is minimum after 50 years;

a relatively narrow channel of 300 m shows a horizontal displacement of about $20h_o$; the channel depth is reduced by about 40% after 50 years;

a channel with a side slope of 1:50 yields a wider channel and hence less sedimentation in the middle of the channel compared with a channel with a slope of 1:12.5;

the water depth outside the channel has a relatively large effect on the channel sedimentation; a small depth of 15 m yields a much larger wave effect resulting in a significant increase of the incoming sand transport ($80 \text{ m}^3/\text{m/year}$); a water depth of 25 m results in a decrease of the net annual transport ($40 \text{ m}^3/\text{m/year}$) at the inlet boundary.

7. Flow and morphology (2DH) in large scale mining pits, The Netherlands

Klein (1999) has studied the flow in large-scale mining pits (rectangular planform).

The study comprised the following elements:

- stationary flow;
  - pit length $L$ between 2 and 100 km; pit width $W$ of 5 and 10 km;
  - water depth $h_1$ in pit between 22 and 30 m; water depth outside the pit is $h_o=20$ m;
  - approach angles of 0° and 45°; approach velocity of 0.5 m/s; Chézy value of 65 m$^{0.5}$/s;

- stationary flow with Coriolis effect;
  - length $L$ between 10 and 40 km; width $W$ of 5 and 10 km;
  - water depth $h_1$ in pit of 30 m; water depth outside the pit is $h_o=20$ m;
  - approach angles of 0°, -22.5°, -45°, 22.5° and 45°; approach velocity of 0.5 m/s;
  - Chézy value of 65 m$^{0.5}$/s;

- tidal flow with and without Coriolis effect;
  - length $L$ between 10 and 40 km; width $W$ of 5 and 10 km;
  - water depth $h_1$ in pit of 30 m; water depth outside the pit is $h_o=20$ m;
  - approach angles of 0°, -45°, and 45°;
  - upstream flow velocity varying between about 0.67 and -0.52 m/s;
  - water level variations of about 0.75 m; Chézy value of 65 m$^{0.5}$/s;

- morphology;
  - pit length of 25 km, pit width of 5 km;
  - water depth in pit of 22 and 30 m, water depth outside pit of 20 m;
  - approach angles of 0°, -45° and 45°; sediment size of 0.2 mm;
  - bed load and suspended load transport capacity (no lag effects);
  - model was tuned based on a comparison with SUTRENCH model results;
  - morphological time scale of 1000 years for pit evolution (Coriolis effect included).

Table 3.2 summarises the most important morphological indicators for the mining pits considered. The upstream side slope is defined as the side slope upstream of the dominant flow. The most important conclusions are summarized below:
<table>
<thead>
<tr>
<th>Pit Dimensions (length in km, width in km, depth in m, angle)</th>
<th>Maximum deposition (+) or erosion (-) in middle of pit (m)</th>
<th>Lateral (cross) direction</th>
<th>Longitudinal direction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Maximum migration of upstream side slope (km)</td>
<td>Maximum erosion length at upper corner of side slope (km)</td>
</tr>
<tr>
<td>LxW=25 x 5 d=10 m, 45°</td>
<td>-1</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>LxW=25 x 5 d=10 m, 0°</td>
<td>-0.5</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>LxW=25 x 5 d=10 m, -45°</td>
<td>1</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>LxW=10 x 5 d=10 m, 0°</td>
<td>-0.5</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>LxW=25 x 5 d=2 m, 45°</td>
<td>-0.5</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>LxW=25 x 5 d=2 m, 0°</td>
<td>-0.5</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>LxW=25 x 5 d=2 m, -45°</td>
<td>0.5</td>
<td>3</td>
<td>10</td>
</tr>
<tr>
<td>LxW=10 x 5 d=2 m, 0°</td>
<td>-0.5</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>LxW=25 x 5 d=10 m, 0° (net residual velocity increased to 0.1 m/s)</td>
<td>2</td>
<td>complete filling of original planform</td>
<td>complete filling of original planform</td>
</tr>
</tbody>
</table>

Table 3.2 Characteristic indicators of long term (after 1000 years) mining pit evolution; tidal flow (-0.5 to 0.5 m/s) including Coriolis effect, upstream depth=20 m, sediment of 0.2 mm.

**Stationary flow**

- the maximum flow velocity in the pit is larger than the flow velocity outside the pit for a length-width ratio larger than 3 (L/W>3);
- the equilibrium flow velocity in the pit (width of 5 km and a water depth of 22 m) is only reached if the pit length is larger than 60 km (L/W>12); the equilibrium depth-averaged flow velocity can be reasonably well described by the Chézy equation;
- the adjustment length scale increases with increasing pit depths; the model values are somewhat larger (50%) than the theoretical values;
- the Coriolis force has a significant effect on the flow pattern due to the asymmetrical inflow of the pit; the Coriolis force opposes and follows the inertial force in different areas of the pit; the maximum flow velocity in the pit increases (5% to 10%) taking the Coriolis effect into account for approach angles of +22.5° and 45° and decreases for angles of -22.5° and -45°;
**Tidal flow**

- the maximum flow velocity in the pit is larger than the flow velocity outside the pit for a length-width ratio larger than 4 (L/W>4);
- time lag effects are present for cases with L/W>>4;
- the residual velocities show circulation patterns near the corner areas of the pit for approach angles of 22.5° and 45°; the circulation cells increase in size for increasing approach velocity (1 m/s).

**Morphology**

- the side slopes of the pits are flattened (erosion);
- a pit parallel (0°) to the flow or under a positive angle (45°) migrates in the direction of the main longitudinal axis; the maximum migration distance after 1000 years is about 5 km (approximately 250 h₀);
- a pit under a negative angle of -45° migrates in the direction normal to the main longitudinal axis (Coriolis effect); the maximum migration distance after 1000 years is about 3 km (approximately 150 h₀);
- the depth of a pit parallel to the flow or under a positive angle (45°) tends to become somewhat larger; deposition is remarkably small after 1000 years;
- the rectangular and square planforms of the pits are transformed into less regular shapes.

An example of the computed morphology of a pit of 25x5 km² is given in Figure 3.2.

![Figure 3.2](image-url)
8. **Morphology (2DH) of large scale pits, The Netherlands**

The behaviour of a sandpit in the North Sea has been studied by using the method of morphodynamic instability analysis of a sandy bed subject to asymmetric tidal motion (Roos et al., 2001; Németh, 1998; Peters, 2000). The starting point is the linear stability analysis proposed by Hulscher et al. (1993), focussing on the response of small wavy bed perturbations under the influence of a M₂ tidal component. The fastest growing mode of the bed perturbations in an otherwise flat bed is assumed to represent the dominant wave length and orientation of the large scale sandbed features which are present in the system. More realistic conditions were simulated by including the M₀ and M₄ tidal components.

The model consists of the 2DH flow equations (including Coriolis effect and linear bed friction) in combination with a simplified sand transport equation (including a bed slope term). Tidal asymmetry causes migration of the bed features. The sandpit is represented as a superposition of wavy bed perturbations of small amplitude. The sandpit considered has a depth of 2 m in a water depth of 30 m and a Gaussian plan shape, given by \( h_{pit} = \exp(-\pi/L^2(x^2+y^2)) \) with \( L \) = non-dimensional diameter.
The pit in a flat bed appears to behave as a morphodynamic instability feature. The pit effect can be isolated from the growth of rhythmic patterns on the surrounding flat bed, assuming that these latter patterns represent a higher order effect compared to the pit effects. The presence of a sand pit triggers the formation of circulation cells resulting in the development of a sandbank pattern, see Figs 3.4 and 3.5. As time evolves, the sand bank pattern spreads out and migrates, alternatingly generating trough and crest zones. The pit itself deepens and the pattern spreads at a rate of 10 to 100 m/year. The migration rate of the centre of the pit is of the order of 1 to 10 m/year. An explanation of the hydrodynamic response to the presence of the pit can be found in terms of the vorticity dynamics. Vorticity is generated either by Coriolis and streamwise bed slopes or by bottom friction and transverse bed slopes.

Figure 3.4 Physical mechanisms explaining secondary flow in circular sandpit (one depth contour is shown) according to Roos et al., 2001. Top left: Flow from left to right (no Coriolis); small fluid column is on slope of pit; flow velocity and bottom friction is smaller on deeper side of column; column experiences a torque, which tends to bend the flow to the right. Top middle: Fluid below pit axis experiences a clockwise rotation and a counter clockwise rotation above the pit axis (no Coriolis). Top right: Generated vorticity induces residual cells that are carried slightly downstream by advection (no Coriolis). Bottom left: Flow is from right to left (no Coriolis). Conversely, two other residual cells are generated on other side of pit. Bottom middle: A four-cell pattern emerges after tidal averaging showing lateral inflow and longitudinal outflow with respect to tidal flow direction. Bottom right: Coriolis force is included (northern hemisphere). The two clockwise cells are amplified, which leads to the merging of the slightly damped counter clockwise cells into one larger elongated cell.
9. Shoreline changes due to modification of wave refraction patterns over extraction pits, UK

Motyka and Willis (1974) and Price et al. (1978) present results of a study of the shoreline changes caused by wave refraction over offshore dredged pits. A mathematical model is used of an idealized sand beach, typical of those on the English Channel and North Sea coasts of Great Britain. Depth and side slopes of dredged area and original water depth before dredging were varied.

The basic question addressed by the authors is: How far offshore and in deep enough water should the dredged pit be that refraction of waves over it will not cause significant changes in the pattern of alongshore transport of beach material?

The model computations on a grid of 176 m consisted of: 1) determination of paths of refracted wave orthogonals over the nearshore seabed, 2) determination of breaking wave conditions at edge of surf zone, 3) application of longshore transport equation to estimate the littoral drift along the beach, 4) determination of alongshore gradients in littoral drift and 5) computation of shoreline changes as function of time and return to wave refraction model based on updated bathymetry.

Deep water wave directions were selected to produce a net alongshore transport of about $30,000 \text{ m}^3/\text{yr}$ for an infinitely long, straight and sandy beach. The wave climate consisted of waves between 0.5 and 2 m (periods between 5 and 8 s) from directions between $+20^\circ$ and $-10^\circ$ degrees with respect to the cross-shore normal line. The pit was assumed to have a rectangular shape with a length of 880 m parallel to the beach and a width of 305 m perpendicular to the beach.

The cases considered are:
- water depth= 17.1-17.6 m (offshore distance= 3050 m): pit depth= 1, 3 and 4 m;
- water depth= 15.6-16.4 m (offshore distance= 2440 m): pit depth= 3 m;
- water depth= 11.3-14.3 m (offshore distance= 1820 m): pit depth= 3 m;
- water depth= 4.1-7.9 m (offshore distance= 1220 m): pit depth= 2 and 3 m.

The model was run for a period equivalent to 10 years and in each case stable equilibrium results were obtained after about 2 years. Shoreline erosion was observed to occur in the central lee zone of the pit and accretion on both sides. The maximum shoreline erosion values in the lee of the pit for the four water depth ranges are: 4, 6, 8, 12 and 30 m after 2 years for the deepest pits. Shoreline erosion is less for less deep pits. After 2 years a new stable shoreline equilibrium is obtained. In the long run the shoreline may approach to the old situation if the extraction pit is filled by sediments from the shelf zone. In reality the shoreline erosion will be less than the predicted ones due to diffraction effects by which wave energy will be spread out along the wave fronts.

It was concluded that extraction pits beyond the 14 m depth contour do not lead to any significant shoreline erosion (Motyka and Willis, 1974; Price et al., 1978).

Initial results of a similar study of modification of wave refraction patterns for the Sandbridge shoal off the Virginia Beach along the USA coast using a numerical wave transformation model and a shoreline change model were reported by Basco and Lonza (1997).

Demir et al. (2003) studied the effect of a extraction pit at a depth of 20 m (pit depths of 3 and 4 m) on the shoreline change in the Black Sea. The SWAN-model was used to determine
the transformation of the waves passing the extraction pit. Breaking wave parameters obtained from the SWAN-model were used to compute the shoreline evolution using the one-line GENESIS-model. Decreasing the side slopes of the pit and increasing the length of the pit were found to be good measures to minimize the effect of the pit on the shoreline.

10. Sand extraction in central Gulf of St. Lawrence, Canada

Anctil and Quellet (1990) describe the results of a study into the morphological impact of sand extraction in the coastal waters of Canada. The Iles-de-la-Madeleine Archipelago essentially consists of seven bedrock islands linked together by sandy barrier beaches. The local sand is transported by wave action, ultimately to one of the two spits: Sandy Hook in the south and Pointe de l'Est to the northeast where the mean accretion rate is estimated to reach 14 m/yr. The longshore-averaged (over about 5 km) net littoral drift is estimated to be about 100,000 m$^3$/yr near Sandy hook and about 70,000 m$^3$/yr near Pointe de L'Est. Two potential dredging grounds exist near these spits, where sand proves to be silica rich.

Fisheries (especially lobster) is an important economic activity of the Archipelago. The dredging company must prove to the government officials that the exploitation of the seabed will not affect the fragile biota and physical environment of the islands. The annual dredging volume is planned to be 0.5 to 1 million tons of sand by using a trailing-suction hopper ship in depths beyond the 10 m contour.

Three extraction schemes with adjusted bathymetry (maximum layer thickness between 1 and 2 m) at both potential dredging locations to simulate 20 years of extraction (volume up to 10 million m$^3$ of sand) were designed and the changes in littoral drift due to the modified wave refraction patterns (based on model computations) along the coast were estimated. The most favourable schemes with a 1 m deep excavation yielded an increase of 15% of the local annual littoral drift rate near the tip of the spit. The most unfavourable scheme with 2 m deep excavation yielded an overall 30% drift increase, with a local increase of 100% near the end of the spit. It was advised: 1) to operate the dredging activities in as deep water as possible and 2) to plan the dredging operations in such a way that the seabed is excavated as gradual as possible (no multiple dredging at the same site) to allow ample time for the morphological system to adjust.

11. Extraction site offshore of Ocean City, Maryland, USA

Anders and Hansen (1990) from the Coastal Engineering Research Center (CERC) studied potential extraction sites for beach nourishment schemes. Nine potential extraction sites between 1 and 5 km from the shoreline (offshore Ocean City) were examined adjacent to the entire Delmarva coast (USA) facing the Atlantic Ocean. The maximum significant wave height at a depth of about 10 m was about 4 to 5 m in the period of 1956 to 1975; waves larger than about 2 m occurred during about 5% of the time. Most sites were Holocene age linear shoals with a typical length scale of 5 km and a typical width scale of 1 km in depths of 9 (at crest) to 15 m (at trough). One shoal site was in shallow water (crest depth of 2.5 m) within the closure depth zone and was rejected, because model studies showed that removal of sand from this shoal would result in shoreline erosion. High resolution sounding surveys and 5 m long vibracores were used to define the sedimentological properties of the potential extraction sites. Environmental assessments were completed for each site and surrounding areas to identify potential dredging impacts to flora and fauna. Archeological surveys were conducted to ensure dredging would not damage any historically valuable objects. Numerical wave refraction studies were conducted to examine potential erosional effects of
extraction site mining on adjacent shorelines. The sites with sediment compositions similar to the required beach nourishment materials were finally selected for dredging of sediment.

12. Extraction site offshore of Harwich, UK

HR Wallingford (1983) studied the extraction of sand (layer of 1 and 2 m over area of 30 million square metres) from the Shipwash bank in the Outer Thames Estuary (North Sea). This sandbank is situated offshore of Harwich at a distance of about 10 km from the shoreline. The water depth at the crest of the bank is about 3 m at LWST (Low Water Spring Tides) and 6.5 m at HWST (High Water Spring Tides). The spring tidal range is about 3.5 m. HWST is 3.4 m above CD. This sandbank is located inside the 18 m water depth contour, whereas dredging usually is restricted to depths seaward of the 18 m depth contour in order to safeguard coastal protection.

A physical scale model (1 to 60) was constructed in a concrete wave tank with typical depths of 0.3 m. The area covered by the model shows seabed soundings in the range from 3 to 16.5 m below Chart Datum. At the seaward end a random wave generator was installed. Significant wave heights up to 5.5 m were simulated (normal wave incidence only). Incident wave heights were measured at the -16.6 m depth contour (blow CD) on the seaward side of the bank and transmitted wave heights were measured at the -10 m depth contour on the landward side of the bank. Wave dissipation by breaking at the crest of the sandbank was found to be dominant. The model results were used to calibrate a numerical wave model as the physical scale model could not be used directly to predict wave attenuation in the prototype situation (due to presence of side walls, incorrect bed friction and only normal wave incidence).

<table>
<thead>
<tr>
<th>Water level (m to CD)</th>
<th>Dredging scheme</th>
<th>Water depth above crest of bank</th>
<th>Offshore significant wave height at -16.6 m contour (to CD);</th>
<th>Inshore significant wave height at -10 m contour (to CD);</th>
</tr>
</thead>
<tbody>
<tr>
<td>HWST= 3.4 m</td>
<td>None</td>
<td>6.4 m</td>
<td>4.5 m (water depth= 20 m)</td>
<td>2.04 m (water depth=13.4 m)</td>
</tr>
<tr>
<td></td>
<td>Layer of 1 m</td>
<td>7.4 m</td>
<td>4.5 m (water depth= 20 m)</td>
<td>2.14 m (water depth= 13.4 m)</td>
</tr>
<tr>
<td>LWST= 0.2 m</td>
<td>None</td>
<td>3.2 m</td>
<td>4.5 m (water depth= 16.8 m)</td>
<td>1.59 m (water depth=10.2 m)</td>
</tr>
<tr>
<td></td>
<td>Layer of 1 m</td>
<td>4.2 m</td>
<td>4.5 m (water depth= 16.8 m)</td>
<td>1.63 m (water depth=10.2 m)</td>
</tr>
</tbody>
</table>

Table 3.3 Test results of Shipwash bank, Outer Thames Estuary, England.

Based on all model results (physical and numerical), it can be concluded that even for a very severe storm at the worst possible angle of incidence, the effect of dredging of 1 m is negligible on wave conditions at the shoreline. The inshore significant wave height is about 5% larger after removal of a layer of 1 m from the sand bank (storm event with offshore significant wave height of 4.5 m), see values in Table 3.3.

13. Extraction site at Sandbridge shoal, Virginia, USA

Kelley et al. (2002) have studied the significance of extraction pit impact on wave refraction patterns and hence on longshore sand transport in relation to the long term variability of longshore transport due to variability in wave height and direction. The maximum variation in sediment transport potential caused by a mining pit within the sandbridge shoal was determined to be about 25,000 m³/yr, whereas the standard deviation
of the natural sediment transport variability was about 100,000 m$^3$/yr. Long term wave records (10 to 20 years) should be available to determine the variability of the longshore transport rate. The longshore gradient in sediment transport and hence the shoreline changes due to the effect of the extraction pit can also be compared with the natural variability of shoreline changes (observed values). Problems are insignificant if the estimated changes in the shoreline position due to extraction pit dredging are small compared with the variability of observed shoreline changes.

14. Sand extraction sites offshore of Alabama, USA

Five sand resource areas in depths varying between about 10 and 20 m offshore of the Alabama coast (USA) were studied (Byrnes et al., 2004a). Nearshore wave, current and sediment transport patterns were modelled for existing and post-dredging conditions, with extraction site sand volumes ranging from 2 to 8 million m$^3$. Wave transformation modelling results indicated that minor changes will occur to wave fields under typical seasonal conditions and sand extraction scenarios. Localized seafloor changes at extraction sites are expected to result in negligible impacts to prevailing wave climate at the coast. For all potential sites, the maximum variation in annual littoral transport related to the post-dredging bathymetry was predicted to be approximately 10%. Predicted infilling rates (annual maximum of 2% of initial volume) and sediment types were relatively small and within natural variations. Impacts on benthic communities were evaluated on the basis of earlier studies. The levels of infaunal abundance and diversity are predicted to recover within 1 to 3 years, but recovery of species composition may take longer.

15. Sand extraction sites offshore of New Jersey, USA

Eight sand resource areas in depths varying between about 10 and 20 m offshore of the New Jersey coast (USA) were studied (Byrnes et al., 2004b). Nearshore wave, current and sediment transport patterns were modelled for existing and post-dredging conditions, with extraction site sand volumes ranging from 2 to 9 million m$^3$. The study results are similar to those for the Alabama coast (see under 14.)

16. Sand extraction sites offshore of Maryland and Delaware, USA

Two offshore shoals in water depths between 10 and 20 m were identified as potential sand sources for beach-quality sand with a maximum cumulative volume of about 25 million m$^3$ (one-time removal of 2 million m$^3$). Wave transformation modelling was based on a series of runs of the REF/DIF-1 model with boundary conditions from a nearby, offshore wave gauge (Maa et al., 2004). Model calibration was applied using measured nearshore wave data. The modelled, post-dredging data indicated an increase in wave height up to a factor of 2 in the area between the dredged shoals and the shore. Current modelling indicated that dredging related changes are negligible. The effects on sediment transport patterns were not modelled. The impacts on benthos communities were studied by field sampling surveys (Diaz et al., 2004). A mining scenario that removed the top meter of the shoal will disturb about 8 km$^2$ with the potential acute impact on about 150 million individuals representing about 300 kg of wet biomass. To minimize the impact, the total removal of the substrate should be avoided. Small areas within the project area should be left alone to serve as refuge patches. Project timing is recommended to lessen impacts (end mining activities in time for Spring/Summer recruitment of certain species).
17. Sand extraction site offshore of South-Central Louisiana, USA

A shoal located at the 10 m depth contour off south-central Louisiana was studied (Stone et al., 2004) as a potential source of sand (about 1 billion m$^3$). Numerical wave modelling was applied (overprediction up to about 25%). Removal of the shoal causes a maximum increase of the significant wave height by about 50% to 100% in the lee of the shoal complex for two storm events. Increased erosion along the Isles Dernieres is not expected to be caused by the nearshore wave changes. Directional waves, currents and sediment transport using OBS-sensors (optical backscatter) were measured during winter storms using three bottom-mounted arrays deployed on the seaward and landward sides of the shoal. Episodic increases in wave height, mean and oscillatory current speed, shear velocity, and sediment transport rates during storm events were measured. Waves tend to be higher and longer in period on the seaward side of the shoal. Mean currents are generally higher on the landward side.

18. Sand extraction sites on the U.S. Gulf and Atlantic Continental Shelves

Using a spectral or phase-resolving wave model combined with two-dimensional hydrodynamic and sand transport models, the behaviour of sand ridges and shoals was studied (Hayes and Nairn, 2004). Sand transport was found to converge along most of the crest of the shoal and net shoreward sand transport towards the steep flank of the shoal. Further model development focussing on the maintenance of these sand ridge features by wave-generated sand transport processes is recommended. At present the knowledge of ridge maintenance processes is too limited to be able to assess properly how much sand can be removed from a ridge or shoal without disrupting the processes that maintain the feature.

19. Shoreline response to offshore sand extraction at three U.S.A. sites

Wave modifications of an idealized extraction site were studied using the STWAVE model to determine the effects of offshore bathymetry changes to wave conditions and resulting sediment transport patterns (Kelley et al., 2004). The idealized extraction site was located approximately 400 m offshore, centered on the -10 m depth contour (below MSL) with an excavation depth of 3 m below the seafloor. Wave spectra, centered at -30°, -15°, 0°, 15° and 30° relative to shore normal, were modelled, each with the same significant wave height and peak period and having an equal percentage of occurrence (20%). The longshore range of influence at the breakerline is about 900 m on both sides of the site for wave directions of -30° and 30°. The longshore sand transport rate was computed using the CERC formula for different wave conditions and transformed into a normalized curve representing annual conditions. Based on gradients of the longshore sand transport rates, the shoreline changes were computed. Wave modelling was performed for three locations for a 20-year period and for 20 one-year blocks of the wave record. From these model runs the sand transport potential curves were derived for average annual conditions and for one year periods. Based on this, the averages and standard deviations ($\sigma$) of the computed longshore transport rates were determined for every 200 m section of the shoreline. If any portion of the longshore transport potential curve associated with the extraction site exceeds $\pm 0.5\sigma$ of the normal temporal variability about the longshore transport potential curve determined for existing (pre-dredging) conditions, the site is rejected. Using this method, there is a 62% chance that the mean longshore transport for any given year is outside the $\pm 0.5\sigma$ envelope about the mean. The method was applied to determine the maximum excavation depth giving longshore transport rates just within the $\pm 0.5\sigma$ envelope at three sites: North Carolina, New Jersey and Florida.
20. Impacts of dredging on shoreline change, Turkey

Demir et al. (2004) described a method for estimating both direct and indirect effects of sand extraction (Black Sea coast of Turkey) on shoreline change. The direct effects result from infilling of the dredged pit due to cross-shore sediment transport processes (if pit is within the depth of closure limit) and is addressed statistically, assuming that the beach profile is in some arbitrary equilibrium shape. The pit volume is transformed into a shoreline recession value $\Delta y$ ($\Delta y = \Delta V/(h_d + B)$), with $\Delta V =$ pit cross-sectional area per m length alongshore, $h_d =$ water depth above the pit, $B =$ beach berm height above mean sea level). The indirect effects arise from pit-induced wave transformations (neglecting pit infill being the worst case scenario), which alters the wave height at the nearshore breaker line and hence the longshore sand transport gradients yielding shoreline variations. Wave transformations were described by numerical models. Refraction over the longshore pit slopes is the dominant mechanism. Diffraction effects are minor for relatively shallow pits with gentle slopes. The results of sensitivity computations show that the shoreline response is extremely sensitive to the water depth at the dredging location, moderately sensitive to the cross-shore width of the pit, and nearly insensitive to the longshore length of the pit once the ends of the pit are far enough that their effects do not superpose. It is recommended to place the pit in the deepest water that is practical and minimize both the change in depth due to dredging and the side slopes of the pit. If the dimensions must be increased to dredge a larger volume and the cross-shore effects are insignificant, it is recommended to increase the longshore length of the pit.

21. PUTMOR Case, The Netherlands

Data set
Between October 1999 and March 2000 an extensive measuring campaign was held to collect data concerning water movement, water quality parameters and morphology in and around a large sand pit at the North Sea some 10 km off the Dutch coast near Hoek van Holland. The dimensions of the pit are 1300 m x 500 m x 10 m (relative to the seabed at an approximate depth of 24 m water depth, which gives a total volume of circa 6.5 Mm$^3$). The measurements comprise bathymetry, flow velocities, water levels, temperature, conductivity, turbidity, oxygen content and sampling and analysis of seabed material. The monitoring activities took place after dredging of the pit.

The main measurement locations are location M near the centre of the sand pit, and location A, outside the sand pit. Both at location M and A current velocities (in x, y and z direction) were continuously measured with an ADCP (Acoustic Doppler Current Profiler) throughout the vertical. Twice, flow track measurements were carried out along tracks, of which the first series were of doubtful quality because of directional inaccuracies. The position of the measurements stations, as well as the tracks sailed with a towed ADCP are shown in Figure 3.5.
Two Hydrolab instruments were available, one in the pit at location M and one outside, at location A, measuring the near seabed water temperature, conductivity, turbidity and depth. The Aanderaa string measured the temperature and conductivity at 5 different depths at location M. The Mors instrument was mainly used for its pressure sensor, but also temperature near the seabed was measured. The Mors was located at location B. The Seabird observations, consisting of water temperature, conductivity, turbidity, salinity, oxygen content and oxygen saturation percentage, were taken from a ship about once or twice a week at locations A and M, and comprise (almost) the entire vertical. In addition to these PUTMOR data, use is made of prolonged meteorological and hydrological data like water levels at nearby stations, waves, wind, air temperature and river discharge. Since October 1999 (considered as the reference situation), six bathymetric surveys were carried out in the pit area to study the morphological development of the sand pit. Also seabed samples were taken. Details on the surveys and the samples can be found in Svašek (2001).

The dataset set was mainly used for verification of the DELFT3D hydrodynamic field models (Walstra et al., 2003 and Walstra and Van Rijn, 2002).

**DELFT3D model results**

The evaluation study has shown that the DELFT3D-model is capable of reproducing the measurements with reasonable to good accuracy. However, the agreement did vary in the two periods that were considered. In the first period I (14 October-24 November, 1999; around neap tide with relatively high waves and wind) occasionally large deviations between the predictions and measurements were observed. These deviations are believed to be caused by the fact that the overall HCZ-model grid, in which the PIT-model was nested, was unable to accurately account for (high) wind speeds. The second period II (14 December 1999-14 January 2000; around spring tide with low waves and wind) was reproduced accurately.
In the 2DH-simulations the effect of waves, wind and salinity was limited. The tidal forcing appeared to be dominant at the pit site. It has to be stressed however that especially wind effects are under-estimated in the present model set-up. The comparison with the flow track measurements showed that the model was capable of reproducing the current velocities with reasonable accuracy. The deceleration of the flow across the long axis of the pit was represented well, especially during the ebb measurements. However, during flood the deceleration was under-estimated in comparison with the flow tracks on the southern slope. This under-estimation is mainly caused by the 2DH approximation as the 3D simulations were able to model this phenomenon. Because the tracks were sailed during maximum flood and ebb, small errors in the phase could also result in deviations, especially during flood which has a characteristic peaked character. The error statistics show that the trends in water level predictions are reasonable with correlation coefficients of 0.76 and 0.97 for Periods I and II 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 0.18 m/s for the longshore velocities and between 0.06 and 0.09 m/s for the cross-shore velocities.

**DELFT3D model results**

The DELFT3D model was capable of reproducing the 3D character of the flow accurately. The vertical distribution of the residual velocities was reproduced well. The northward residual velocities in the upper layers and the southward residual velocity near the bed were also predicted by the model for Period I. For Period II the longshore residual velocities agreed well near the bed, but higher in the water column significant deviations were present. The relative short time period over which the residual were determined is probably the main cause of this deviation. The cross-shore residual velocities agreed well for this period. The statistical analysis showed that the correlation for the longshore velocities was comparable to the results of the 2DH-simulations. As was the case for the 2DH-simulations, the 3D cross-shore velocities had lower correlations compared to the longshore statistics. Moreover, the correlation for the cross-shore velocities did show relative large variation across the vertical whereas for the longshore velocities this parameter was approximately constant. The Relative Error Vector also had an approximate constant vertical distribution for both periods with an average value of 0.5 to 0.54 for Period I and 0.28 to 0.31 for Period II. This characterises the model performance as ‘reasonable’ and ‘good’ for Periods I and II respectively. The 3D-model showed good agreement with the flow track measurements. In all cases the vertical distribution of the longshore velocities was represented well. The cross-shore velocities often had a complex character with opposite velocity directions in the upper and lower layers, this was reproduced remarkably well by the 3D-model. For most tracks the Relative Error Vector was in the range of 0.20 to 0.25, which classifies the predictions as ‘good’.

**Morphodynamic model results**

The morphodynamic evaluation, based on a 2DH simulation with representative tidal, wind and wave forcing, showed a reasonable agreement with the sedimentation-erosion patterns derived from the bathymetric surveys. As the measured morphological development only consider a relatively short period of about 1 year with considerable uncertainties, an unambiguous conclusion regarding the morphological predictive capabilities of the Delft3D could not be drawn.

The morphodynamic sensitivity analysis revealed some significant differences between the results obtained in 2DH and 3D-mode. In general the morphological changes were larger in
3D. Especially the flattening of the seaward pit slope was significantly larger in the 3D simulations. This is mainly caused by onshore transports in this region due to secondary onshore currents. Furthermore, the residual longshore transports south of the pit and on the southern slope of the pit were larger in 3D. This is mainly attributed to flow contraction effects. The quality of these predictions can not be evaluated properly due to the lack of a reliable measured morphological development. The differences between the 2DH and 3D morphodynamic simulations on the considered time scale of one year are limited.

Conclusions

The hydrodynamic and morphodynamic effects of extraction pits (various cases in USA, UK, Canada and The Netherlands) at various depths in the nearshore coastal zone have been studied by using wave refraction, flow, sand transport and shoreline change models. The wave climate at and inshore of the extraction area is affected (reduced wave heights). The flow patterns outside the extraction area are modified over a distance of maximum twice the width and length of the extraction area. In particular, the deceleration and acceleration flows on the slopes of the pit are affected. The wave transformation and flow patterns can be simulated quite well provided that the boundary conditions at the model inlet are accurately known. The DELFT3D-model (based on PUTMOR-case) can represent these phenomena with reasonable accuracy, although these phenomena were generally slightly underestimated by the model. However, the application of the DELFT3D model resulted in a significant increase of the accuracies involved (better agreement between measured and computed velocities).

As regards morphodynamics, the cross-shore morphological changes are relatively small for pits beyond the 15 m depth contour; the migration rates are mainly affected by the local water depth and not by the pit dimensions (depth, width, length). The migration velocity of the pit in longshore direction was found to be 10 to 15 m/year. The morphological changes remain within the local surrounding of the pits. On the time scale of 100 years the overall longshore migration of the pit is of the order of 1 to 2 km. The sedimentation of the pit (infilling rate) increases strongly with decreasing water depth outside the pit. The modelling of morphodynamics is not yet very accurate due to the absence of accurate field data of sand transport processes. In the absence of such data the uncertainty margins are relatively large (up to factor 5).

The presence of a sand pit results in the formation of circulation cells which may trigger the development of a sandbank pattern (based on stability analysis studies). As time evolves, the sand bank pattern spreads out and migrates, alternatingly generating trough and crest zones. The pit itself deepens and the pattern spreads at a rate of 10 to 100 m/year. The migration rate of the centre of the pit is of the order of 1 to 10 m/year.

Beach erosion in the lee area of the pit was found to increase with increasing pit depth and with decreasing original water depth. It can be concluded that extraction pits beyond the 15 m depth contour do not lead to any significant shoreline erosion.
4 Results of state-of the art DELFT3D model

4.1 Introduction

An important part of the present study is to assess the performance of morphological Delft3D-Online model to predict the morphological development and impact of sand mining pits, trenches and sand banks in relative deep water (~ 20 m). This assessment was worked out for a number of laboratory and field experiments which were used to perform a detailed validation of the latest DELFT3D-Online model version. This Delft3D model was upgraded with the TRANSPOR2004 transport formulations. The most important improvements involve the refinement of the predictors for the bed roughness and the suspended sediment size. Up to now these parameters had to be specified. As a consequence of the use of predictors for bed roughness and suspended sediment size, it was necessary to recalibrate the reference concentration of the suspended sediment concentration profile. Furthermore, some other minor improvements were implemented, such as the option to prescribe a constant wave over the entire flow domain without having to use a wave model. Detailed information on the recent improvements can be found in Van Rijn et al. (2004). As the upgrade of Delft3D and the subsequent validation were jointly funded by Rijkswaterstaat (the present project) and the European Union (through the Sandpit project) benchmark tests available within the Sandpit project were also used for the validation of the present version. Note that the transport formulations in the Sutrench and Unibest-TC models have also been updated. However, this model is not evaluated in this report.

The cases considered with the upgraded Delft3D model are the benchmark tests which are also used in the Sandpit project:

Laboratory cases
- Test 1: trench normal to flow and parallel to waves in basin;
- Test 2: trench normal to flow and waves in flume;

Field cases
- Test 3: Scheveningen trench in North Sea, The Netherlands.
- Test 4: 2nd PUTMOR pit in North Sea, The Netherlands.
- Test 5: Artificial Sand Dam in North Sea, The Netherlands.

In the next section the validation methodology is described in detail, followed by discussion of the model results for the above listed experiments. Finally, conclusions are drawn regarding the applicability of the Delft3D model.

4.2 Validation Methodology

A model validation on the morphological development of trenches or mining pits should provide insight in the quality of the predictions of sediment transport and the morphological behaviour of the trench or pit (sedimentation and migration). In many validation studies
there is often a tendency to focus on the back filling of the trench or pit only, without providing information on the reliability of the sediment predictors. This occurs due to lack of data (only monitoring of back filling) or because scaling the undisturbed transports (outside the pit) to realistic/measured values results in an unrealistic morphological behaviour of the studied pit. In terms of processes the above implies an assessment of the reliability of the sediment transport rates outside the pit/trench and the sediment transport distribution across a trench/pit. This problem was also recognised in the Sandpit project, where it was decided to make a clear distinction between calibrations using measured sediment transports (A approach) and calibrations using observed morphological changes (B approach).

In the present validation study we have adopted the Sandpit methodology. For the laboratory cases it was possible to apply the A approach which is aimed at scaling the undisturbed (upstream) sediment to measured or realistic values and use these settings to perform morphological validations. For the field experiments there was no (direct) data available, so the B approach is followed. However, it is ensured that realistic residual transports are used based on literature or measurements in comparable circumstances:

- **Laboratory Cases:** A approach - as measured sediment transport rates were available upstream of the trench, these can be used to scale the simulated transport rates.
- **Field cases (Scheveningen, 2nd PUTMOR and Sand Dam case):** B approach - no transport measurements were available to scale the simulated transports. In stead the models were scaled to measured transports at Noordwijk (Scheveningen) or it was checked that the calculated transports were within ranges reported in literature (2nd PUTMOR and Sand Dam).

To assess the model performance we will be using the following parameters (see Walstra and Ruessink, 2001) for more detail on the statistic parameters:

- **Volumes:** initial, measured and calculated volumes will be used as a measure of the back filling of the trenches/pits.
- **Centre of gravity (centroid):** The horizontal and vertical coordinates will be compared as a measure of the migration.
- **Correlation:** (0: no correlation, 1 perfect correlation).
- **Best-fit slope forced through the origin:** (m>1: over-prediction of sedimentation, m<1 under-prediction).
- **Root-Mean-Square Error:** RMSE (0: perfect prediction)
- **Brier Skill Score:** perfect agreement gives a BSS of 1 whereas modelling the baseline condition gives a score of 0. If the model prediction is further away from the final measured condition than the baseline prediction, the skill score is negative. This skill score is reduced for errors in the prediction of amplitude, phase and mean. It provides an objective measure of model performance. The baseline prediction for morphodynamic modelling will usually be that the bed remains unaltered. In other words the initial bathymetry is used as the baseline prediction for the final bathymetry. This means that the BSS is not altered by the inclusion of an inactive (usually offshore) region in the model. Simple correlation coefficients between predicted and measured final bathymetries would be increased by the inclusion of an inactive area. Their value would depend on how large an area is included in the modelling. The Brier Skill Score was applied extensively in the Coast3D-project where it was used to assess morphodynamic models in the surf zone and tidal inlets (Van Rijn et al., 2002 and Sutherland et al.,
Moreover, Van Rijn et al. (2003) provides a table (see Table 4.1 below) which links the BSS to a general quality characterisation.

<table>
<thead>
<tr>
<th>Qualification</th>
<th>Brier Skill Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Excellent</td>
<td>1.0 – 0.8</td>
</tr>
<tr>
<td>Good</td>
<td>0.8 – 0.6</td>
</tr>
<tr>
<td>Reasonable/Fair</td>
<td>0.6 – 0.3</td>
</tr>
<tr>
<td>Poor</td>
<td>0.3 – 0.0</td>
</tr>
<tr>
<td>Bad</td>
<td>&lt;0.0</td>
</tr>
</tbody>
</table>

Table 4.1 Qualification or error ranges for the Brier Skill Score (after Van Rijn et al., 2003).

### 4.3 Laboratory cases

For both laboratory experiments simple 2DV models were constructed to simulate the longitudinal centre line of the flumes. For both cases an upstream velocity boundary and a downstream water level boundary were used. For both cases a limited number sensitivity runs were carried out to test the performance of the TRANSPOR2004 formulations for sediment mixing, the suspended sediment diameter and roughness heights. For each run the transports were scaled to the measured upstream values.

#### 4.3.1 Test 1: Trench normal to flow and parallel to waves in basin

The experiment has been carried out in a wave-current basin. A channel (width of 4 m) with a sediment bed consisting of fine sand (0.1 mm) was made at the end of the basin. The bed surface was at the same level as the cement floor of the surrounding basin. Irregular waves were generated by a directional wave generator. The wave spectrum (JONSWAP form) was single-topped with a peak frequency of 0.4 Hz. The water depth was about 0.4 m in all tests. Three wave directions were considered 60°, 90° and 120° (angle between wave orthogonal and current direction). Three significant wave heights 0.07, 0.1 and 0.14 m have been used for each wave direction. A pump system was used to generate a current in the channel. Guiding boards were used to confine the current in the movable-bed channel (width 4 m). The guiding boards were placed normal to the wave crests in all experiments to allow free passage of the waves. Three different current velocities (0.1, 0.2 and 0.3 m/s) were generated by varying the pump discharge. The velocity distribution across the channel was found to be almost uniform (current alone). The vertical distribution of the velocity in the middle of the channel was perfectly logarithmic in all tests (current alone). The vertical distribution of the turbulence intensity was found to be in good agreement with values reported in the literature (current alone). The basic data are given in Table 4.2.
Experiment in basin

<table>
<thead>
<tr>
<th>Inlet conditions</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water depth $h_0$ (m)</td>
<td>0.42</td>
</tr>
<tr>
<td>Approach angle $\alpha_0$ (degrees)</td>
<td>90</td>
</tr>
<tr>
<td>Flow velocity $v_a$ (m/s)</td>
<td>0.245</td>
</tr>
<tr>
<td>Wave height $H_s$ (m) and period $T_p$ (s) normal to flow direction</td>
<td>0.105; 2.2</td>
</tr>
<tr>
<td>Sediment size $d_{50}, d_{90}$ (fine sand in mm)</td>
<td>0.1; 0.13</td>
</tr>
<tr>
<td>Fall velocity of sand (mm/s)</td>
<td>6</td>
</tr>
<tr>
<td>Sediment transport (in kg/ms)</td>
<td>0.022</td>
</tr>
<tr>
<td>(in m$^3$/m, dry solid volume during 25.5 hrs)</td>
<td>0.75</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Channel dimensions</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water depth in channel $h_1$ (m)</td>
<td>0.62</td>
</tr>
<tr>
<td>Bottom width (m)</td>
<td>0.5</td>
</tr>
<tr>
<td>Top width (m)</td>
<td>4</td>
</tr>
<tr>
<td>Slope</td>
<td>1:8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sedimentation values</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sedimentation layer thickness (m)</td>
<td>0.15</td>
</tr>
<tr>
<td>Sedimentation area (cross-channel, dry bulk volume in m$^3$/m, including pores)</td>
<td>0.35</td>
</tr>
<tr>
<td>Sedimentation period (hours)</td>
<td>25.5</td>
</tr>
</tbody>
</table>

Table 4.2 Channel and sedimentation characteristics for Test 1.

The computational grid has a resolution of 0.10 m in the area in the vicinity the trench which increases up to 0.40 m at the distal ends to minimise the number of grids and thus the computational time, see Figure 4.1. The computational grid size in y-direction (transverse) has been set to 0.50 m. The grid is smoothed in longitudinal direction in order to minimise truncation errors in the finite difference scheme. In vertical direction the grid consists of 10 layers with a high resolution near the bed which decreases towards the water surface. The flow model is driven by an upstream current boundary and a downstream water level boundary. The model uses the relevant measured parameters listed in the table above an overview of the main model parameters is given in Table 4.3.

![Figure 4.1 Computational grid and initial bottom profile for Test 1.](image-url)
<table>
<thead>
<tr>
<th><strong>Model dimensions</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>13.0 to 26.0 [m]</td>
</tr>
<tr>
<td>Grid resolution (horizontal)</td>
<td>0.10 [m]</td>
</tr>
<tr>
<td>Number of layers (vertical)</td>
<td>10 [-]</td>
</tr>
<tr>
<td>Time step</td>
<td>300 [s]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Hydrodynamic boundary conditions</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Water depth at inlet, $h_0$</td>
<td>0.42 [m]</td>
</tr>
<tr>
<td>Discharge, $Q$</td>
<td>0.1082 [m$^3$/s]</td>
</tr>
<tr>
<td>Wave height, $H_s$</td>
<td>0.105 [m]</td>
</tr>
<tr>
<td>Wave period, $T_z$</td>
<td>2.16 [s]</td>
</tr>
<tr>
<td>Wave direction, Dir</td>
<td>90° (with respect to the current direction)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Sediment characteristics</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Median grain size, $d_{50}$</td>
<td>0.1 [mm]</td>
</tr>
<tr>
<td>90% grain size, $d_{90}$</td>
<td>0.13 [mm]</td>
</tr>
<tr>
<td>Sediment fall velocity, $w_s$</td>
<td>TR2004</td>
</tr>
<tr>
<td>Ripple height and length</td>
<td>TR2004</td>
</tr>
<tr>
<td>Reference level, $z_a$</td>
<td>TR2004</td>
</tr>
<tr>
<td>Wave-related roughness height, $r_w$</td>
<td>TR2004</td>
</tr>
<tr>
<td>Current-related roughness height, $r_c$</td>
<td>TR2004</td>
</tr>
</tbody>
</table>

Table 4.3 Model settings for Test 1.

In Table 4.4 an overview is given of the simulations carried out for Test 1. In total 5 simulations were made to investigate the effects of the improved TRANSPOR2004 formulations. For each model run the transports were scaled with the factors listed in the second column to match the upstream measured values. The base run is H02 which uses all the defaults according to TR2004. Delft3D can either use the vertical sediment mixing parameterization of TR2004 or use the k-$\varepsilon$, this was tested in run H01. The sediment fall velocity is an important parameter which determines the amount of sediment in suspension and as a consequence the back filling of the trench. The fall velocity is determined by the median diameter of the suspended sediment, $D_{sus}$, for which TR2004 has a predictor. This predictor is used in run H02 and a commonly applied setting: $D_{sus} = 0.8D_{50}$ was used in run H03. To compare the roughness predictor of TR2004 (run H02), a simulation was carried out with a roughness height equal to the measured ripple height (H04). Finally, a simulation was executed with TR1993 formulations with default settings (run H05).
Table 4.4 Main model settings used in the sensitivity runs for laboratory case Test 1.

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Scaling Factor</th>
<th>Transport Form.</th>
<th>Sediment Mixing Coeff.</th>
<th>Sediment Fall Velocity</th>
<th>Roughness</th>
</tr>
</thead>
<tbody>
<tr>
<td>H01</td>
<td>1.49</td>
<td>TR2004</td>
<td>k-ε</td>
<td>TR2004</td>
<td>TR2004</td>
</tr>
<tr>
<td>H02</td>
<td>1.05</td>
<td>TR2004</td>
<td>TR2004</td>
<td>TR2004</td>
<td>TR2004</td>
</tr>
<tr>
<td>H03</td>
<td>0.78</td>
<td>TR2004</td>
<td>TR2004</td>
<td>$D_{SUS} = 0.8D_{50}$</td>
<td>TR2004</td>
</tr>
<tr>
<td>H04</td>
<td>1.61</td>
<td>TR2004</td>
<td>TR2004</td>
<td></td>
<td>$r_c = r_w = 0.01 m$</td>
</tr>
<tr>
<td>H05</td>
<td>4.20</td>
<td>TR1993</td>
<td>TR1993</td>
<td>$D_{SUS} = 0.8D_{50}$</td>
<td>$r_c = r_w = 0.01 m$</td>
</tr>
</tbody>
</table>

In Figure 4.2 the resulting morphological developments are compared for simulations listed above. From the comparison it apparent that when scaling the transports to measured values the model gives a satisfactory agreement for all model settings. This is confirmed by the statistic parameters shown in Figure 4.1. For most settings the volume decrease was predicted well and a relative high correlation (>0.8) was generally found. The averaged RMS-error is about 0.015-0.020 m which is less than 10 % of the initial pit depth. According to the qualifications in Table 4.1 the Brier skill scores of all simulations can be characterised as ‘excellent’ having values higher than 0.8. This mainly illustrates the robustness and accuracy of the advection-diffusion solver in Delft3D. So by using calibrated transports the modification of transport settings (for TR2004) only has a limited effect on the morphological development. This implies that the scaling factors listed in Table 4.4 above are the main arbitrators for the quality assessment of the TR2004 transport formulation. Comparison of these factors shows that TR2004 gives the best prediction having a scaling factor closest to one. Note that after having discussed Test 2 we will give a comprehensive discussion on the performance of TR2004 in Delft3D.
Figure 4.2  Morphological development of trench for Test 1. Top: comparison using different sediment mixing relations, Second: TR2004 suspended sediment size predictor vs. constant factor, Third: TR2004 roughness predictor vs. prescribed roughness height, Bottom: comparison of transport formulations TR2004 vs. TR1993.
### 4.3.2 Test 2: Trench normal to flow and waves in flume

An experiment in a flume (length= 17 m, width= 0.3 m, depth= 0.5 m) was carried out concerning the migration and sedimentation of a channel perpendicular to the current direction; (following) waves were superimposed on the current (see also Table 4.5). The experimental set up is shown in Figure 4.4. The sand bed ($d_{50}$= 0.1 mm and $d_{90}$= 0.13 mm) had a thickness of about 0.2 m. A channel with side slopes of 1:10 and a depth of 0.125 m was excavated in the sand bed. The water depth and current velocity upstream of the channel were $h= 0.255$ m and $u = 0.18$ m/s. Regular waves with a period of 1.5 s were generated by a simple wave paddle, which was perforated to allow the passage of the current. The wave height upstream of the channel was 0.08 m. Wave height measurements in the channel showed an irregular pattern with (small) local wave height variations, probably as a result of secondary waves generated by the wave paddle and the bottom variations in the channel. To maintain equilibrium conditions (no scour or deposition) upstream of the channel, sand of the same size and composition as the bed material was supplied at a constant rate of 0.0167 kg/sm. Ripples with a height in the range of 0.01 to 0.02 m and a length in the range of 0.05 to 0.08 m were generated at the surface of the sand bed. Current velocities were measured by using an acoustic Doppler method. Sand concentrations were determined from water samples collected by use of a siphon system at various locations in the center line of the flume. Analysis of the suspended sand samples showed particle sizes in the range of 0.11 mm (near the bed) to 0.08 mm (near the water surface). The corresponding particle fall velocities are in the range of 0.01 m/s to 0.005 m/s
(water temperature of 17 °C).

Figure 4.4  Flume experiment on sedimentation in a trench in combined current and wave conditions.

<table>
<thead>
<tr>
<th>Experiment in flume</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Inlet conditions</strong></td>
</tr>
<tr>
<td>Water depth $h_o$ (m)</td>
</tr>
<tr>
<td>Approach angle $a_o$ (degrees)</td>
</tr>
<tr>
<td>Flow velocity $v_o$ (m/s)</td>
</tr>
<tr>
<td>Wave height $H_s$ (m) and period $T_p$ (s) normal to flow direction</td>
</tr>
<tr>
<td>Sediment size $d_{50}$, $d_{90}$ (fine sand in mm)</td>
</tr>
<tr>
<td>Fall velocity of sand (mm/s)</td>
</tr>
<tr>
<td>Sediment transport (in kg/ms)</td>
</tr>
<tr>
<td>(in m$^3$/m, dry solid volume during 25.5 hrs)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Channel dimensions</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Water depth in channel $h_1$ (m)</td>
</tr>
<tr>
<td>Bottom width (m)</td>
</tr>
<tr>
<td>Top width (m)</td>
</tr>
<tr>
<td>Slope</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Sedimentation values</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Sedimentation layer thickness (m)</td>
</tr>
<tr>
<td>Sedimentation area (cross-channel, dry bulk volume in m$^3$/m, including pores)</td>
</tr>
<tr>
<td>Sedimentation period (hours)</td>
</tr>
</tbody>
</table>

Table 4.5 Channel and sedimentation characteristics for Test 2.

The model grid for Test 2 is based on similar considerations and has a comparable resolution as for Test 1 and is not shown here. Also the relevant parameters are again obtained from the physical experiment, see also the table below.
Model dimensions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>5.0 to 25.0 [m]</td>
</tr>
<tr>
<td>Grid resolution (horizontal)</td>
<td>0.05 [m]</td>
</tr>
<tr>
<td>Number of layers (vertical)</td>
<td>10 [-]</td>
</tr>
<tr>
<td>Time step</td>
<td>150 [s]</td>
</tr>
</tbody>
</table>

Hydrodynamic boundary conditions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water depth at inlet, ( h_0 )</td>
<td>0.255 [m]</td>
</tr>
<tr>
<td>Mean current velocity at inlet, ( u_0 )</td>
<td>0.18 [m/s]</td>
</tr>
<tr>
<td>Wave height, ( H )</td>
<td>0.08 [m]</td>
</tr>
<tr>
<td>Wave period, ( T )</td>
<td>1.5 [s]</td>
</tr>
<tr>
<td>Wave direction, ( \text{Dir} )</td>
<td>0° (with respect to the current direction)</td>
</tr>
</tbody>
</table>

Sediment characteristics

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Median grain size, ( d_{50} )</td>
<td>0.1 [mm]</td>
</tr>
<tr>
<td>90% grain size, ( d_{90} )</td>
<td>0.13 [mm]</td>
</tr>
<tr>
<td>Sediment fall velocity, ( w_s )</td>
<td>TR2004</td>
</tr>
<tr>
<td>Reference level, ( z_a )</td>
<td>TR2004</td>
</tr>
<tr>
<td>Wave-related roughness height, ( r_w )</td>
<td>TR2004</td>
</tr>
<tr>
<td>Current-related roughness height, ( r_c )</td>
<td>TR2004</td>
</tr>
</tbody>
</table>

Table 4.6 Model settings for Test 2.

In Table 4.7 an overview is given of the simulations carried out for Test 2. The same runs were carried out as for Test 1, so again 5 simulations were made to investigate the effects of the improved TRANSPOR2004 formulations. For each model run the transports were scaled with the factors listed in the second column to match the upstream measured values. The base run is G02 which uses all the defaults according to the TR2004. Delft3D can either use the vertical sediment mixing parameterization of TR2004 or use the \( k-\varepsilon \), this was tested in run G01. The sediment fall velocity is an important parameter which determines the amount of sediment in suspension and as a consequence the back filling of the trench. The fall velocity is determined by the median diameter of the suspended sediment, \( D_{\text{sus}} \), for which TR2004 has a predictor. This predictor is used in run G02 and a commonly applied setting: \( D_{\text{sus}} = 0.8D_{50} \) was used in run G03. To compare the roughness predictor of TR2004 (run G02), a simulation was carried out with a roughness height equal to the measured ripple height (run G04). Finally, a simulation was executed with TR1993 formulations with default settings (run G05).
Table 4.7 Main model settings used in the sensitivity runs for laboratory case Test 2.

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Scaling Factor</th>
<th>Transport Form.</th>
<th>Sediment Mixing Coeff.</th>
<th>Sediment Fall Velocity</th>
<th>Roughness</th>
</tr>
</thead>
<tbody>
<tr>
<td>G01</td>
<td>3.34</td>
<td>TR2004</td>
<td>TR2004</td>
<td>TR2004</td>
<td>TR2004</td>
</tr>
<tr>
<td>G02</td>
<td>1.59</td>
<td>TR2004</td>
<td>TR2004</td>
<td>TR2004</td>
<td>TR2004</td>
</tr>
<tr>
<td>G03</td>
<td>1.26</td>
<td>TR2004</td>
<td>TR2004</td>
<td>TR2004</td>
<td>TR2004</td>
</tr>
</tbody>
</table>
| G04        | 0.62           | TR2004          | TR2004                 | TR2004                 | $r_c = 0.02m$  
$r_w = 0.035m$  |
| G05        | 2.32           | TR1993          | TR1993                 | $D_{SUS} = 0.8D_{50}$  | $r_c = 0.02m$  
$r_w = 0.035m$  |

A typical result is shown in Figure 4.5 where simulations using different sediment mixing coefficient are compared. The top plot compares the suspended transports across the trench with measurements and the bottom plot compares the morphological development. The transports of both simulations compare reasonably well with the measured transports upstream of the trench which is due to the scaling of the transports. Across the trench the sediment mixing based on TR2004 gives better agreement with the measurements. This is also reflected in the predicted trench development. The migration of the trench and the sedimentation of the trench is predicted more accurately when using the sediment mixing of TR2004. In Figure 4.6 the statistic parameters are shown for all the simulations listed above. From these parameters it is clear that all simulations, providing that the upstream sediment transports are scaled, give a reasonable estimate of the predicted morphology. The Brier skill score indicates that apart from the run G01 which uses the k-ε for the sediment mixing, which has a ‘good’ qualification, all other simulations can be characterized as ‘excellent’. However, the sedimentation of the trench is under-estimated by all simulations. This is mainly due to the fact that the erosion of the downstream slope is over-estimated. The satisfactory agreement of all simulations implies, as was the case for Test 1, that the scaling factors listed in Table 4.7 above are the main arbitrators for the quality assessment of the TR2004 transport formulation. Comparison of these factors shows that run G03 using $D_{SUS} = 0.8D_{50}$ in stead of the TR2004 predictor for $D_{sus}$ gives the best prediction having a scaling factor closest to one. Simulation G02 which uses TR2004 for all predictors only has a third ranking. However a scaling factor 1.56 is still an acceptable value.
Figure 4.5 Initial transports along the trench and a comparison of the profile development for Test 2 with TR2004 using different sediment mixing relations.
4.3.3 Model performance for Laboratory benchmark tests

To give an indication of the robustness of the prediction we calculated the ratios of the scaling factors for Tests 1 and 2. The ideal case would be to have a ratio of 1 (and have scaling factors of 1).

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Varied Parameter</th>
<th>Scaling Factors</th>
<th>Ratio of Scaling Factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>#01</td>
<td>k-ε</td>
<td>1.49 3.34</td>
<td>0.4</td>
</tr>
<tr>
<td>#02</td>
<td>TR2004</td>
<td>1.05 1.59</td>
<td>0.7</td>
</tr>
<tr>
<td>#03</td>
<td>$D_{sus} = 0.8D_{50}$</td>
<td>0.78 1.26</td>
<td>0.6</td>
</tr>
<tr>
<td>#04</td>
<td>Fixed $r_c$ &amp; $r_w$</td>
<td>1.61 0.62</td>
<td>2.6</td>
</tr>
<tr>
<td>#05</td>
<td>TR1993</td>
<td>4.20 2.32</td>
<td>1.8</td>
</tr>
</tbody>
</table>

Table 4.8 Summary of scale factors and the ratios of the scaling factors for Tests 1 and 2.
From the ratios it is very clear that TR2004 is a much more robust transport predictor than TR1993 (Compare runs #02 and #05). Also the TR2004 roughness predictor and the sediment mixing parameterization result in a more robust prediction if the ratios for these simulations are compared. The suspended sediment size predictor does not have such a big influence.

### 4.4 Field cases

The field cases selected for the validation of Delft3D are all located off the coast near Scheveningen. This provided a unique opportunity to set-up a consistent validation approach for all three validation cases (Artificial Sand Dam Hoek van Holland, Schevening trial trench, 2nd PUTMOR pit). At the base of this approach lies a large scale model of the Dutch coast called the Holland Coastal Zone (HCZ, see Figure 4.7) model (Roelvink et al., 2001). This model is used to provide boundary conditions for smaller scale models zooming in on the three validation cases. A similar approach was followed for a very successful hydrodynamic validation study in the same area using field data from the PUTMOR experiment (Walstra et al., 2003). Detailed information of the local model schematisations can be found in the following sub-sections.
4.4.1 Artificial Sand dam Hoek van Holland, The Netherlands

General

From 1982 to 1986 dumpings at Hoek van Holland created an artificial sand ridge, known as Artificial Sand Dam Hoek van Holland, of about 3600 m normal to the peak tidal current and the shore, (location Hoek van Holland, see Figure 4.8) in an area with depths between 15 m. and 23 m. located North of the Euro-Maas channel (access channel to Rotterdam Harbour). In all, 3.5 million m3 sand was dumped over the period 1981 to 1986 (Woudenberg, 1996).

The Sand Dam Hoek van Holland is used for an extensive validation study of Delft3D to simulate banks in deeper water. The work presented here is largely based on the (forthcoming) Msc.-thesis of P.K. Tonnon. First a brief overview is given of the data, followed description of the modelling approach and this sub-section is concluded by discussion on the validation results.

![Figure 4.8 Location sand dump Hoek van Holland.](image)

The ridge dimensions just after creation of the bar were: length of about 3600 m; toe width between 250 m and 370 m; height between 1.3 and 4 m; slopes between 1:50 and 1:100 on the south flank and between 1:20 and 1:50 on the north flank; d50 between 0.15 mm and 0.45 mm. The landward end of the ridge is about 6300 m from the shoreline.

The Sand Dump Hoek van Holland was created to study different morphological processes and investigate possible utilizations of submerged sandbars. It is located close to Loswal Noord, which is a dumping site for class I and II silt from the harbour of Rotterdam. The bar is perpendicular to the coast and thus normal to the tidal flow. Primary goals (at the time of
construction) were to study the stability of a submerged bar, normal to the tidal flow and to study the effect on shoreface sand transport. Also the possible use of submerged bars as silt traps for backflow of silt from Loswal Noord to the port of Rotterdam was an issue. Furthermore similarities with sandwaves were to be investigated.

Since 1982 yearly bathymetric surveys were carried out by Directorate North Sea (DNZ). Soundings before 1991 were not available on tape and were digitized from maps or microfilm. Data collection before 1991 was carried out with the less-accurate singlebeam method, while data collection after 1991 was carried out with the more accurate multibeam method. Table 4.9 below gives an overview of the soundings.

<table>
<thead>
<tr>
<th>sounding</th>
<th>date</th>
<th>year</th>
<th>method</th>
<th>ship</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8 and 9th of September</td>
<td>1982</td>
<td>single-beam</td>
<td>unknown</td>
</tr>
<tr>
<td>2</td>
<td>16, 17 and 18th of February</td>
<td>1983</td>
<td>single-beam</td>
<td>unknown</td>
</tr>
<tr>
<td>3</td>
<td>4, 5, 10, 11 and 14th of June</td>
<td>1985</td>
<td>single-beam</td>
<td>unknown</td>
</tr>
<tr>
<td>4</td>
<td>12 and 23th of Dec. 25, 26th of Jan.</td>
<td>1985/86</td>
<td>single-beam</td>
<td>unknown</td>
</tr>
<tr>
<td>5</td>
<td>14, 15 and 18th of March</td>
<td>1991</td>
<td>multi-beam</td>
<td>Octans</td>
</tr>
<tr>
<td>6</td>
<td>9, 10,16 and 17th of April</td>
<td>1992</td>
<td>multi-beam</td>
<td>Octans</td>
</tr>
<tr>
<td>7</td>
<td>5, 8 and 9th of March</td>
<td>1993</td>
<td>multi-beam</td>
<td>Octans</td>
</tr>
<tr>
<td>8</td>
<td>22, 29 of April 2nd of May</td>
<td>1994</td>
<td>multi-beam</td>
<td>Octans</td>
</tr>
<tr>
<td>9</td>
<td>1, 2, 3 and 4th of May</td>
<td>1995</td>
<td>multi-beam</td>
<td>Octans</td>
</tr>
<tr>
<td>10</td>
<td>22 March, 16 and 17 April</td>
<td>1996</td>
<td>multi-beam</td>
<td>Octans</td>
</tr>
<tr>
<td>11</td>
<td>20, 21 and 22 of August</td>
<td>1997</td>
<td>multi-beam</td>
<td>Octans</td>
</tr>
<tr>
<td>12</td>
<td>5, 13, 16, 17 and 19 October</td>
<td>2000</td>
<td>multi-beam</td>
<td>Octans</td>
</tr>
</tbody>
</table>

Table 4.9 Soundings carried out at the Sand dump Hoek van Holland by Directorate North Sea (DNZ).

The Institute for Coastal and Marine Management (RIKZ) provided two datasets, the first dataset contains the surveys from 1982 to 1997 and the second dataset covers the period 1991 to 2000. The dataset with soundings from 1982 to 1997 originates from research by Woudenberg (1996), while the second dataset, including the sounding in 2000, was directly obtained from the “Iodingen” database of RIKZ. The sounding in 2000 also includes several large pits that were dredged within the framework of the PUTMOR project, which will be discussed in the next section. In the first dataset, the single beam soundings before 1991 previously were corrected for differences between singlebeam and multibeam sounding by increasing the datum of these datasets by 0.2 m (Woudenberg, 1996). Comparison of the two datasets shows that the second dataset (1991 to 2000) is somewhat out of line with the first (1982 to 1997), as it is situated about 10 to 15 cm lower.

**Calibration/Validation Approach**

The approach was to calibrate the model on the period from 1986 to 1991 for one transect across the dam and perform validation runs for 1991 to 2000 along this transect. Validation
runs for both periods were carried out at different transects across the dam (See Figure 4.10). To ensure a consistent comparison a number of ray-models were constructed which were all executed with identical settings. The calibrated model settings were also used to perform morphodynamic simulations with the PIT-model (in depth-averaged mode, 2DH) for both the calibration period (1986-1991) and validation period (1991-2000). All models presented in this section obtain their boundary conditions from the HCZ-model.

The presented models all use the TR2004 transport formulations (predictors are included). Furthermore, a constant representative wave is imposed ($H_s = 2.25$ m, $T_p = 6.6$ s, Direction = $315$ °N) in all simulations. The 2DV simulations 10 vertical layers were used with a high resolution near the bed decreasing towards the water surface.

As mentioned above, the PIT-model (Figure 4.9) developed for the hydrodynamic validation with the PUTMOR experiment (Walstra et al., 2003) is also used in the present study. Although the area of interest in Walstra et al. (2003) was focussed on a more offshore located pit (1\textsuperscript{st} PUTMOR pit), the longshore location is approximately the same which has resulted in a high grid resolution covering the artifical sand dam. The PIT-model was driven by harmonic boundary conditions derived from the HCZ-model. The morphological tide was selected based on an optimal representation of residual transports covering a complete neap-spring tidal cycle. This tide was converted into harmonic components which were used as boundary conditions. All Delft3D models were applied without scaling the transports and using the TR2004 transport formulation including the predictors for roughness and suspended sediment diameter.
Figure 4.9  Grid of the PIT model (Walstra et al., 2003).

An overview of the calibration and validation simulations is given in Table 4.10.
<table>
<thead>
<tr>
<th>Run</th>
<th>Purpose</th>
<th>2D or 3D</th>
<th>Tide</th>
<th>Turb. model</th>
<th>Cross-sections or Area</th>
<th>Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>D01</td>
<td>Calibration</td>
<td>2DV</td>
<td>Morph.</td>
<td>k-ε</td>
<td>3</td>
<td>86-91</td>
</tr>
<tr>
<td>D02</td>
<td>Calibration</td>
<td>2DV</td>
<td>NS</td>
<td>k-ε</td>
<td>3</td>
<td>86-91</td>
</tr>
<tr>
<td>D03</td>
<td>Calibration</td>
<td>2DV</td>
<td>Morph</td>
<td>k-ε</td>
<td>3</td>
<td>86-91</td>
</tr>
<tr>
<td>D04</td>
<td>Calibration</td>
<td>2DV</td>
<td>Morph</td>
<td>Alg.</td>
<td>3</td>
<td>86-91</td>
</tr>
<tr>
<td>D05</td>
<td>Calibration</td>
<td>2DV</td>
<td>Morph</td>
<td>k-L</td>
<td>3</td>
<td>86-91</td>
</tr>
<tr>
<td>D06</td>
<td>Validation</td>
<td>2DV</td>
<td>Morph</td>
<td>Alg.</td>
<td>4,5,6</td>
<td>86-91</td>
</tr>
<tr>
<td>D07</td>
<td>Validation</td>
<td>2DV</td>
<td>Morph</td>
<td>Alg.</td>
<td>4,5,6</td>
<td>91-00</td>
</tr>
<tr>
<td>D08</td>
<td>Validation</td>
<td>1DH</td>
<td>Morph</td>
<td>-</td>
<td>3,4,5,6</td>
<td>86-91</td>
</tr>
<tr>
<td>D09</td>
<td>Validation</td>
<td>1DH</td>
<td>Morph</td>
<td>-</td>
<td>3,4,5,6</td>
<td>91-00</td>
</tr>
<tr>
<td>D10</td>
<td>Validation</td>
<td>2DH</td>
<td>Morph</td>
<td>-</td>
<td>Area</td>
<td>86-91</td>
</tr>
<tr>
<td>D11</td>
<td>Validation</td>
<td>2DH</td>
<td>Morph</td>
<td>-</td>
<td>Area</td>
<td>91-00</td>
</tr>
</tbody>
</table>

Table 4.10 Overview of calibration and validation simulations for Sand Dam case.

1) Gives the Run-ID’s. Note that the RUNID can imply more than one simulation (simulations in ray-mode for different transects have identical Run-ID).

2) All simulations apply the TRANSPOR2004 formulation including the predictors for roughness, suspended sediment diameter and sediment mixing. The transports are NOT scaled.

3) Depth-averaged or considering vertical dimension. 1DH and 2DH are depth-averaged simulations in the ray-model and area model, respectively (2DV and 3DV are the 3 dimensional equivalents).

4) Implies tidal schematization, a morphological tide (Morph) and a full neap spring tidal cycles (NS) are considered.

5) Turbulence model: Alg. Implies the algebraic turbulence closure model.

6) Number refers to cross-section number (see Figure 4.10 for locations), area implies the PIT-model.

7) Refers to the simulated periods: 1986 to 1991 (86-91) and 1991 to 2000 (91-00).

First some typical results from the calibration phase are discussed followed by a discussion on the calibration and validation results for both the ray-models and area model.
Figure 4.10 Sand dump Hoek van Holland with grids of the ray-models (ray-models are number 3, 4, 5 and 6 from left to right).

**Calibration Results**

In Figure 4.11 a comparison is made in which a complete neap-spring tidal cycle or a morphological are used. The migration the sand dam with the morphological tide is over-predicted somewhat and the decrease of the top of the dune is over-predicted by both simulations. The enhanced migration with the morphological tide is caused by the stronger gradients of the suspended transports compare to the run with th neap-spring tide. However, also the bed load transports are different. This is caused by the fact that the morphological tide was derived with a uniform bathymetry set to 17.5 m. This illustrates that input reduction itself can have a significant influence. For practical reasons we have kept the morphological tide and used it to perform the remaining simulations. Transports in this region are reported to be 25 m$^3$/m/year with an inaccuracy range of 15 m$^3$/m/year. It can be seen that both model runs predict residual transports within this range. Below we will show that also the choice of turbulence model has a large impact on the final predicted sand bank.
Figure 4.11 Comparison of simulations using a full neap spring tidal cycle and a morphological tide.

In Figure 4.12 a number 2DV simulations are presented which use different turbulence models. From the comparison it becomes clear that the choice of turbulence model has a rather large influence on the final profiles despite the fact that the transports south of the sand dam are very similar. Although the overall migration of the sand dam is similar the height of the dam top is affected. These differences are still subject of investigation, but it seems they are primarily caused by small deviations of vertical velocity distributions which in turn influence the morphological predictions. The results using the algebraic turbulence model are encouraging and show that not only the overall migration is modelled satisfactory, but that the top of the dam is showing an improved agreement with the observations. The height of the dam top is even slightly increasing. Based on these calibration results the algebraic turbulence model is applied in all subsequent 2DV simulations.
Validation Results

Based on the settings derived from the calibration, the different ray-models over the dam were executed for the 1986-1991 and 1991-2000 periods. For each ray-model runs were made in depth-averaged (1DH) and 3D mode (2DV). Furthermore, the PIT-model was also executed for both periods in depth-averaged mode (2DH). Below the results are compared for ray-models 3 and 5 (see also Figure 4.10 for locations). To enable a direct comparison between the ray-models and the PIT-model the latter results have been interpolated to the same transects.

In Figure 4.13 the results are shown for Ray 3, the top plot shows the 1986-1991 period and bottom plot the 1991-2000 period. It can be seen that from 1986 to 1991 the sand dam has a northward migration of about 50 m and that the top of the dam has a more or less constant height. From 1991-2000 the migration is hardly present, but the height of the dam has decreased by about 0.5 m. the 2DV simulation is able to give a fairly accurate representation of the migration of the southern slope and height of the dam. However, the migration of the northern slope is over-estimated. For the second period the 2DV simulation over-estimates the migration and is unable to predict the height decrease of the dam. In both periods the dept-averaged simulations (1DH and 2DH) show a considerable over-estimation of the
decrease of the dam top. The migration is more or less represented, but overall agreement is poor. The same conclusion can be drawn for Ray 5 shown in Figure 4.14. In Figure 4.15 a plan view of the predicted sedimentation-erosion is shown for the simulation covering the period 1991 to 2000. The decay of the top of the dam is present over the complete bar and is over-predicted, as was discussed above. However, the sedimentation patterns show that the shallower part of the dam is migrating northwards, whereas the deeper part of the dam is more or less stable or is even migrating southward. Although the southward migration is probably questionable, the prediction that the morphological behaviour of the dam is different at different depths is consistent with the findings of Woudenberg (1996). There it was stated that in water depths of 15 m to 19 m the dam is migrating northward by about 12 m/year, the region deeper than 19 m is more or less stable.

Figure 4.13   Comparison of 1DH, 2DV and 2DH simulations for Ray 3.
Figure 4.14  Comparison of 1DH, 2DV and 2DH simulations for Ray 5.
Figure 4.15 Predicted sedimentation-erosion for the period 1991-2000.

The overall performance for modelling the artificial sand dam at Hoek van Holland is not satisfactory. Because the results presented here are drawn from research that is still ongoing, it is not yet possible to make any firm conclusions on the model performance. However, the results seem to indicate that the modelling of sand bars will not be able to reach the levels of agreement as for the trenches and pits also shown in this study. The limited level of agreement is probably caused by a combination of several factors, such as:

- Input reduction (i.e. schematisation of wave and tidal climate) seem to have an unacceptable large influence on the final predictions.
- The sediment pick-up due to the combined action of currents and waves seems to be modelled with insufficient accuracy. This can be caused by hydrodynamic predictions or sediment transport formulations.

4.4.2 2nd PUTMOR pit in North Sea, The Netherlands

The second PUTMOR pit was dredged in 1999 to dump silt from the Rotterdam Harbour in it. However, after the dredging of the pit was completed it was not used for several years (until 2003). During this period Rijkswaterstaat performed a number of surveys which are used here for validation of the model. Because there is a large amount of dredging and dumping activities in the area we selected to model the period 2001 to 2002, since the surveys indicated that during this period dredging and dumping was limited.

For the validation study we again used the PIT-model (see also Figure 4.9) developed for the hydrodynamic validation with the PUTMOR experiment (Walstra et al., 2003). Although the pit that was used in Walstra et al. (2003) was different from the pit which of interest in this study, an inspection of the grid showed that the original model-grid had sufficient resolution in and around the second PUTMOR pit. The morphological tide selected for the Artificial Sand near Hoek van Holland validation (see previous section) was applied. Also the same representative wave condition ($H_s = 2.25$ m, $T_p = 6.6$ s, Direction = 315 °N) was
used. The Delft3D model was applied in depth-averaged mode without scaling the transports and using the TR2004 transport formulation including the predictors for roughness and suspended sediment diameter.

The initial depth is shown in Figure 4.16 and the predicted sedimentation-erosion is shown in Figure 4.17. From the sedimentation-erosion patterns it becomes clear that the virtually all changes occur on the slopes of the pit. However, these changes are in the order 10-20 cm. This is also illustrated if a cross-section along the central axis of the pit is compared in Figure 4.20 (cross-section is indicated in Figure 4.16 and Figure 4.17). The plot shows that the model hardly predicts any sedimentation at the bottom of the pits. The only significant changes are at the bar dividing the two pits: its height has decreased by about 0.4 m and its northern flank also experiences some erosion. Although the simulation was from 2001 to 2002, the 2003 profile was also included as the bar between the pits showed the behaviour that was predicted. However, the observed sedimentation at the bottom of the pit was not predicted by the model. This could be due to the fact that the gross and residual transports are under-estimated. However, the residual transports are in line with values reported in literature. The sedimentation can also be caused by the settling of mud in the pits which is not included in the presented simulation results. Furthermore, the measured sedimentation-erosion patterns for 2001/2002 (Figure 4.18) and 2002/2003 (Figure 4.19) reveal that the surveys for the north-eastern pit have significant inaccuracies. The overall sedimentation from 2001 to 2002 (which theoretically could be due to dumping) is followed, from 2002 to 2003, by severe erosion on the slopes and accretion on the pit floor. Since the observed and simulated changes are small (absolute and relative to the accuracy of the surveys) no statistical parameters are presented for this case. Although the morphological developments are small, this case does illustrate the robustness of the numerical scheme for the bed updating. As the bed is been updated every flow time step, the number of bed updates is about 8000 for the simulations presented here. Despite this large number of updates, no visible numerical smoothing has occurred.
Figure 4.16  Initial bathymetry at the Lowered Dump Site (black line indicates reviewed cross-section).
Figure 4.17 Predicted sedimentation (yellow to red) and erosion (blue) after one year (black line indicates reviewed cross-section).

Figure 4.18 Observed sedimentation erosion patterns for 2001-2002.
Figure 4.19 Observed sedimentation erosion patterns for 2002-2003.

Figure 4.20 Comparison of model prediction and observed development along the central axis of the pits.
4.4.3 Scheveningen trench in North Sea, The Netherlands

A trial trench was dredged in the North Sea bed (sand between 0.2 and 0.3 mm) near Scheveningen in March 1964 to obtain information of deposition rates with respect to the construction of a future sewer-pipeline trench (Svasek, 1964). More details on this case can be found in Section 2.4.3 (see Figure 2.6 and Table 2.8). This case was also selected as one of the benchmark cases for the Sandpit project. For the validation two (horizontal) model schematizations were considered: a ray-model across the trench in about 8 m of water (see Figure 4.21) and an area model covering the entire area of interest (see Figure 4.22). Both model grids had an increased resolution in the vicinity of the trench decreasing towards the distal ends. The ray-model was used to perform a large number of sensitivity simulations investigating the effect of changing the boundary conditions for tide and waves. The area model was simulated using the settings of the reference ray-simulation to intercompare the results so as to verify that simplified ray-model was allowed. Furthermore, both models were used in depth-averaged and in 3D (or 2DV) mode. For the latter simulations a vertical grid with 10 layers with a relatively high resolution near the bed was used.

Both models were driven with boundary conditions obtained from the HCZ-model. A tide was selected to give a good estimate of the residual transports in this area. A wave exceedence table was available for the considered period for wave height and wave period. However no directions were measured. This wave exceedence table was correlated to wind measurements to reconstruct a time series of waves (see Klein, 2004). In stead of running the SWAN wave model we assumed the wave to be constant over the modelling domain without inducing any wave driving currents. The stirring influence of the waves was however included. This simplification was adopted to reduce simulation time and since waves are not breaking in the vicinity of the trench it is not thought to have a major influence on the model predictions.

As no transport measurements were available for this case, field data from the Sandpit field campaign at Noordwijk were used to calibrate the sand transports.

Figure 4.21 Overview of the Scheveningen trench and the selected cross-section for the ray-model (Walstra et al., 2004).

Figure 4.22 The area model used for the Scheveningen case.
The study area of the EU-Sandpit field measurements, Sandpit 1, is located 2 km off the coast of Noordwijk aan Zee, The Netherlands (Figure 4.23). Here a representative, natural shoreface environment is found, undisturbed by constructions, pits or navigational channels. Also limited impact of mud transport is expected, because of limited dredging or dumping sites nearby. Furthermore, a permanent measuring platform and a long-term dataset of flow field are available. Measuring efforts are carried out in the same transect as Sandpit measurements to determine mud transport in the Dutch coastal zone. More information and results can be found on the Sandpit web-site (http://sandpit.wldelft.nl). An analysis of measurements performed by Utrecht University which were used in the present study is presented in Tonnion (2003).

Based on this field data, a condition typical for Scheveningen (Hs=1.3 m, Tp=5.5 s, Depth=8 m and longshore velocity=0.6 m/s) resulted in a transport of 0.165 kg/m/s. This condition and transports were used to scale the the transports for all Scheveningen simulations.

In Table 4.11 an overview is given of the executed simulations. In total 7 simulations were made in which: the sediment mixing was varied (S01), the reconstructed wave time series was used (S07), a residual flow of 0.07 m/s was added to the tidal velocity signal (S03), a depth-averaged run was made (S04). To illustrate the effect of the transport scaling, a simulation was carried out with no scaling of the transports (S08). Furthermore, two area model runs in 2DH (S22) and 3D (S33) were made using the settings of reference run (S00). The simulations with the constant wave applied the wave condition used for the transport calibrations. The scaling factors (see Table 4.11) show again that TR2004 gives a fairly good estimate of the measured transports.
<table>
<thead>
<tr>
<th>Simulation</th>
<th>Scaling Factor</th>
<th>Dimensions</th>
<th>Sediment Mixing Coeff.</th>
<th>Wave Climate</th>
<th>Tide</th>
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</thead>
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<tr>
<td>S00</td>
<td>1.56</td>
<td>2DV</td>
<td>TR2004</td>
<td>Constant</td>
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<tr>
<td>S01</td>
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<td>2DV</td>
<td>k-ε</td>
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<td>TR2004</td>
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</tr>
<tr>
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<td>1.56</td>
<td>2DV</td>
<td>TR2004</td>
<td>Constant</td>
<td>With Residual</td>
</tr>
<tr>
<td>S04</td>
<td>1.77</td>
<td>1DH</td>
<td>TR2004</td>
<td>Constant</td>
<td>No Residual</td>
</tr>
<tr>
<td>S08</td>
<td>1.00</td>
<td>2DV</td>
<td>TR2004</td>
<td>Constant</td>
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<tr>
<td>S22</td>
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<td>2DH</td>
<td>TR2004</td>
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</tr>
<tr>
<td>S33</td>
<td>1.56</td>
<td>3D</td>
<td>TR2004</td>
<td>Constant</td>
<td>No Residual</td>
</tr>
</tbody>
</table>

Table 4.11 Main model settings used in the sensitivity runs for laboratory case Test 3.

In Figure 4.25 and Figure 4.26 results are compared for simulations using the k-ε and the TR2004 parameterization for the vertical mixing of sediment. For both settings the model gives a good estimate of the sedimentation of the trench. This is also illustrated by the statistical parameters shown in Figure 4.24. Both simulations have a high correlation and also the position of the centroids (both x and z coordinate) are in good agreement with the measured values. The RMS-error is about 0.20 m which is only 5 % of the initial trench depth. The Brier skill scores are about 0.9 which gives qualifies these simulations as ‘excellent’.

In Figure 4.27 the simulation using the reconstructed wave time series is presented. It can be seen that the sedimentation of the trench is under-estimated. To investigate the cause of this under-estimation the wave height time series are shown in combination with the depth at the centre of the trench in Figure 4.28. From this comparison it is evident that the trench only experiences sedimentation for the higher wave conditions in the time series whereas the sedimentation for the simulation with the constant wave is occurring gradually. The sensitivity of the model for the wave higher wave conditions implies that an accurate prediction can only be made if the reconstructed wave time series is reliable. It is therefore thought that the reconstructed wave time series is the main source of error for the presented simulation. The statistical parameters indicate that this model run still gives a good estimate of the sedimentation of the trench (better than S00 and S01). Furthermore, the Brier skill score also qualifies this simulation as ‘excellent’.

In Figure 4.29 the development of the trench is shown if a residual tidal current of 0.07 m/s is added to the tidal signal. This results in a significant over-estimation of the migration and sedimentation of the trench. This is also reflected by the statistical parameters: the correlation is relatively low (~0.4), the RMS-error has doubled compared to the other simulations and the Brier skill score is relatively low (but is still qualifies this simulation as ‘good’).

The depth-averaged run is shown in Figure 4.30, it illustrates that the description of the advection-diffusion of sediment plays an important role in this 1DH/2DV case. In depth-
averaged mode the Quasi-3D approach of Galappatti (1983) is used in stead of the full 3D a.d.e. when considering the vertical dimension. In depth-averaged mode the trench is almost completely filled up. In Figure 4.31 the results are shown for the simulation where the transports have not been scaled. This results in an (expected) under-estimation of the transports. In fact, it is only the morphological time scale which is now different, running this simulation for about 9 months in stead of 6 (i.e. applying the scaling factor of the reference run) would results in the prediction made by the reference run (S00).

Finally, the results for the area models interpolated along the same cross-section of the ray-models is shown in Figure 4.32. Plan views of the predicted sedimentation-erosion patterns 3D simulations are shown Figure 4.33, in Figure 4.34 the observed sedimentation-erosion patterns are shown. The sedimentation-erosion patterns predicted by the depth-averaged area model are very similar to patterns predicted by the 3D model and are not shown here. It can be seen that the observed infill is comparable to the predicted values. However, the predicted erosion along the outer areas of the trench are not found in the measurements. This is mainly caused by the fact that there is a slight mismatch between the initial bathymetry of the trench and the remaining bathymetry which was obtained from the PIT-model. The comparison along the cross-section (Figure 4.32) shows that the sedimentation seems to be slightly over-estimated but the overall agreement is ‘excellent’ (based on a BSS which is generally larger than 0.9). Interestingly, the agreement in the area model between the depth-averaged and the 3D model is much better than for the ray model (in depth-averaged, 1DH, and 3D, 2DV). It seems that hydrodynamic diffusive processes in the area model are relative important (e.g.: lateral mixing of momentum, cross-shore velocities and flow refraction across the trench).

The simulations for the Scheveningen trench again show that with reliable hydrodynamic boundary conditions and scaling the transports to realistic values a very good estimate can be given of the morphological development of a trench. All the simulations can be qualified ‘excellent’ or ‘good’ with Brier skill scores generally higher than 0.8.
Figure 4.24 Overview of aggregated and statistic parameters for Test 3 (Top Left: Volumes, Top Right: Correlation, Middle Left: Horizontal and vertical centroid coordinates, Middle right: RMS Error, Bottom Left: Best-Fit Slope, Bottom Right: Brier Skill Score).

Figure 4.25 Comparison of the profile development for Test 3 using TR2004 for mixing sediment (Delft3D-mode: 2DV).
Figure 4.26  Comparison of the profile development for Test 3 using k-ε model for the mixing of sediment (Delft3D-mode: 2DV).

Figure 4.27  Profile development for Test 3 using the reconstructed wave climate (Delft3D-mode: 2DV).

Figure 4.28  Time series of wave height (Top) and bottom change in the centre of the trench (red: constant wave condition – Run S00, blue: varying wave condition – Run S07).
Figure 4.29  Profile development for Test 3 with additional residual current of 0.07 m/s (Delft3D-mode: 2DV).

Figure 4.30  Profile development for Test 3 running depth-averaged (1DH) model.

Figure 4.31  Profile development for Test 3 without scaling the transports (Delft3D-mode: 2DV).

Figure 4.32  Comparison of the profile development for Test 3 using the area model in depth-averaged mode (2DH) and in 3D mode.
Figure 4.33 Plan view of sedimentation-erosion patterns predicted by the 3D area model (3D).

Figure 4.34 Plan view of measured sedimentation-erosion (March to August 1964).
5 Summary, conclusions and recommendations

5.1 Summary of Literature Reviews

5.1.1 Literature review results of sediment transport and ecological processes at the shoreface

Sediment transport
An overview of the sediment transport processes in undisturbed marine conditions has been given, focussing on sand and mud transport. Sand can be transported by wind-, wave-, tide- and density-driven currents (current-related transport), or by the oscillatory water motion itself (wave-related transport). The waves generally act as a sediment stirring agent, whereas the sediments are transported by the mean current. Wave-related transport may be caused by the deformation of short waves (wave asymmetry) under the influence of decreasing water depth. Low-frequency waves interacting with short waves may also contribute to the sediment transport process (wave-related transport), especially in shallow water in the surf zone.

In friction-dominated deeper water on the lower shoreface zone the transport process generally is concentrated in a layer close to the sea bed and mainly takes place as bed-load transport in close interaction with small bed forms (ripples). Bed-load transport is dominant in areas where the mean currents are relatively weak compared to the wave motion (small ratio of depth-averaged velocity and peak orbital velocity). Net sediment transport by the oscillatory motion is relatively small in depths larger than 15 m, because the wave motion tends to be more symmetrical in deeper water.

Suspended load transport will become increasingly important with increasing strength of the tide- and wind-driven mean currents due to the turbulence-related mixing capacity of the mean current (shearing in boundary layer). By this mechanism the sediments will be mixed up from the bed-load layer to the upper layers of the flow. On the lower shoreface the suspended sand transport generally is dominant during storm conditions only.

Net annual sand transport rates are in the range of 25 to 75 m$^3$/m/year for the longshore direction and in the range of 0 to 15 m$^3$/m/year for the onshore direction. The maximum sand transport rate at the Noordwijk location during a storm event in Spring 2003 was found to be about 0.1 kg/s/m (or about 5 m$^3$/m/day).

The limit of significant sand transport processes and associated bed level changes (also known as closure depth) defines a limit beyond which no measurable bed level variations due to wave and current motion are assumed to occur (approximately 20 to 25 m based on closure depth concept of Hallermeier, 1981).

The sediments of the North Sea bed contain a few percentage of fines (between 1% and 3 %) in the Dutch coastal zone. The natural flux of fine sediments (size<0.05 mm) in the Dutch sector of the North Sea is concentrated in a relatively narrow coastal zone of about 20
km due to geostrophical effects. The total flux of fine sediments is about $20 \times 10^6$ ton/year or 50,000 ton/day. The mean annual sediment concentration is about 0.1 kg/m$^3$ or 10 mg/l.

The sand mining activities affect the volume, transport and fate of fine grained sediments in the Dutch coastal zone in two ways: (i) large amounts of fines can be mobilised and released in the environment during the sand mining activities and (ii) fine grained sediments may accumulate temporarily or permanently in the resulting deep sand pits in the sea floor.

**Ecological processes**

Sand mining/dredging and dumping have various direct and indirect short and long term effects on marine and coastal benthic communities of plants and animals (ecological processes). The ecological impacts depend on complex and dynamic interactions of abiotic and biotic factors including: (i) composition and dynamics of the sediment, (ii) methods of dredging and dumping and the sediment spill and (iii) the occurrence and sensitivity of seagrass and macro-zoobenthic communities and the rate of recovery of the communities affected. An important problem of sand mining may be the release of fine sediments (silt and mud) in the environmental system during the dredging process. Roughly about 1% to 3% of the substratum of the North Sea consists of fine to very fine sediments. One of the consequences of massive sand mining will be the production of an enormous amount of fine sediment, which can be carried over large distances to the coasts and shores of the countries surrounding the North Sea, threatening the environmental system at those places. Many of the processes involved are unknown and should therefore be studied more intensively focussing on the bed, water phase (oxygen cycle) and foodweb by both laboratory and field experiments.

Impact studies of marine sand and gravel mining by dredging operations on benthic communities show recovery rates in the range of in the order of years to decades, depending on local conditions.

### 5.1.2 Literature review results from morphological field data sets

**Extraction from pits**

The available information on the near-field and far-field (coastal impact) effects of mining pits (extraction pits for beach nourishments) can be summarized, using the following zonation:

- **inshore at foot of beachface (2 to 5 m depth contour)**;
  - cheap and attractive method for sheltered beaches (mild wave regimes; small littoral drift); can not be used for open, exposed beaches;
  - infill from beachside and seaside and from shore-parallel directions (annual infill rate is not more than about 3% of initial pit volume for sheltered beaches; infill rates are between 5 and 15 m$^3$/m/yr, depending on wave climate; filling time scale is 10 to 30 years);
  - local recirculation of sand; no new extraction sand is added to beach system;

- **upper shoreface (5 to 15 m depth contour)**;
  - relatively strong impact on inshore wave climate due to modified refraction and diffraction effects;
  - relatively strong modification of gradients of littoral drift in lee of pit resulting in significant shoreline changes (growth of beach salients, see Combe and Soileau, 1987);
o relatively rapid infill of extraction pit with sediments from landside (beach zone) and from shore-parallel directions; annual infill rates are in the range of 20% (depths of 10 to 15 m) to 100% (depths of 5 to 10 m) of initial pit volume; the filling time scale is 5 to 10 years;
o local recirculation of sediment; no new extraction sand is added to nearshore system;
• **middle shoreface (15 to 25 m depth contour);**
o negligible impact on nearshore wave climate (see Motyka and Willis, 1974);
o negligible effect on nearshore littoral drift;
o no measurable shoreline changes;
o new extraction sand is added to nearshore morphological system (nourishment);
o infill of extraction pit mainly from shore-parallel directions and from landside with sediments eroded from upper shoreface by near-bed offshore-directed currents during storm events (see Migniot and Viguier, 1980; Kojima et al., 1986); annual infill rate is about 1% of initial pit volume; the filling time scale is 100 years;
o trapping of mud in pits (negative ecological effect);
o particle tracer studies show small but measurable transport rates, mainly due to storm waves;
o long-term deficit of sand for upper shoreface;
• **lower shoreface (beyond -25 m depth contour);**
o no impact on nearshore wave climate;
o no effect on nearshore littoral drift;
o no measurable shoreline changes;
o new extraction sand is added to nearshore morphological system (nourishment);
o minor infill of sand in extraction pit; only during super storms;
o trapping of mud in pits (negative ecological effect);
o particle tracer studies show minor bed level variations (of order of 0.03 m over winter period) during storms.

Extraction pits in the middle and lower shoreface should be designed with their longest axis normal to the shore to minimize the trapping of sand from the nearshore zone during storm events (to minimize the impact on coast). The estimated time scales for the infilling rates at the middle and lower shoreface are extremely uncertain due to lack of sand transport data at these locations.

**Extraction from sand waves/shoals**
As the field data information of extraction pits in sand wave/shoal areas is extremely limited, general conclusions can not be given. Removal of the crest of a sand wave in the Dutch sector (water depth of 20 to 25 m) of the North Sea, shows almost no regeneration of the sand wave crest over a period of about 6 years. Field data results from Japan shows that sand waves in deep water (15 to 25 m) can recover to their original shape and size over a period of say 10 to 20 years in dynamic conditions (relatively strong currents plus waves) with sufficient supply of sand.

**5.1.3 Literature review results from modelling studies**
The hydrodynamic and morphodynamic effects of extraction pits (various cases in USA, UK, Canada and The Netherlands) at various depths in the nearshore coastal zone have been studied by using wave refraction, flow, sand transport and shoreline change models. The wave climate at and inshore of the extraction area is affected (reduced wave heights). The flow patterns outside the extraction area are modified over a distance of maximum twice the width and length of the extraction area. In particular, the deceleration or acceleration flows on the slopes of the pit are affected. The wave transformation and flow patterns can be
simulated quite well provided that the boundary conditions at the model inlet are accurately known. The DELFT3D-model (based on PUTMOR-case) can represent these phenomena with reasonable accuracy, although these phenomena were generally slightly underestimated by the model. However, the application of the DELFT3D model resulted in a significant increase of the accuracies involved (better agreement between measured and computed velocities).

As with regards to morphodynamics, the cross-shore morphological changes are relatively small for pits beyond the 15 m depth contour; the migration rates are mainly affected by the local water depth and not by the pit dimensions (depth, width, length). The migration velocity of the pit in longshore direction was found to be 10 to 15 m/year. The morphological changes remain within the local surrounding of the pits. On the time scale of 100 years the overall longshore migration of the pit is of the order of 1 to 2 km. The sedimentation of the pit (infilling rate) increases strongly with decreasing water depth outside the pit. The modelling of morphodynamics is not yet very accurate due to the absence of accurate field data of sand transport processes. In the absence of such data the uncertainty margins are relatively large (up to factor 5).

The presence of a sand pit results in the formation of circulation cells which may trigger the development of a sandbank pattern (based on stability analysis studies). As time evolves, the sand bank pattern spreads out and migrates, alternatingly generating trough and crest zones. The pit itself deepens and the pattern spreads at a rate of 10 to 100 m/year. The migration rate of the centre of the pit is of the order of 1 to 10 m/year.

Beach erosion in the lee area of the pit was found to increase with increasing pit depth and with decreasing original water depth. It can be concluded that extraction pits beyond the 15 m depth contour do not lead to any significant shoreline erosion.

5.2 Conclusions

5.2.1 Performance and Applicability of Delft3D

The validation results presented in this study have shown that model is able to give reliable predictions of the morphological development of pits and trenches in deeper water. The Brier skill scores indicated that the performance of the model was ‘excellent’ when using the TR2004 transport formulations. Furthermore, it was shown that the TR2004 predictors for bed roughness and the suspended sediment diameter resulted in accurate and robust predictions of the sediment transport (always accurate within about 50 %). The differences between depth-averaged and 3D simulations could largely be explained Quasi-3D advection-diffusion equation used in the depth-averaged simulations. In general the 3D (or 2DV) simulations resulted in more accurate predictions of the morphological developments of the considered trenches and pits. For the laboratory experiments it was found that by scaling the transports to the measured upstream values (A approach) the model gave the best morphological predictions. It was not necessary to perform an additional calibration on the morphology (B approach). Also for the Scheveningen field the model has shown to be able to give accurate predictions of the morphological trench development under the provision that accurate wave and tidal boundary conditions are used. The sensitivity runs for the Scheveningen case have shown that the predicted final trench development is relatively sensitive to small errors/inaccuracies in the prescribed tide and waves. Also, the scaling of the transports to measured values improved results considerably. The 2nd PUTMOR field
case could not be used to verify the model extensively due to the fact that the morphological changes were of the same order of magnitude as the measurement errors. However, this case did illustrate that despite a large number of bed updates no (visual) numerical diffusion was present.

The validation results for the artificial sand dam near Hoek van Holland are less satisfactory. Although the migration of the dam is usually predicted reasonably well, the diffusion of the dam and as a consequence the dam height can not be predicted accurately. The present results seem to indicate that the schematisations of wave climate and tide have a relative large impact on the model predictions. It has to be concluded that no firm conclusions can be drawn regarding the accuracy of predictions made for sand banks at deeper water.

Although experience with the updated Delft3D model is still limited we conclude that at its present status the model can be applied confidently to model the morphological behaviour of pits/trenches and to assess the near field and far field impacts. However, the presented sensitivity studies have shown that the final predictions can be significantly affected by small inaccuracies in the applied hydrodynamic forcing conditions and a number of model settings. It is our opinion that apart from refining and improving the in Delft3D included processes it imperative to conduct further research on input reduction techniques for long term morphological predictions. A large part of the uncertainties in the model predictions is likely to be caused by the severely simplified forcing conditions, which are (still) an inevitable part of long term morphological modelling to keep simulation times at acceptable levels.

The adopted approach to validate Delft3D in a consistent manner for a number of field experiments in the same area by using one overall model to generate the boundary conditions for the detailed models has worked well. It underpins the robustness of the Delft3D prediction for sand pits and trenches. However, the validation study relies heavily on a small number of field experiments. Especially the limited amount of morphological field data that was considered here is a limitation on the general validity of the conclusions drawn here.

5.2.2 Overall conclusions

Based on the results of an extensive literature review of mining pit data and mathematical model studies, the following overall conclusions are presented:

*Hydrodynamic and morphodynamic data of mining pits*

- Large-scale mining pits will have a significant impact on the near-field and far-field (up to the coast) flow and wave patterns; the flow velocities inside the pit will be reduced and the wave heights may also be reduced, depending on the depth of the pit. The flow patterns outside the extraction area are modified over a distance of maximum twice the width and length of the extraction area. In particular, the deceleration and acceleration flows on the slopes of the pit are affected.
- As a consequence of reduced flow velocities in the pit, the sand transport capacity inside the pit will decrease and sediments will settle in the pit area, resulting in deposition. Thus, the pit will act as a sink for sediments originating from the surrounding areas and depending on the local flow and wave patterns. Hence, erosion of the sea floor will take
place in the (immediate) surrounding of the pit. This may lead to a direct loss of sediment from the nearshore zone. On the time scale of 100 years the overall erosion area affected by the pit will of the order of 1 to 2 km.

- Indirect (far-field) effects result from the modification of the waves moving and refracting over the excavation area (pit), which may lead to modification of the nearshore wave conditions (wave breaking) and hence longshore currents and sediment transport gradients and thus to shoreline variations.
- Considering the massive scale of future mining of sand and hence the large spatial scales that will be affected by the mining activities, the mining areas need to be situated in the offshore shoreface zone to minimise the effects of nearshore coastal erosion.
- Mathematical model studies indicate that the impact on the coast is minimum if the mining site is offshore of the 15 m depth contour. Given the uncertainties of these model studies due to lack of sufficient sand transport data, a safe approach is to select the 20 m depth contour as the offshore limit for sand mining.
- Extraction pits in the middle and lower shoreface should be designed with their longest axis normal to the shore to minimize the trapping of sand from the nearshore zone during storm events (to minimize the impact on coast).
- General conclusions on mining at sand waves/shoals/banks can not be given, as sufficient field data information is lacking. Field data results from Japan shows that sand waves in deep water (15 to 25 m) can recover to their original shape and size over a period of say 10 to 20 years in dynamic conditions (relatively strong currents plus waves) with sufficient supply of sand.

Ecological process results

- Impacts of mining/dredging on the benthic community include a suppression of species variety, population density and biomass, as well as differences in species composition compared with the surrounding deposits.
- Mining/dredging causes an immediate decline in the bottom community followed by a rapid postdredging recovery in the range of years to decades, depending on local conditions.
- Extraction of a few million m$^3$ of sand seaward of the 20 m depth contour is not likely to interfere significantly with local benthos and their consumers.

Modelling results

- The wave transformation and flow patterns can be simulated quite well provided that the boundary conditions at the model inlet are accurately known. The DELFT3D-model (based on PUTMOR-case) can represent the flow patterns with reasonable accuracy, although these phenomena were generally slightly under-estimated by the model. However, the application of the DELFT3D model resulted in a significant increase of the accuracies involved (better agreement between measured and computed velocities).
- The presence of a sand mining pit results in the formation of circulation cells which may trigger the development of a sandbank pattern (based on stability analysis studies). As time evolves, the sand bank pattern spreads out and migrates, alternatingly generating trough and crest zones. The pit itself deepens and the pattern spreads at a rate of 10 to 100 m/year. The migration rate of the centre of the pit is of the order of 1 to 10 m/year.
5.3 **Recommendations**

The following recommendations are given:

- The accuracy of model predictions is rather limited because the sand transport models used in mathematical models have not yet been tested rigorously based on the results of field surveys; detailed field surveys should be carried out more regularly using instrumented tripods so that a database of sand transport rates in coastal waters becomes available.

- The DELFT3D model should be better tested with respect to the morphological development of large-scale sand pits and sand waves/shoals. Especially the behaviour of the TR2004 formulations should be investigated.

- Although input reduction techniques are not directly related to model validation, it was found that for the artificial sand dam near Hoek van Holland input reduction has an unacceptably large influence on the final predictions. Furthermore, it was shown that the final predictions for the Scheveningen trench were significanly influenced by relative small changes to the hydrodynamic forcing conditions. In our opinion this implies that a large part of the uncertainties in the long term morphological model predictions is likely to be caused by the severely simplified forcing conditions, which are (still) an inevitable part of long term morphological modelling studies to keep simulation times at acceptable levels. It is therefore recommended to initiate a study specifically addressing this issue in relation to long term morphodynamic predictions.

- The sediment pick-up due to the combined action of currents and waves seems to be modelled with insufficient accuracy. This can be caused by hydrodynamic predictions or sediment transport formulations and should be investigate further.

- For three cases the Brier skill score were used to objectively characterise Delft3D’s performance. The qualification criteria derived in the Coast3D-project were used for that purpose. Because the focus in the Coast3D-project was in the near shore coast zone it is unclear if this qualification can also be used to characterise model performance in deeper water. It is recommended to specifically address this within the Sandpit project so as to come to a more widely accepted range of qualifications using the Brier skill score.
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