The Netherlands Ministry of Transport,

Public Works and Water Management

Directorate-General of Rijkswaterstaat

The Netherlands National Institute for Coastal and Marine Management/*RIKZ*

Physical Effects of Sea Sand Extraction

REPORT: RIKZ/2001.050

AUTHORS: S.E. Hoogewoning and M. Boers

COMMISSIONED BY: Directorate North Sea

The Netherlands Ministry of Transport,

Public Works and Water Management

Directorate-General of Rijkswaterstaat

The Netherlands National Institute for Coastal and Marine Management/*RIKZ*

Physical Effects of Sea Sand Extraction

REPORT:	**RIKZ/2001.050**
AUTHORS:	**S.E. Hoogewoning and M. Boers**
COMMISSIONED BY:	**Directorate North Sea**

Note: This report is an English translation of:
Hoogewoning, S.E. en M. Boers. 2002.
'Fysische Effecten van Zeezandwinning', rapport RIKZ/2001.050.
As a result, the description of the legislation is outdated

Table of Contents

Summary

Framework of existing policy
Several Dutch policy documents are relevant with respect to sea sand extraction on the Netherlands Continental Shelf (NCS), ie:

- the government directive on shallow mineral reserves SOD (*Structuurschema Oppervlakte Delfstoffen= Master Plan Surface Minerals*),
- the regional directive on extraction at the NCS RON/MER (*Regionaal Ontgrondingsplan Noordzee = Regional Extraction Plan North Sea)*, linked to an Environmental Impact Assessment (MER = EIA),
- the policy document *4^e^ Nota Waterhuishouding* (= *4th Note on Water Management*),
- and the government directive on rural areas SGR (*Structuurschema Groene Ruimte = Master Plan Green Areas)*.

Core principles are to use shallow mineral reserves as economically as possible, to achieve an optimal gearing to other user functions in the North Sea, and to maintain sustainable functioning of the North Sea water system. Several sea sand extraction guidelines have been adopted to realize these core principles. Since 1993, a number of developments have occurred which are not included in the RON/MER. A revised version (RON2) could give these developments their due. Partly for this reason it is desirable to examine the physical effects of temporary sand extraction in the nearshore coastal zone, of large-scale sand extraction by means of navigation channel overdimensioning, and of large-scale sand extraction in designated extraction areas.

Temporary sand extraction in the nearshore coastal zone
In the execution of beach nourishment operations, it may be desirable to construct a transhipment station in the nearshore coastal zone in the form of a temporary sand pit. A delivery pipe then extracts beach nourishment sand from the sand pit, after which dredgers refill the sand pit with sea sand. The maximum volume of such a sand pit is in the order of 1 million m^3. Data from previous sand extraction operations in the nearshore coastal zone show that the characteristic time scale on which the pit is filled to about two-thirds of its capacity, is approximately six to twelve months. Model calculations indicate that an unfilled sand pit in the nearshore coastal zone causes the coastline to recede a maximum of several metres in one year. The direct consequences of a temporary sand pit for coastal safety are negligible if the sand pit is constructed at a depth of the coastal profile below NAP[1] – 7m. Calculations with dune erosion model DUROSTA show that in that case the increase in dune erosion volume is less than 5%.

Large-scale sand extraction by overdimensioning of navigation channels
Overdimensioning, ie widening and deepening of the Euro-Maas Channel and the IJ Channel is one of the options for large-scale sand extraction. If the ‘Zero-Plus option’ in the present RON/MER is executed, the maximum mineable amount is estimated to be 320 million m^3 for the Euro-Maas Channel and 200 million m^3 for the IJ Channel. The consequences for shipping are generally

[1] *Nieuw Amsterdams Peil [NAP}* = Dutch Ordinate Level

positive: the width and depth increase and flow velocity crossing the channel decreases. However, depending on the design of the overdimensioning, around the jetty heads a complex flow pattern can occur which could hinder the shipping through the channel. Larger wave heights could furthermore occur, due to the fact that waves can penetrate further inshore through the navigation channels. Widening and deepening the navigation channels postpones the need for maintenance for an certain period of time. It increases the dredging margin, ie the difference between the actual depth and the target depth, as well as the distance between shipping traffic and slopes. Estuarine circulation, causing a shoreward flow of the salt seawater near the bottom, while the lighter, fresh river water near the surface flows offshore, may strengthen. This could result in an increase of silt transport towards the harbours.

Erosion of the navigation channel banks could result in nearby existing cables and pipelines getting exposed, with risk of breach. Furthermore, erosion of the (deeper parts of the) coastal zone has a negative influence on the total sand budget of the Dutch coast. Over a period of 50 years, the erosion zone can expand over a distance of 6 to 20 kilometres along the deeper section of the coast. It's influence on the nearshore coastal zone adjacent to the shipping channels is expected to be small, as a result of the dominating influence of the harbour jetties, resulting in sedimentation. The effect of navigation channel overdimensioning on coastal safety is of importance only with respect to the seawall around the jetties. This effect is not investigated in this report.

Large-scale sand extraction in designated extraction areas
Large-scale sand extraction in designated extraction areas exceeding 100 million m^3 could affect ecology, cables and pipelines, coastline maintenance and coastal safety. Sand extraction causes the entire bottom fauna of the extraction pit to disappear. The bottom fauna can recover only if the water residence time in the extraction pit is less than approximately 10 days, as a result of which the oxygen content remains at the same level. It is important, therefore, that vortices down the sand pit slope and stratification underneath the original seabed are avoided. By positioning the length of the sand designated extraction areas parallel to the flow direction, a process occurs which causes the designated extraction area to accelerate the flow, which in turn results in quicker water refreshment. The presence of a large-scale sand designated extraction area also has morphological consequences, the most important of which is orientation towards the tidal current and the length/width ratio. Model calculations show that continued deepening after construction is possible, depending on the geometry of the sand designated extraction area. Within a period of 50 years, banks caving in and the extraction pit being moved could cause problems with respect to cables and pipelines within a zone of several kilometres around the extraction pit. If the extraction pit is located near the seaward boundary of the coastal foundation zone, this could cause sand loss in the coastal zone. (At the time of publication of this report, the seaward boundary of the coastal foundation zone was not formally established. This will probably be the established NAP –20m depth contour.) The effects of large-scale sand extraction on coastline maintenance and coastal safety seem to be limited. Based on a limited number of numerical model calculations to predict the effect of a future Second Maasvlakte, the conclusion is drawn that there is no significant increase in hydraulic boundary conditions (water levels, wave heights and wave periods), and that structural receding of the coastline position is not to be expected within a period of 5 years. However, the effect on the coastline position over a longer period, for example 50 years, has not been clearly mapped out as yet.

Recommendations
For temporary sand extraction in the nearshore coastal zone along the straight Dutch coastline and the central coastal sections of the islands, the following recommendations are given:

- It is recommended in any case that after the sand nourishment the temporary sand pit be filled to the original sea bed elevation.
- It is furthermore recommended to demand compensation for the loss of sand transported to the pit from the surrounding area during the use of the temporary sand pit. This compensation can be achieved by overdimensioning the sand nourishment or by creating an extra sand buffer at the temporary sand pit. The volume of this compensation can be estimated by means of a formula presented in this report.
- To prevent any adverse consequences of the temporary sand pit to coastal safety, it is recommended to carry out the extraction operations seaward of the NAP –7m line with a surface area under 10 ha.

For the Zeeland and South Holland islands and for the heads of the Wadden Islands, further conditions need to be determined for temporary sand pits in the nearshore coastal zone.

For large-scale sand extraction by means of overdimensioning of the navigation channels, the following recommendations are given:

- To prevent wave reflection on the navigation channel banks it is recommended that the slopes be at least as gentle as 1:7.
- With respect to cables and pipelines, it is recommended that an influence zone of 6 to 20 kilometres, running parallel to the navigation channels, be taken into account over a period of 50 years. Possible measures are the creation of a 1,000 metre buffer zone, deeper digging in of cables and pipelines, and periodical checks for possibly exposed cables and pipelines.
- As a result of the complex flow pattern around the jetty heads, it is recommended that navigation channel entrance design be studied using a numerical model.
- It is recommended to investigate beforehand if navigation channel overdimensioning results in estuarine circulation changes, and if this is the case, to indicate whether an increase in sedimentation of the harbours may be expected.
- It is recommended to chart the positive and negative effects on the sand budget of adjoining coastal sections. It is furthermore recommended to define the boundaries of this coastal zone parallel to the navigation channels where an influence of the navigation channel is accepted, taking into account a maximum overdimensioning and expected expansion of the morphological influence area in the longer term.
- It is recommended to carry out further studies into the effect of navigation channels on wave conditions in the nearshore coastal zone and to examine how overdimensioning affects wave conditions during extreme conditions.
- It is recommended to examine the effects of large-scale sand extraction by navigation channel overdimensioning in connection with the effects of other large-scale interventions in the North Sea, eg during future Environmental Impact Assessment (EIA) studies.

For large-scale sand extraction in designated extraction areas the following recommendations are given:

- With respect to cables and pipelines, it is recommended that influence zones of several kilometres around the large-scale sand designated extraction areas be taken into account over a period of 50 years. Possible measures are the creation a 1,000 metre buffer zone, deeper digging in of cables and pipelines, and periodical checks for possibly exposed cables and pipelines.
- It is recommended to create a buffer zone of several kilometres between large-scale extraction pits and the coastal zone.
- Despite the fact that large-scale sand extraction in designated extraction areas does not seem to have any significant adverse effect on coastal safety, it is recommended to include this aspect when considering large-scale sand extraction in designated extraction areas.
- If considering large-scale sand extraction in a sand designated extraction area, it is recommended to carry out a study of the oxygen concentration at the bottom by means of a water quality model.
- With respect to the geometry of the sand designated extraction area, it is recommended not to draw up quantitative guidelines. Instead it is recommended to examine the effects on the relevant user functions beforehand for every large-scale sand extraction operation, for example by means of a *Milieu Effect Rapportage*.
- It is recommended to examine the effects of large-scale sand extraction in designated extraction areas in connection with the effects of other large-scale interventions in the North Sea, eg during EIA studies.

1 Introduction

1.1 Developments in sea sand extraction guidelines

Since 1993 the directive on sand extraction at the Netherlands Continental Shelf RON/MER[2] has been into force (**Rijkswaterstaat, 1991**), which lays down guidelines for sea sand extraction. Since 1993, however, a number of developments have occurred which are not included in the RON/MER. A revised version (RON2) could give these developments their due.

Temporary sand extraction in the nearshore coastal zone
Since 1990 many beach nourishment operations have been carried out, which prove their effectiveness for most locations along the Dutch coast. Beach nourishment operations could be executed more efficiently if a temporary sand pit is used in the coastal zone shoreward of the NAP –20m depth contour. This option is not included in the RON/MER, however. As the use of a temporary sand pit implies redistribution of sand in the coastal zone instead of permanent extraction, it could be considered a new alternative in the RON2.

Large-scale and deep sand extraction outside the coastal zone
Over the past years, several plans have been developed to reclaim land off the Dutch coast. Examples of potential coastal expansion are: Second Maasvlakte, Airport at Sea, Coastal Location Nieuw–Holland (Waterman Plan). Possible future coastal expansion is to be realised by means of filling sand from the sea. The required amount of sand over a period of 5 to 10 years is 200 to 2,000 million m^3, depending on the expansion plans. Compared to the amount of approx. 25 million m^3 which is the present annual use for coastal maintenance and the market (see Section 2.3), this would mean an additional sand demand of one to ten times the annual amount.

In addition to large-scale sand extraction for potential coastal expansion plans, it is being investigated if large-scale sand extraction in the North Sea can be employed for the concrete and bricklaying industries. For this purpose a *Milieu Effect Rapportage* for extraction concrete and masonry sand in the North Sea has been drawn up (**RIKZ, 1999/2001**). Proceeds of 40 million tons of suitable concrete and masonry sand and a maximum of approx. 320 million m^3 filling sand is envisaged over a period of 10 years. This amount is comparable with the present sand extraction volume. The sand required needs to be sufficiently coarse and is available from the North Sea bottom to a limited extent only. Preliminary research shows that sand suitable for this purpose is found either at the crests of sand waves, or in sedimentary layers at a depth of at least 5m underneath the sea bed. In the latter case, extraction would take place at a depth exceeding the maximum extraction depth of 2m allowed under the present RON/MER. Also with a view to large-scale sand extraction for the

[2] Regionaal Ontgrondingsplan Noordzee = Regional Extraction Plan North Sea. This directive is voluntarily linked to an Environmental IMPACT Assessment (MER=EIA)

purpose of potential coastal expansion, there is a demand to allow extraction at greater depths to limit the extraction surface area.

The RON2 could take into account the large-scale character of sand extraction, which might take place in the future, as well as the demand to introduce deep sand extraction exceeding 2 metres.

1.2 Question: what are the physical effects of sea sand extraction?

The Directorate North Sea commissioned the The Netherlands National Institute for Coastal and Marine Management/*RIKZ* to conduct a study into the physical effects of sea sand extraction in relation to the above-mentioned developments, which effects are of importance to a number of North Sea user functions and values. The study is to provide basic knowledge and recommendations for a possible review of the sea sand extraction guidelines to be included in the RON2, the successor of the present RON/MER.

Over 1996-1999 a study was conducted within the framework of the *Rijkswaterstaat* research programme KUST*2000, jointly commissioned by the regional coastal Directorates and the Head Directorate of the Directorate-General of Rijkswaterstaat.

1.3 Advisory report approach

In relation to the developments mentioned above, hypotheses were formulated about the physical effects which, in theory, are expected for three types of sand extraction:

- Temporary sand extraction in a relatively deep pit shoreward of the NAP –20m depth contour, for the execution of a beach nourishment project
- Maximum overdimensioning (widening and deepening) of the navigation channels leading to the harbours of Rotterdam (Euro-Maas Channel) and IJmuiden (IJ Channel), in accordance with the so-called Zero-Plus option in the RON/MER
- Large-scale and deep extraction in a single designated extraction area exceeding 100 million m^3 in volume, located seaward of the NAP –20m depth contour.

Field data were subsequently collected and analysed, and model calculations performed to test the hypotheses as far as possible. The research activities carried out as part of KUST*2000 are listed below.

Temporary sand extraction in the nearshore coastal zone

- Analysis of measuring data on the morphological evolution of sand pits in the active coastal zone (**Jetten and Lei, 1998; Verhagen and Kosgoda, 1998**)
- Study with the numerical model (Unibest-TC) into the effect of a sand pit in the nearshore coastal zone, over a period of one year (**Klomp, 1996**)
- Study with the numerical model (DUROSTA) into the effect of a sand pit on dune erosion during a storm (DUROSTA)

Navigation channel overdimensioning

- Inventory of morphological experiments along the Dutch coast (**Walstra et al, 1998)**
- Analysis of measuring data on the morphological evolution of the Euro-Maas Channel, and a numerical model study (Sutrench) into the cross-

section evolution of the Euro-Maas Channel over a period of 5 years (**Hoitink, 1997**)

- Additional numerical model study (Sutrench) into the cross-section evolution of the Euro-Maas Channel over a period of 3 years and 50 years (**Walstra et al, 1998**). These results were also used for Chapter 5.
- Expert judgement over the long-term (ie 50 years) morphological evolution of the navigation channels (**Stive et al, 1998**)

Large-scale sand extraction in sand designated extraction areas

- Numerical model study (Waqua) of hydraulics, supplemented with a theoretical study into the effect of the sand pit exerting the flow velocity (**Svašek b.v., 1998**).
- Numerical model study (Delft3D) of hydraulics and long-term (ie up to 1,000 years) morphological evolution (**Klein, 1999**).
- Combination of theoretical and numerical model studies (Delft3D) into the stability of tidal banks and designated extraction areas (**Németh, 1998**)
- Expert judgement over the long-term (ie 50 years) morphological evolution of the designated extraction areas (**Stive et al, 1998**)

For the above activities grateful use was made of data and insights obtained from other projects, such as the *Second Maasvlakte*, the *Drawing Pin experiments*, the European project *RIACON*, the *Simon Stevin pit experiment*, and a *temporary pit near Ameland*. Reporting of research results in the present report was effected within the KUST*2005 programme. Dr D.W. Dunsbergen (*RIKZ*) and Mr A. Stolk (Directorate North Sea) contributed to quality assurance by commenting on the various drafts. Furthermore, it is noted that Ms L. Walburg contributed to the analysis and the map presentation of the temporary sand pits in Chapter 3.

1.4 Delineation of the advisory report

The present advisory report describes the physical effects *after extraction* or, more specifically, effects on hydraulics, sediment transports and morphological evolution. Physical effects *during extraction*, including increased water column turbidity by silt overflow are not included. Bottom fauna changes in the designated extraction areas are also not discussed. The reader is referred to **Van Dalfsen, 1998a and 2000** and **Van Dalfsen et al**, **1999** for more information on this subject. This report, however, does stress the importance of hydraulics as a boundary condition for ecological recovery. In this respect ecology is defined as one of the values to be protected. Knowledge on this topic has already been applied in the report on concrete and masonry sand *MER Beton- en Metselzand* (**RIKZ, 1999/2001**).

Part of the results has already been included in previously published reports. For instance the physical effects of temporary sand extraction were discussed in **Hoogewoning, 1996** and the physical effects of large-scale sand pits were explored in **Hoogewoning, 1997**.

This report reflects the state of affairs in the year 2000, and at this point in time the RON/MER is still the starting point. Results of measurements carried out in 1999 and 2000 in and around the deep sand pit (project PUTMOR) are not incorporated in this report. Studies carried out by Programme Bureau Flyland – into the possible construction of an airport at sea – are not used either.

1.5 Report structure and outline

On the one hand, this report gives an overview of the most important physical effects and the advancing insights in this field (knowledge development). On the other hand, a link is made between the physical effects and the user functions (recommendation). The following structure was chosen to discuss both parts sufficiently and to do justice to the nature of the basic report as well as that of the advisory report:

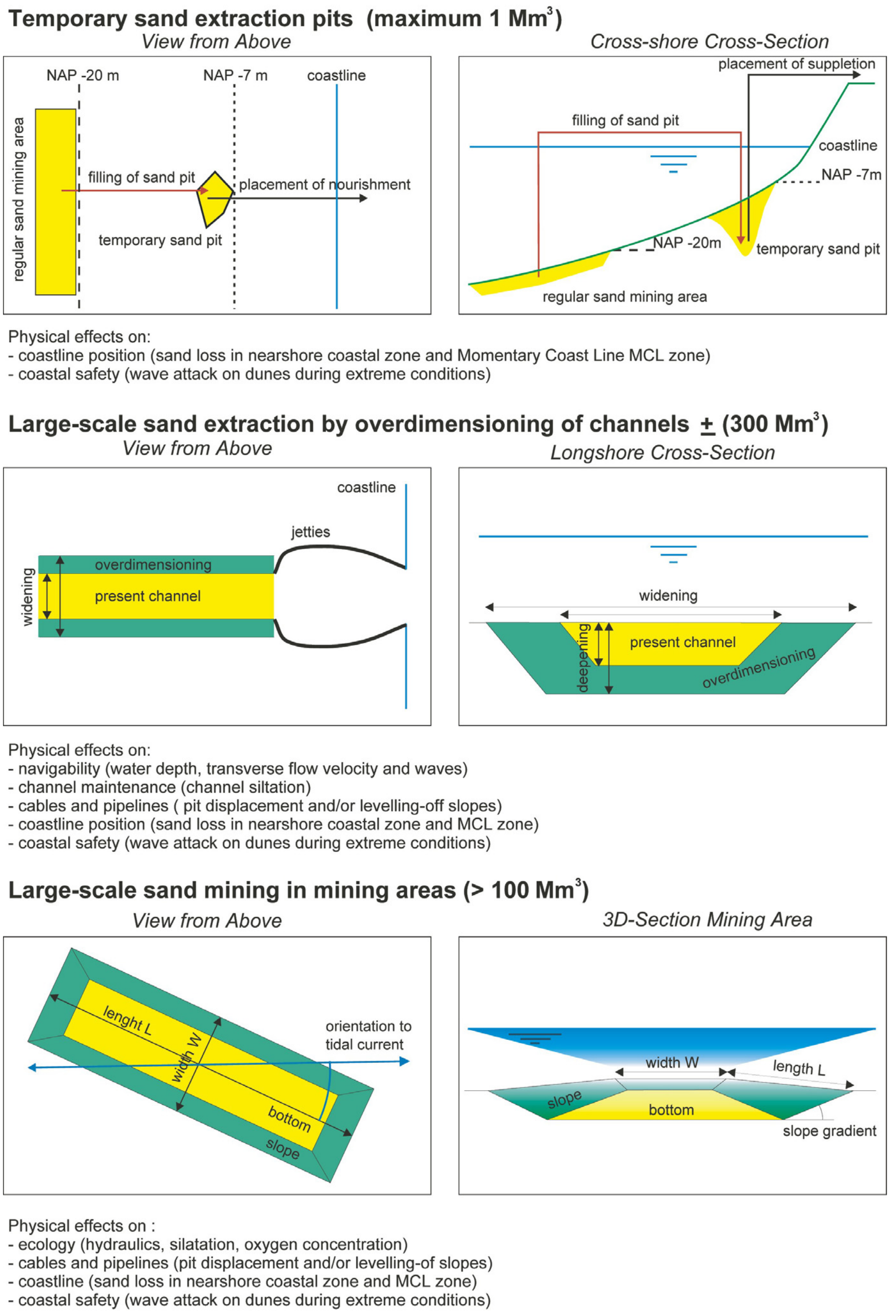


Figure 1.1 The three types of sand extraction discussed in this report

- The three types of sand extraction are discussed in three separate substantive chapters (see Figure 1.1).
- Every chapter begins with the central question (Section .1) followed by background information on the relevant part of the coastal system (Section .2).
- In the third section (Section .3) a link is made between the physical effects at various temporal and spatial scales, and several North Sea user functions.
- The physical effects, related to the user functions, are worked out per scale level (from small to large scale) in separate sections (Sections .4, .5 and .6).
- The chapter closes with conclusions at the level of both the physical effects (knowledge development) and their influence on the user functions (recommendation) (Section .7).

The chapter outline is as follows:

- Chapter 2 contains backgrounds of the present policy and sand extraction guidelines. The three substantive chapters follow this chapter.
- Chapter 3 discusses the use of temporary sand pits in the nearshore coastal zone for the execution of coastal sand nourishment projects. The physical effects of such sand pits are discussed in relation to the possible consequences for coastal maintenance and coastal safety.
- In Chapters 4 and 5 the attention is focussed on possible future sand demand of large proportions,
  eg for land reclamation. Sand extraction could take place by means of widening and/or deepening, ie overdimensioning, of the Euro-Maas Channel and the IJ Channel (Chapter 4), or in sand designated extraction areas designated for this purpose (Chapter 5). In addition to coastal maintenance and coastal safety, subjects as repair work, shipping, location of cables and pipelines and ecology are also discussed.
- The report concludes by a recommendation regarding guidelines in the field of temporary sand pits in the nearshore coastal zone and large-scale sand extraction in navigation channels and sand extraction pits (Chapter 6).

2 Sand Extraction Policy and Guidelines (2000)

2.1 Policy framework for sea sand extraction

Surface minerals have been mined in the Netherlands for many years. The national policy for the extraction of surface minerals is described the government directive on shallow mineral reserves SOD[3] (**SOD, 1996**). Surface mineral extraction is also carried out on the North Sea. In 1993, the regional directive on extraction at the NCS RON/MER[4], linked to an Environmental Impact Assessment (MER = EIA), has become into force, and is abbreviated to RON/MER (**Rijkswaterstaat, 1991)**. The RON describes the general conditions to be observed by the concession-holder for extraction of surface minerals (sand, gravel, shell and clay) at the North Sea. The EIA describes the environmental effects of extraction in a zone along the entire Dutch coast to 50 kilometres offshore. The EIA also includes a broad weighing of interests with respect to North Sea erosion.

Apart from the SOD and the RON/MER, other policy documents are also relevant. Anyone wanting to extract surface minerals at sea also has to take into account for example the main objective of policy document *vierde nota Waterhuishouding*[5] (**Ministry of Transport, Public Works and Water Management, 1998**): "to have and maintain a safe and inhabitable country and to preserve and reinforce healthy and resilient water systems so as to guarantee sustainable use". In the structure plan for rural areas *Structuurschema Groene Ruimte*[6] (**Ministry of Agriculture, Nature Management and Fisheries, 1995**), the North Sea is designated as a core area on ecological values. This means that before any extraction of surface minerals is carried out, testing should take place for possible damage to area characteristics and values.

There has not only been an extension of the policy on the sea, but there have also been changes in legislation. The act on extraction (*Ontgrondingenwet* 1997) is now effective for the entire Netherlands Continental Shelf (NCS). Furthermore, international treaties and European Union legislation have become effective.

2.2 Sand extraction guidelines

The RON/MER is meant to ensure sufficient supply of surface minerals from the North Sea for the private, corporate and public sectors over a longer period of time, ie 1991-2000. This concerns extraction of sand, gravel, shell and clay, for which the following is taken into consideration:

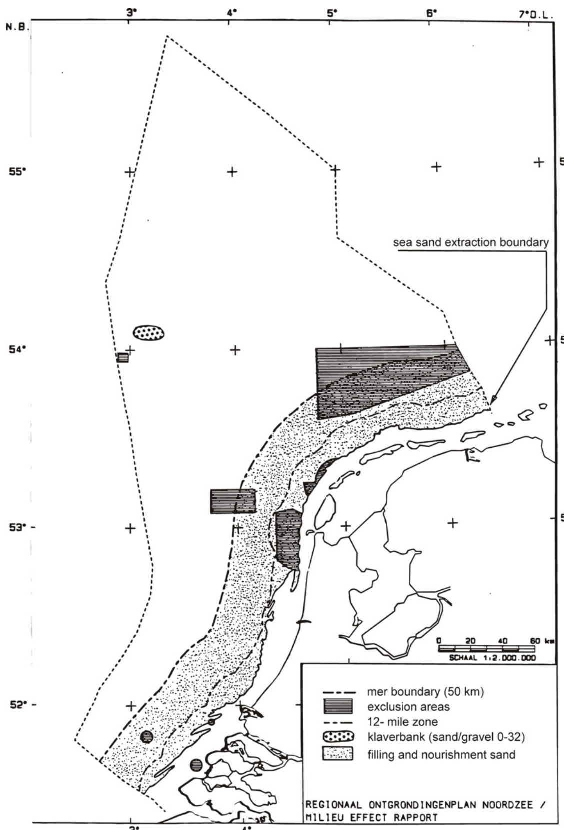
- Surface minerals are to be used as economically as possible

[3] Structuurschema Oppervlakte Delfstoffen= Master Plan Surface Minerals
[4] Regionaal Ontgrondingsplan Noordzee = Regional Extraction Plan North Sea
[5] 4[e] Nota Waterhuishouding = 4[th] Note on Water Management
[6] Structuurschema Groene Ruimte = Master Plan Green Areas

- An optimum gearing to other North Sea user functions, both through space and time
- A sustainable functioning of the North Sea water system, the adjoining waters and the mainland

The RON/MER planning area covers the territorial sea and the part of the NCS located seaward of it. The EIA describes the area up to 50 km offshore. For the extraction of *sea sand*, (large) areas have been designated for extraction (see Figure 1.1). This concerns:

- The Euro-Maas Channel and the IJ Channel (maintenance dredging work)
- Additional deepening to a maximum of 5m, and widening of the IJ Channel and the Euro-Maas Channel to a maximum of 2,000m and 2,700m respectively.
- The territorial sea and the NCS, seaward of the NAP –20m depth contour or the 20-kilometre line if this is closer to the coast than the NAP-20m depth contour with a maximum extraction depth of 2m. Designated exclusion areas/zones are excluded from sand extraction[7].
- Navigation channels in the outer deltas of the Delta area, for necessary dredging work and nourishments only, if in accordance with the policy plan for the Outer Delta Region[8] (**Bestuurlijk Overleg Voordelta, 1993)**
- The tidal outlets between the Wadden Islands, if in accordance with management plan for Extraction in the Wadden Sea[9] (**Rijkswaterstaat, 1985**)



[7] Sand extraction is by now allowed seaward of the **established NAP** -20m line.
[8] Integraal Beleidsplan Voordelta
[9] Beheersplan Ontgrondingen Waddenzee

Figure 2.1 Potential designated extraction area for filling sand and nourishment sand with exclusion areas, from **Rijkswaterstaat, 1991**

Several areas are excluded from sand extraction (see Figure 2.1). This concerns:

- Military grounds[10]
- Present and former dumping sites
- Zones around cables and pipelines

An overview of the extraction locations on the NCS in 1999 is given in Figure 2.2.

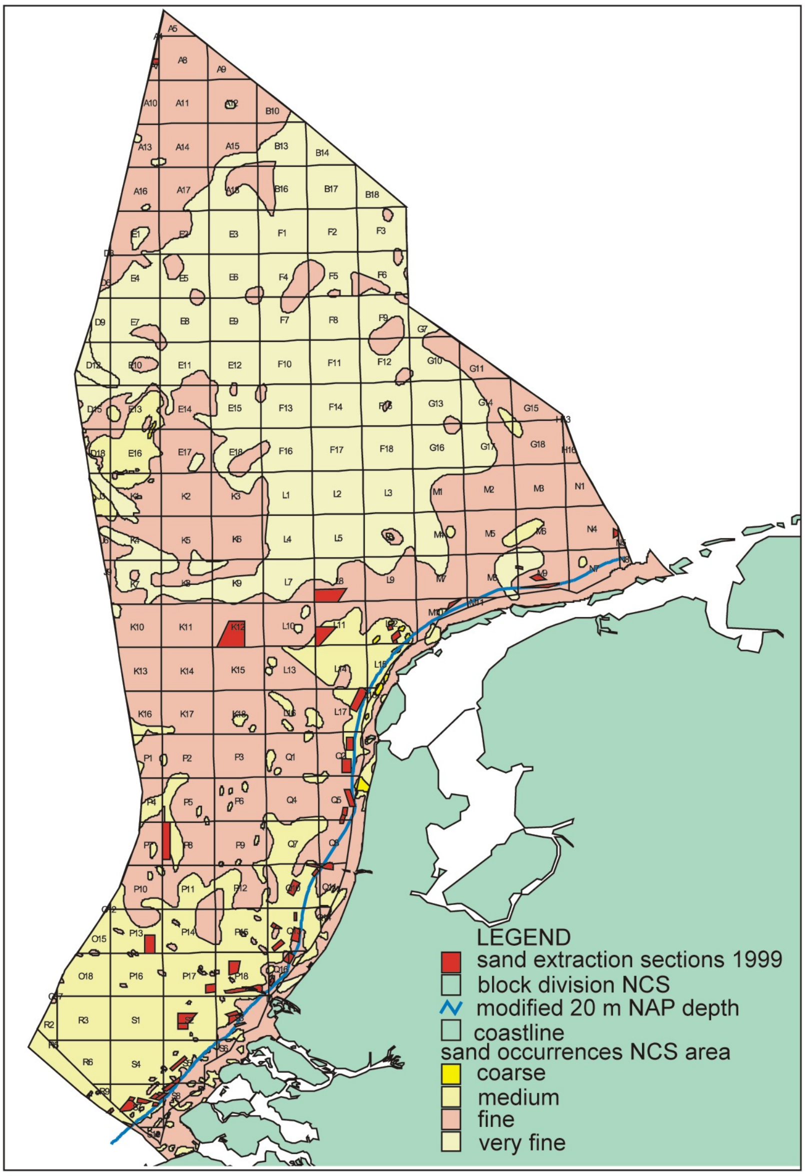


Figure 2.2 Designated extraction areas in 1999 (in red) on the NCS, source: **Directorate North Sea**

[10] Sand extraction in military training areas is by now allowed under certain conditions.

2.3 Present sea sand extraction volume

Figure 2.3 shows the total volume of sand extracted annually for the sand trade on the one hand and for coastal maintenance on the other hand. After 1987 annual sea sand extraction for the sand trade increased substantially in comparison to the preceding period, which was partly as a result of the sand extraction restrictions in the Wadden Sea and Voordelta. Since 1990 the total volume of sea sand extraction has further increased owing to the introduction of the policy of dynamic maintenance (see Subsection 3.1.2.).

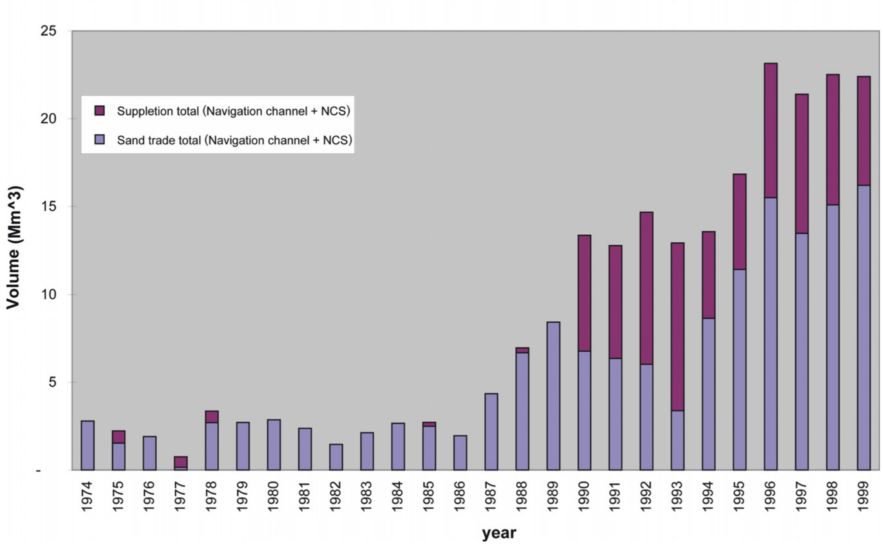


Figure 2.3 Sea sand extraction totals in the navigation channels and in designated extraction areas on the NCS 1974 – 199, source: **Directorate North Sea**

3 Temporary Sand Extraction in the Nearshore Zone

3.1 Introduction to temporary sand extraction

3.1.1 Question: what are the effects of temporary sand extraction in the nearshore coastal zone?

The sand balance of the coastal zone, which is the zone stretching to NAP – 20m or to 20 km offshore, is an important factor in long-term coastal stability. For this reason the RON/MER does not allow any sand extraction in the coastal zone. The use of a temporary sand pit for beach nourishments, however, implies a temporary redistribution instead of a permanent extraction of sand from the coastal zone. After backfilling the temporary sand pit with sand from outside the coastal zone, sand is added – as in a regular sand nourishment - to the coastal zone.

In combination with the execution of beach nourishment operations, the use of a temporary sand pit can be considered a new alternative in addition to the RON/MER. Knowledge of possible adverse ecological and physical effects is required to substantiate this.

Sand extraction destroys the local bottom fauna. The temporary pit is backfilled after use with sediment foreign to the area – from the navigation channels or areas seaward of the coastal zone. To prevent that ecologically poor areas remain, the bottom fauna needs to recover within a period of approx. 6 years. In the remainder of this report, such ecological effects are left out of consideration.

An increased depth of the sea bed elevation affects the local hydraulic parameters and sediment transport. This can of course not be at the expense of coastal safety, and, if possible, receding of the momentary coastline (MCL) has to be prevented.

The main questions in this chapter are:

> *What physical effects occur as a result of a temporary sand pit in the nearshore coastal zone and what influence do these effects have on the user functions of 'coastal maintenance' and 'coastal safety'?*

3.1.2 Background: dynamic maintenance of the coastline

Sand nourishments on the coast have been carried out since the 1950s, mainly after dune erosion as a result of storms. In 1990 the policy of 'dynamic maintenance' of the Dutch coastline became effective (**Rijkswaterstaat, 1990**). A Basic Coast Line (BCL) was defined for a large part of the Dutch coastline, against which the location of the MCL is tested. Receding of the MCL as a result of structural erosion is compensated by carrying out sand nourishments (see box below); in 1999, 6.2 million m^3 sea sand was extracted for the purpose of coastal maintenance (see Figure 2.3).

Many beach nourishments have been carried out since 1990. Empirical data show that beach nourishments have proven to be effective for most locations along the Dutch coast (**Walhout et al, 2000**). They could nevertheless be even more effective. After a successful experiment involving shoreface sand nourishment near Terschelling (**NOURTEC, 1997**), shoreface nourishments have been carried out at various locations along the Dutch coast. As placing one m^3 sand under water is cheaper than pumping it onto the beach, more sand can be used for the same amount of money. Natural processes then transport part of the sand to the coastline.

Sand extraction for the purpose of coastal maintenance

Sand nourishments on the beach or shoreface nourishments are an essential part of annual coastal maintenance. In most cases sand is extracted by trailing suction hopper dredgers in one of the designated designated extraction areas and is subsequently transported to the nourishment site (Figure 3.1).

Figure 3.1 Trailing suction hopper dredger extraction sand from the North Sea bed, source: **RIKZ**

In the case of a sand nourishment on the beach, the trailing suction hopper dredger is coupled to a pipeline at several hundreds of metres offshore. The sand is pumped through the pipeline onto the beach and spread by bulldozers (Figures 3.2a and b). In the case of a shoreface nourishment, the trailing suction hopper dredger dumps the sand onto the bottom close to the coastline ('klappen'*).*

Figure 3.2 Beach nourishment operations off the island of Texel. Sand is transported through a pipeline onto the beach (a), after which it is spread by bulldozers (b), source: RIKZ

The effectiveness of a shoreface nourishment depends on several factors, such as the location along the Dutch coast, the volume of the shoreface nourishment and the position within the cross-section. In the coming years, the effectiveness of the shoreface nourishments which have been carried out, will be evaluated as part of research programme KUST*2005 (**Dunsbergen, 2001**).

The effectiveness of shoreface nourishment will vary along the Dutch coast. Reduced effectiveness can be expected, for instance, in coastal areas where a possibly deep navigation channel runs just off the coast. In such situations beach nourishment is to be preferred. Beach nourishment is also preferred if maintaining of the coastline is essential.

The execution of coastal maintenance can be summarised as follows:
Shoreface nourishments where possible, beach nourishment where there is no other option.

3.1.3 Temporary sand pit for the execution of beach nourishment

In a conventional beach nourishment operation with a trailing suction hopper dredger, it is not possible to carry out sand extraction and sand nourishment at the same time. Coupling the hopper to the pipeline furthermore requires relatively quiet weather conditions. Both aspects affect the continuity and therefore the duration of the operation.

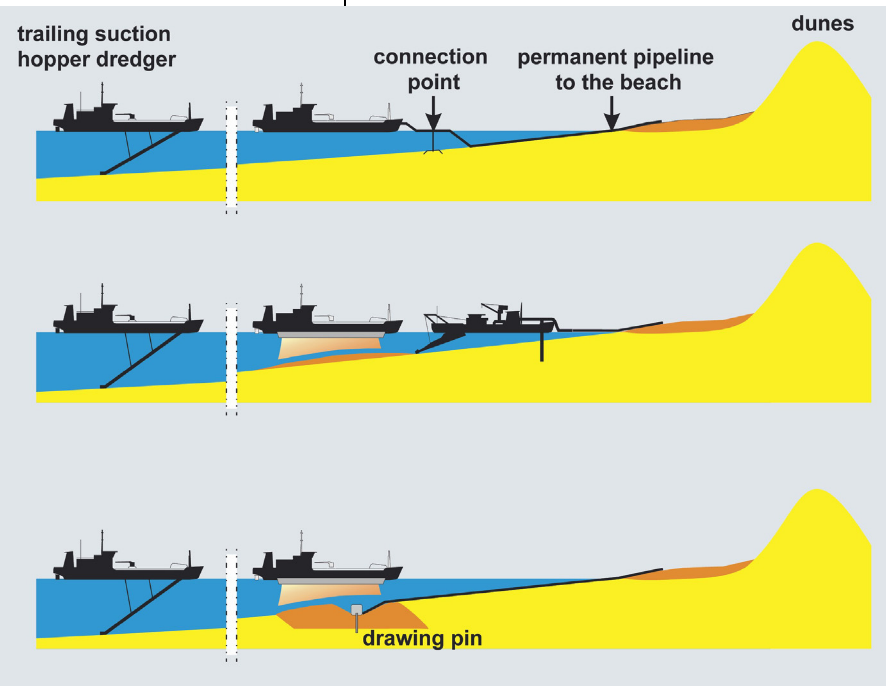


Figure 3.3 Beach nourishment operations. Top: conventional execution. Middle and below: a hopper suction dredger and a 'drawing pin' respectively, creating a temporary sand extraction pit.

A beach nourishment operation can possibly be carried out more quickly and at a lower cost if a temporary sand pit is used in the nearshore coastal zone. Sand is extracted from the shoreface by a separate stationary suction dredger and is pumped directly onto the adjoining beach. This can be done by a cutter suction dredger (ie hopper suction dredger), but also by means of a submerged dredging system, better known as the 'Drawing Pin' (Figure 3.3). After carrying out the beach nourishment operation, the pit is filled with sand from the designated designated extraction area. This sand is extracted and supplied by means of a trailing suction hopper dredger (see box below for other aspects of execution).

Aspects of the execution of a beach nourishment operation with a temporary sand pit

A temporary sand pit should preferably be located near the nourishment site, just off the coast, for instance around the NAP –8m depth contour. The closer to the coast, the less effort is required to transport the sand through a pump connection onto the beach. If the temporary sand pit is too close to the coastline, however, the transhipment risks are too great due to shallow water and wave breaking.

The pit volume should not exceed the sand nourishment volume, which is a maximum of 1 million m^3. Surface area and depth of the sand pit depend on the type of stationary suction dredger. The Drawing Pin creates relatively deep sand pits – up to a maximum of 20m below the local sea bed elevation – with relatively steep slope gradients.

If necessary, the temporary sand pit can function as a transhipment pit. A trailing suction hopper dredger first dumps sand from the designated designated extraction area – outside the coastal zone – into the pit, after which the stationary suction dredger pumps it onto the beach. In this situation, the beach nourishment volume exceeds that of the sand pit. This can be desirable for execution reasons or to limit any adverse effects of the presence of a sand pit.

A nourishment operation takes a maximum of several months.

3.2 Brief system description of the nearshore coastal zone

The temporary sand designated extraction area is located close to or within the nearshore coastal zone, but outside the wave breaking area and/or the area where sand extraction would cause too great a risk because of the vessel draught. The nearshore coastal zone is defined as the shallow coastal area to a depth of approx. NAP –10m.

On the seaward side of the nearshore coastal zone the tide dominates the hydraulic parameters. Within the nearshore coastal zone the effect of waves and wind waves in relation to the tidal movement becomes increasingly important. This effect increases as the water becomes shallower. When waves penetrate from the North Sea into the nearshore coastal zone, they lose energy as a result of bed friction or breaking (Figure 3.4).

As soon as waves break, they generate a flow into the direction of propagation. As the waves usually approach the coast at an angle, this creates a flow component along the coast, which is also called the 'wave-driven longshore flow', which transports sand along the coastline.

When sand transports along the coast change in volume, for instance because the local coastal angle changes, there are coastal sections in which sand accumulates (ie sedimentation) and from which sand is removed (ie erosion). The most significant bed changes in the nearshore coastal zone occur if the longshore sand transports are interrupted by solid obstacles, such as the Maasvlakte, the jetties at IJmuiden, the longitudinal dam at the island of Texel (Figure 3.5) or the slightly smaller groynes.

Figure 3.4 Dissipation of wave energy as a result of breaking off the coast between Egmond aan Zee and IJmuiden, as seen from the argus video station 'Coast3D' (see also www.wldelft.nl/argus).

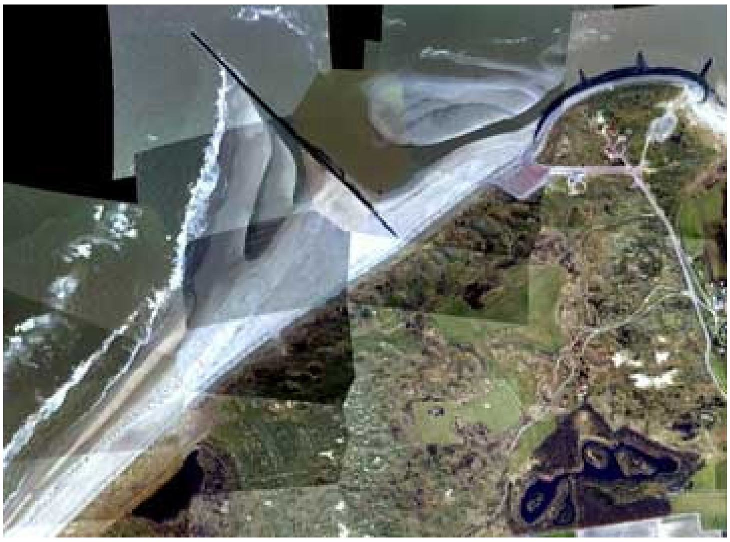


Figure 3.5 Compilation photograph of northwest Texel. The accretion on both sides of the Eierland dam is clearly visible.

Bed changes also occur perpendicular to the coastline. The most extensive and quickest changes occur during storm conditions. During a storm sand is washed away from the dune (ie dune erosion) and is deposited onto the beach and the shoreface (Figure 3.6).

During the calmer summer months the beach and dunes recover, so that the slope of the beach profile is milder during the winter months than during the summer months.

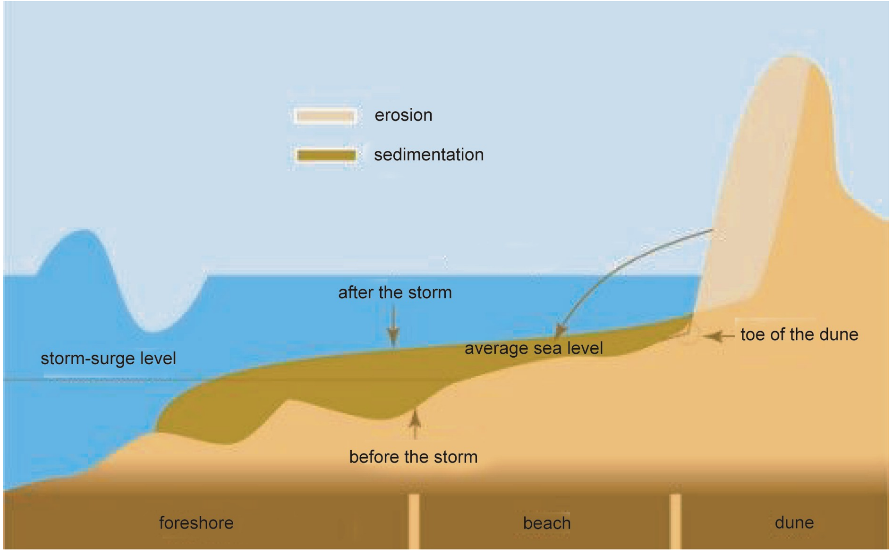


Figure 3.6 Principle of dune erosion after a storm, source: **TAW, 1995**

3.3 Effects of temporary sand extraction and user functions

3.3.1 Physical aspects and user functions of temporary sand extraction

The possible physical effects have various spatial scales and corresponding temporal scales. For each spatial scale, from small to large, the possible effects are related to relevant user functions (Table 3.1).

Physical Aspect	Relevant User Functions
Morphological evolution of a temporary sand pit and immediate surroundings (**Section 3.4**)	Coastline maintenance
II. Morphological evolution of the nearshore coastal zone (**Section 3.5**)	Coastline maintenance
III. Dune erosion under storm conditions (**Section 3.6**)	Coastal safety

Table 3.1 Physical aspects in relation to relevant user functions of temporary sand extraction

3.3.2 Delineation of the study into the effects of temporary sand extraction

Scenarios for temporary sand pits

- The volume of a temporary sand pit has a maximum of 1 million m^3.
- A temporary sand pit is defined as a sand pit which, during the nourishment operations, is used for a period of several months. An upper estimate of possible effects is given as a maximum period of 1 year.

Starting points for description of effects

<u>Bed</u>
In theory both the bed structure, defined by grain size distribution and sediment porosity, and the presence of dynamic bed structures such as mega ripples and sand waves, determine the degree of friction between hydraulics and bed. From this point onward the hypothesis is made that:

- The effect of locally changed bed friction on the hydraulics is negligible compared to the effect of a changed water depth.

Hydraulics and sediment transport
When a depth-averaged approach is used, the hypotheses are formulated that:
- The vertical profile of the tidal current is logarithmic in shape.
- The slope gradient of the designated extraction area is not too steep (milder than approx. 1:10), so that the vertical flow velocity profile in the designated extraction area remains identical in shape with the surrounding area; consequently a lower (or higher) depth-averaged flow velocity results in a proportionally lower (or higher) flow velocity near the bottom.

A further hypothesis is that:
- The effect of the wave field changes on the proportions of the sediment transport volume in the designated extraction area and immediate surroundings is negligible compared to the sediment transports forced by the tidal current changes.

To conclude it is noted that the descriptions of sediment transport volumes are relative only, as absolute values are subject to wide uncertainty margins. Generally speaking sediment transport is a function of the depth-averaged flow velocity to a certain power *n* (the value of *n* being between 3 and 5).

3.3.3 Physics with respect to temporary sand extraction

I. Morphological evolution of a temporary sand pit and immediate surroundings
At the sand pit site, the water depth exceeds that of the immediate surroundings. The greater water depth has an important effect on the local flow and tidal current velocities. The law of preservation of water mass applies at all times: the quantity of water supplied by a vertical plane (ie flow rate) equals the quantity removed.

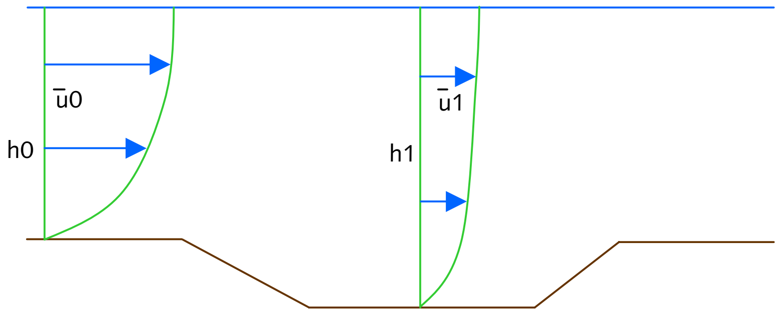


Figure 3.7 The depth-averaged flow velocity decreases over a local deepening of the bottom (‘flow deceleration’)

As a result of the greater water depth over the pit, the water flows more slowly. This is called ‘flow deceleration’. The value of the depth-averaged velocity over the designated extraction area is inversely proportionate to the water depth: $u_0/u_1 = h_1/h_0$ (see Figure 3.7).

As the depth-averaged flow velocity decreases, the sediment transport capacity in the pit also decreases. The increased water depth furthermore results in reduced sediment suspension by wave action, which is another factor in the decrease in sediment transport capacity in the pit (**Van Rijn, 1993**).

Consequently sediment is deposited in the pit, so that the sand pit becomes shallower.

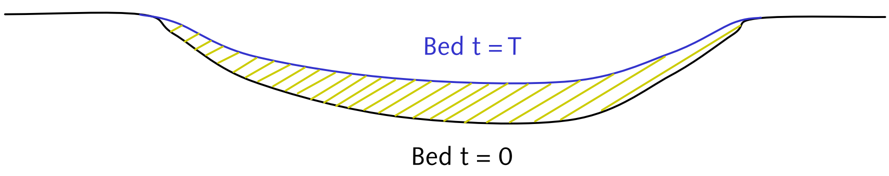


Figure 3.8 Shoaling of a temporary sand pit

The effect of sand pit deposition can roughly be approached as decreasing exponentially through time: immediately after construction the deposition is greatest, after which it decreases through time owing to a decreasing pit volume (Figure 3.9). Characteristic time scale T_e for decrease in pit volume V is then given through the time elapsed to the point of a 63% decrease in pit volume (=1-1/e; e=2.718). If two or more consecutive observations of the sea bed elevation of a designated extraction area are available, a rough estimate can be made of the characteristic time scale of the decrease in the pit volume.

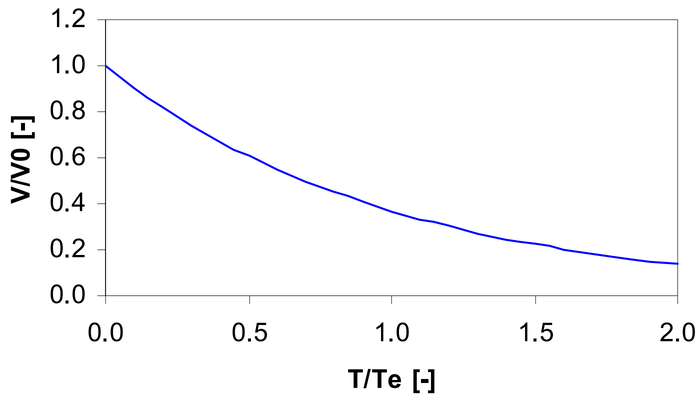


Figure 3.9 Pit volume V as a function of time T

Further hypotheses are:

- The characteristic time scale of filling decreases as local natural sediment transports increase.
- Natural sediment transports increase further inshore.
- The characteristic time scale for filling increases as the sand pit volume increases.
- The more the pit fills, the less flow deceleration occurs; sediment deposition virtually decreases.

Sedimentation sand originates partly from the immediate surroundings of the designated extraction area. In principle the erosion area is large compared to the pit area in which sedimentation takes place. As a result, bed changes of the surrounding area are smaller than the changes in the pit. *Further details can be found in Section 3.4.*

II. Morphological evolution of the nearshore coastal zone
Apart from the above-mentioned effects at the sand pit and its immediate surroundings, effects on the nearshore coastal zone as a whole are also to be

expected. These are connected to the effect of a local sand pit in the wave field.

At the sand pit site, the water depth exceeds that of the surrounding area. Consequently there
is in theory less friction between wave field and bed, which causes less wave energy dissipation. As a result the wave height directly shoreward of the pit slightly exceeds the wave height in the situation without the pit (Figure 3.10). The extent of this reduced decrease in wave energy depends in theory on the surface area of the sand pit and its absolute and relative depth compared to the immediate surroundings.

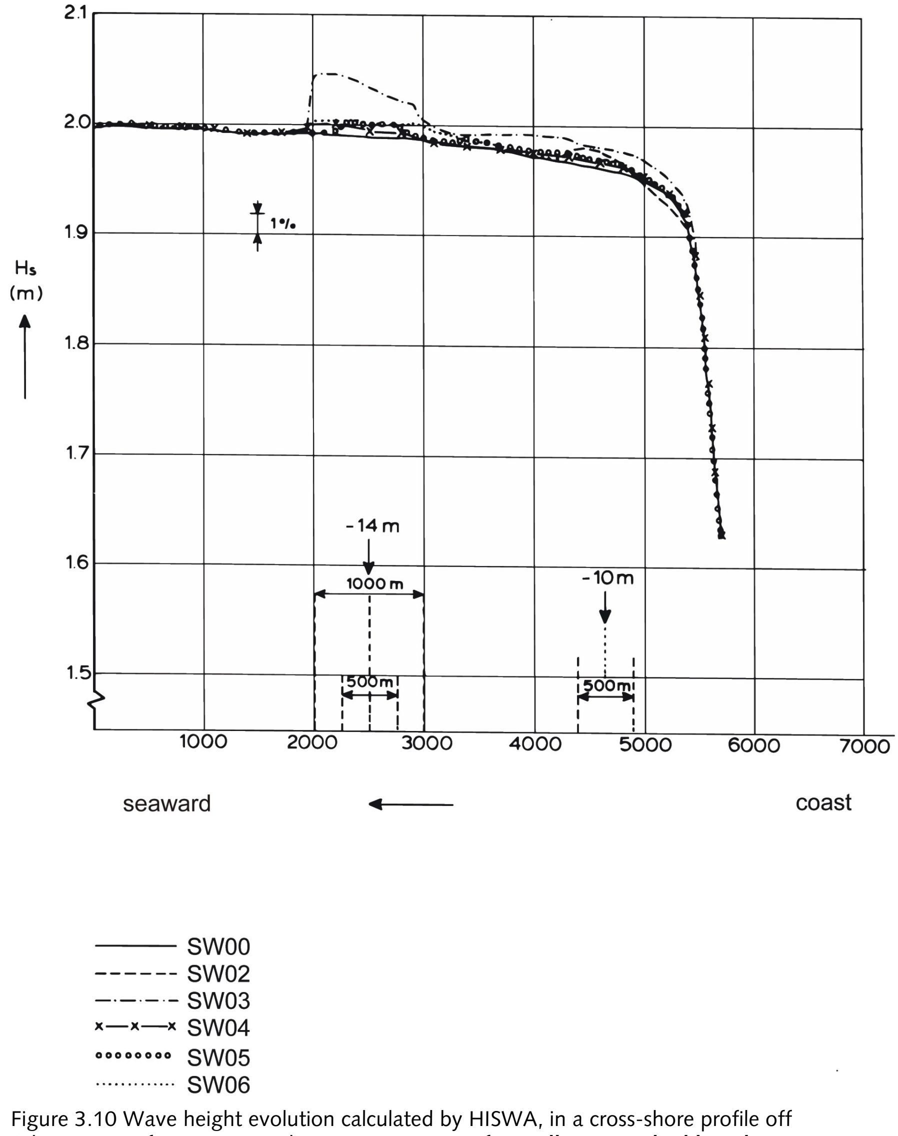


Figure 3.10 Wave height evolution calculated by HISWA, in a cross-shore profile off Scheveningen for various sand extraction variants, from **Allersma and Ribberink, 1992.** For sand extraction variant ZW03 (at NAP –14m, width 1,000m and extraction depth 5m), the wave height decrease in a shoreward direction is less pronounced than in the shallow extraction variants.

Moreover waves can change direction by refraction or reflection, resulting in a different wave energy distribution along the coast. This affects the wave-driven sand transports in the nearshore coastal zone, with the consequence of morphological changes to the shoreline. *Further details can be found in Section 3.5.*

III. Dune erosion under storm conditions
The sand pit can also have an influence on the wave field during storm conditions. This could lead to a change in the extent of dune erosion. Dune erosion is determined by the combination of water level, wave height and wave period during a storm. *Further details can be found in Section 3.6.*

3.4 Morphological evolution of temporary sand pits

3.4.1 User function: coastline maintenance

The use of a temporary sand pit for the purpose of beach nourishment provides an alternative to conventional methods of beach nourishment for the annually required coastal maintenance. There is a possibility, however, that the presence of the temporary sand pit near the beach nourishment site affects the effectiveness of the beach nourishment.

This section investigates if the morphological evolution of a temporary sand pit could lead to receding of the MCL. This is determined by (1) the filling rate in combination with (2) an expansion and/or shoreward shift of the pit surface area of the temporary sand pit.

The following pages examine observations of the sea bed elevation around former and present small-scale sand pits (Subsection 3.4.2), followed by the results of several morphological calculations (Subsection 3.4.3).

3.4.2 Morphological observations of small-scale sand pits

I. Tests with temporary sand pits
For the testing of a new dredging technique, the drawing pin, three experimental beach nourishment projects were carried out, using temporary sand pits. The first two tests concerned the locations Bloemendaal and Zandvoort (1993/1994), and the third test concerned the location Heemskerk/Wijk aan Zee (1996/1997) (see Figure 3.11).

An additional monitoring programme was extensively included in the tests to discover if a temporary sand pit would involve undesirable ecological and physical effects. The programme consisted of bed samples from the sediment and the bed fauna at the extraction location (before and after extraction / after backfilling of the sand pit) and in an undisturbed reference area. Furthermore soundings of the sand pit and its immediate surroundings were carried out before, during and after the execution. Measurements of the flow velocities or sand transports were not included in the monitoring programme. Technical evaluations of the execution were carried out afterwards (**Rakhorst and Mens, 1995; Rakhorst and Mens, 1997**). The monitoring results were described in the following reports: **Van Moorsel, 1994; De Looff and Hallie, 1995; Van Dalfsen, 1997; Van Dalfsen and Storm, 1998 a and 1998 b; Van Dalfsen et al, 1999**. The following subsections examine the sounding analyses.

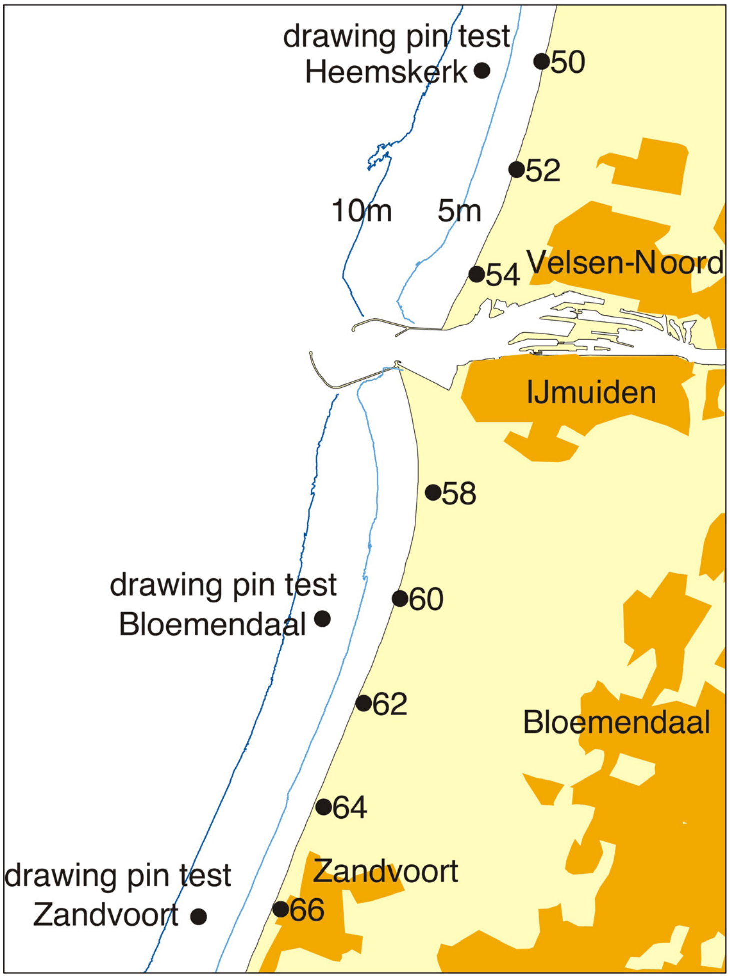


Figure 3.11 Position of the three 'Drawing Pin' tests

<u>'Drawing Pin' tests at Bloemendaal and Zandvoort:</u>
For testing purposes temporary sand pits were used for the execution of sand nourishment projects off Bloemendaal (near RSP[11] 61.5 km) and off Zandvoort (near RSP 67 km) in 1994. Both pits were constructed by means of the 'Drawing Pin', with the original sea bed elevation at NAP –7m. At Bloemendaal the pit was refilled as soon as 8 days after concluding the extraction operation, while at Zandvoort the periods of extraction and refilling overlapped. Consequently no data are available on the autonomous morphological evolution of the temporary extraction pits off Bloemendaal and Zandvoort.

<u>'Drawing Pin' test off Heemskerk/Wijk aan Zee:</u>
Off Heemskerk, near RSP 50 km, a second temporary sand pit was used as a test for the execution of a beach nourishment project (between RSP 49.65 and 51.25 km) in 1996/1997. The original sea bed elevation at the pit site was between NAP –7 and –8m.

[11] *RijksStrandPalen*: National beach poles located at regular intervals along the entire Dutch coast.

On 21 November 1996, extraction from the pit was suspended due to a broken pipeline, and it turned out that repair was not possible. Until 7 January 1997 the pit was left undisturbed, after which the pit was filled up (**Rakhorst and Mens, 1997**). Soundings during the undisturbed period were carried out on 28 November 1996 and on 7 January 1997. The following subsection briefly explains the autonomous morphological evolution over the period of 40 days between these two soundings.

Figure 3.12 presents a difference map of both soundings, which shows that sedimentation (yellow and red) is concentrated around the deep parts of the pit. Near the pit banks, a lightly eroded area is visible. The cross-section map (Figure 3.13) shows a slight levelling-off of the seaward and shoreward slopes. This indicates that backfilling of the pit mainly occurs by cross-shore sand transport. The minimum bed elevation increases from NAP –16.9m to NAP –13.7m.

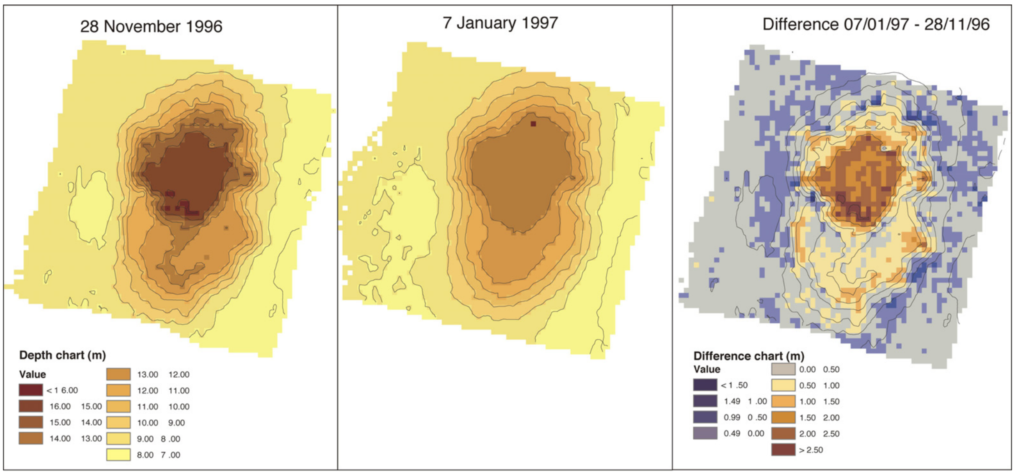


Figure 3.12 Difference chart of the bed elevation (7 January – 28 November 1996) at the temporary sand pit and surrounding area off Heemskerk.

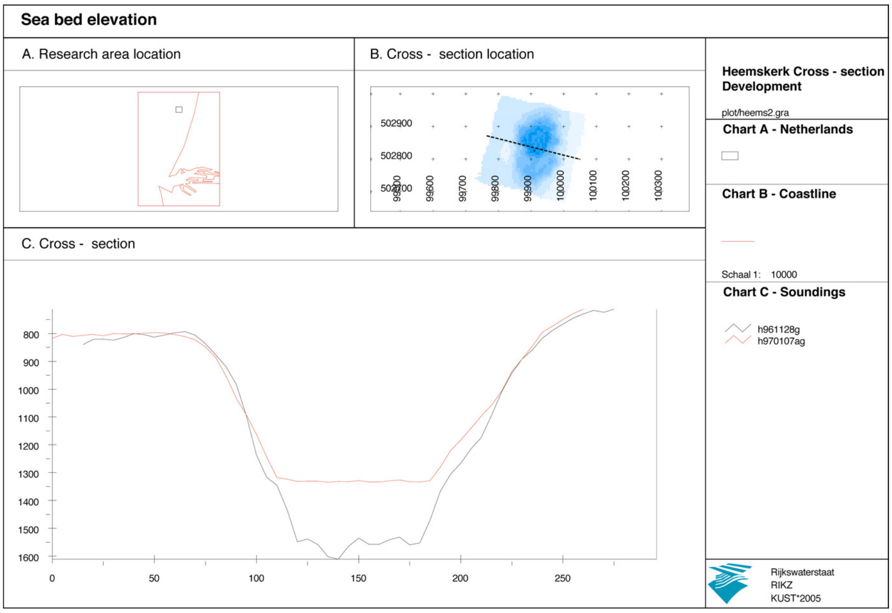


Figure 3.13 Cross-section evolution of the temporary sand pit off Heemskerk

According to the sounding of 28 November, the pit volume was approx. 154,000 m^3. As the soundings of 7 January then show that over a period of 40 days the pit volume decreased to a volume of approx. 128,000 m^3 (**Rakhorst** and Mens, 1997). This means that the characteristic time scale for backfilling of the pit is 222 days.

II. Former sand designated extraction areas in the nearshore coastal zone

Test trench off Scheveningen

For the construction of a wastewater pipeline off Scheveningen, a test trench was dredged between 3 and 5 March 1964. The most shoreward part of the trench was 700m seaward of the RSP line (RSP102) and stretched to a distance of 1,350m seaward of the RSP line (Figure 3.14). The width was approx. 50m and the depth was a maximum of 2m in relation to the surrounding bed. The undisturbed bed elevation varied from NAP –7m on the shoreward side to NAP –10.5m on the seaward side of the trench.

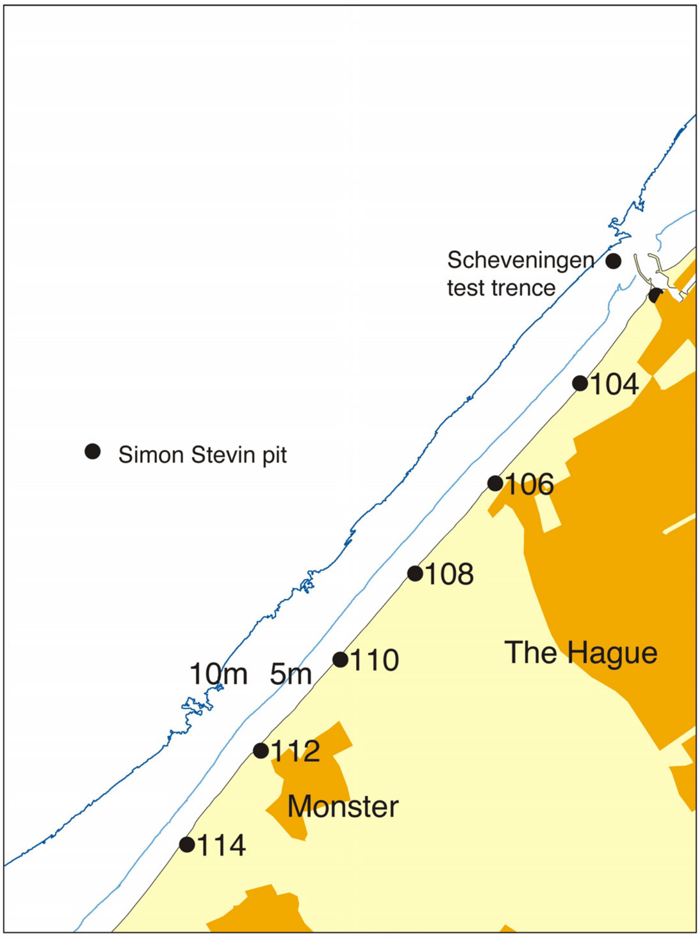


Figure 3.14 Location of the Scheveningen test trench and the Simon Stevin pit off the coast of South Holland

Based on 9 soundings, which were defined as reliable, the bed evolution of the trench was deduced. Immediately after construction, the total trench volume amounted to approx. 20,000 m^3 (**Svašek, 1965**). After a period of 173 days an accretion of 13,000 m^3 had occurred, which implies that the characteristic time scale for backfilling of the trench is 165 days.

The following was concluded about the cross-section evolution (see Figure 3.15):

- The decrease in the maximum depth takes place faster than the rate at which the volume changes as a result of levelling of the test trench slopes. Local erosion of the slopes therefore occurs in favour of the deepest part of the trench.
- Immediately after construction the maximum gradient of the trench was 1:5, and within two months gradients of 1:10 to 1:15 were observed. According to all soundings, the southern slope remained steeper than the northern slope.

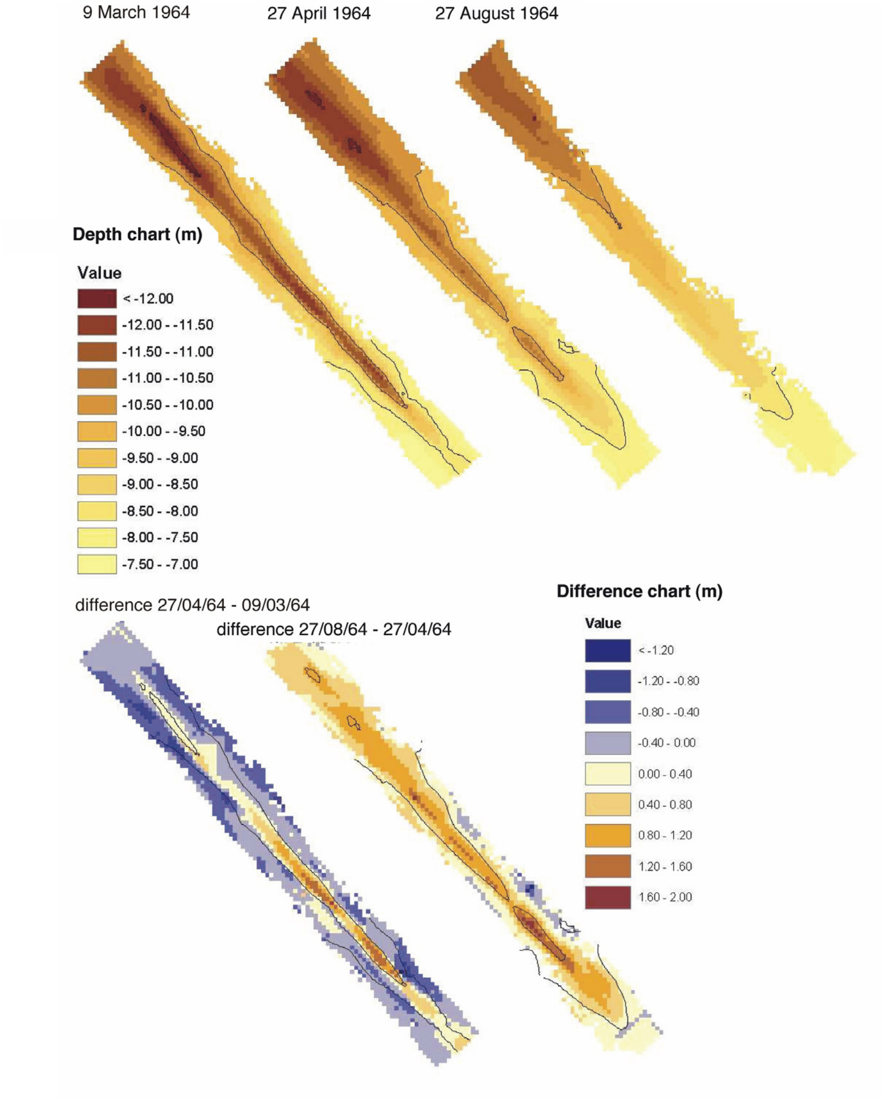


Figure 3.15 Bed evolution of the Scheveningen test trench: erosion on the banks and sedimentation in the trench

Simon Stevin pit

In preparation of the possible construction of a deep extraction pit for dumping dredged material from the port of Rotterdam, the 'Simon Stevin pit' (Figure 3.14) was constructed as an experiment. The pit was constructed on 3 July 1981, after which the pit was open until 5 July 1983. The pit was then restored to its former depth, by means of an extraction, and immediately afterwards filled with harbour silt. The surface area of the pit was 100 * 100 m^2, while the depth below the original bed was 6 metres; the original bed elevation was NAP –15.5m.

The natural morphological evolution of the pit was closely monitored (**Pluijm and Bossinade, 1986; Pluijm, 1994**) (Figure 3.16). It turned out that the pit filled up too quickly – within a year the pit volume had decreased from 60,000 m^3 to 10,000 m^3. Sedimentation consisted of sand as well as silt. After a year sedimentation still occurred, until a bed elevation was reached of NAP –17.5 m. Based on the above data, it can be calculated that the characteristic time scale for backfilling this pit is 204 days.

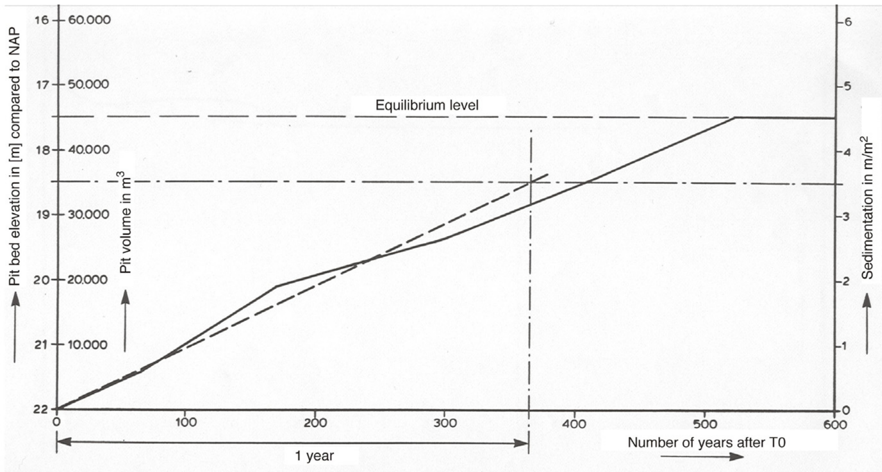


Figure 3.16 Pit volume evolution through time, from **Pluijm and Bossinade, 1986.**

Sand pit off the island of Ameland

A beach nourishment project of approx. 1 million m^3 was carried out off the island of Ameland in the autumn of 1990, for which a transhipment pit was used located at RSP 14 km in the nearshore coastal zone, around the NAP –9m depth contour (Figure 3.17). A leak in the pipeline which pumped the sand to the beach caused a local sand bulge on the shoreward side, being the south side. This bulge was largely removed when the pipeline was repaired, but a bulge remnant (above NAP –8m) is visible in the soundings.

The pit was constructed by means of a 'cutter suction dredger' or hopper suction dredger. After conclusion of the beach nourishment operations, the pit was *not* backfilled. It appears from the sounding of 19 December 1990 that the pit volume was approx. 140,000 m^3, the surface area approx. 0.5 ha and the maximum pit depth NAP –16.4m, which is over 7m below the local bed elevation (**Van der Woude, 1992**).

The natural morphological evolution over the period from 19 December 1990 to 10 July 1991 was analysed on the basis of sounding data of the pit and surroundings by **Van der Woude, 1992**. The sounding data show that the pit volume decreased through time in relation to a horizontal reference level at NAP –10m. On 10 July 1991, which was after 203 days, the volume had decreased by approx. 60,000 m^3 and the maximum pit depth from NAP – 16.4m to NAP –12.7m. Based on an exponential decrease in the pit volume, the estimated characteristic time scale of natural backfilling of the sand pit is approx. 1.0 year.

In addition to backfilling, a shift of the centres of gravity of the sand pit and the bulge in an eastward direction (ie longshore) was observed. The sand pit shifted approx. 12m, the bulge approx. 32m. In a cross-shore direction, the shift of the centre of gravity is much smaller. The sand pit remains at approximately the same position, the bulge shifts approx. 13 m shoreward.

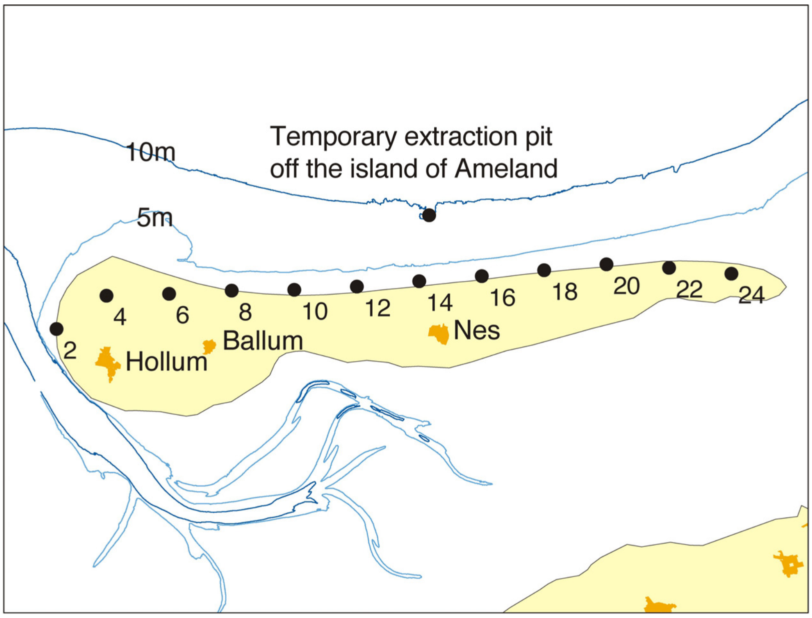


Figure 3.17 Location of the temporary sand pit off the island of Ameland

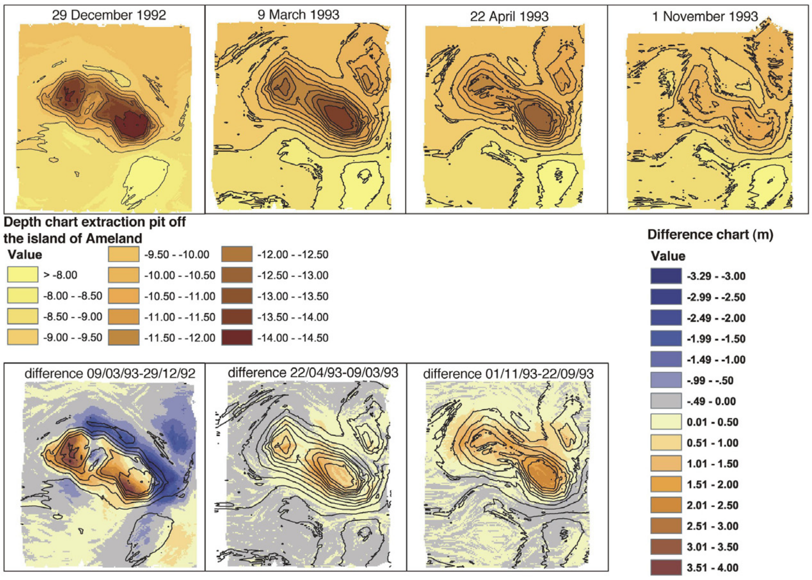


Figure 3.18 Morphological evolution of the temporary sand pit off the island of Ameland

In 1992 the sand pit was used again for the execution of a beach nourishment project. After conclusion of the beach nourishment operations, the pit was again not backfilled. The remaining pit had a maximum pit depth of NAP – 14.5m, which is over 4m beneath the local bed elevation.

The natural morphological evolution between 29 December 1992 and 1 November 1993 was analysed on the basis of sounding data of the pit and surrounding area (see also **Jetten and Lei, 1998**). Figure 3.18 shows the morphological evolution of the pit. Between 29 December 1992 and 3 March

1993, the pit shifted in a north-westerly direction. After 9 March, however, shifting greatly reduced and the pit mainly filled up. Based on an exponential decrease in the pit volume between 9 March 1993 and 1 November 1993, the characteristic time scale of natural backfilling of the sand pit can be estimated at approx. 187 days (see Table 3.2).

Date	Days After 09-03-93	Volume (m^3)	Depth (m + NAP)
9 March 1993	0	257000	–13.8
22 April 1993	44	193000	–12.9
1 November 1993	237	71000	–10.9

Table 3.2 Decrease in sand pit volume and depth off the island of Ameland

III. Observations of sand extraction locations in the deeper parts of the North Sea

The hydrodynamic conditions and the sediment composition in the deeper parts of the North Sea are not entirely comparable to those in the nearshore coastal zone. Observations of former sand designated extraction areas nevertheless may give qualitative values.

Terschelling designated extraction area

In the deeper parts of the North Sea, sand extraction for the sand trade and for beach nourishments is carried out in the designated designated extraction areas (see Figure 2.2). Usually the bed elevation of a designated extraction area is only measured just before sand extraction starts, and again immediately afterwards to determine the sand volume extracted. The bed elevation of one designated extraction area northwest of the island of Terschelling, seaward of the NAP –20m depth contour, was measured more often (Figure 3.19). This was done as part of the European RIACON project (**Van Dalfsen and Essink, 1997**), which focused on the ecological effects of sand extraction. The sand from the designated extraction area was used for the first experimental shoreface nourishment off the island of Terschelling in 1993.

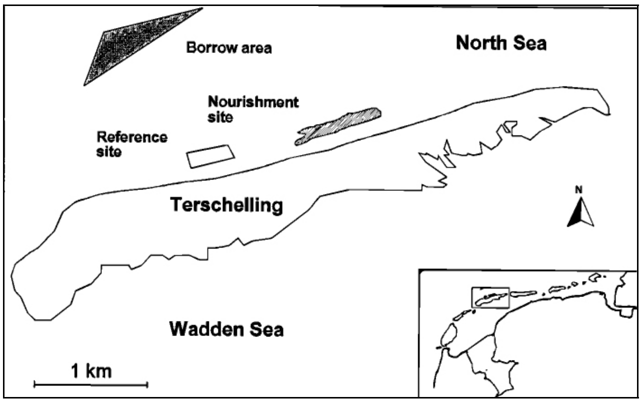


Figure 3.19 Bed elevation 1997 of the designated extraction area northwest of the island of Terschelling, from **Van Dalfsen, 1998b**.

Soundings of the designated extraction area and its immediate surroundings prove that the bed elevation hardly changes over a period exceeding 4 years (Figure 3.20). As a result of the slight deepening of the designated extraction area of approx. 2m, and the relatively large water depth (20m), the natural processes are affected to a limited degree only. It may be assumed that the morphological adaptation of the designated extraction area occurs on a large time scale (**Van Dalfsen, 1998b**).

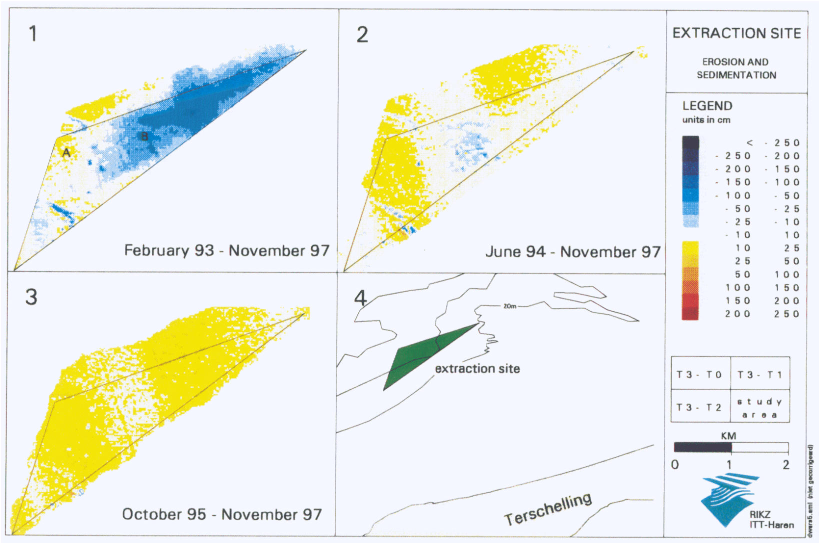


Figure 3.20 Bed difference maps of the designated extraction area off the island of Terschelling (RIACON Project). Sedimentation (yellow) and erosion (blue) are visible for the period of February 1993 - November 1997, from **Van Dalfsen 1998b**.

IV. Observations of sand extraction locations in the Wadden Sea

The hydrodynamic conditions and sediment composition in the Wadden Sea differ from those in the nearshore coastal zone and in the deeper parts of the North Sea. Observations of former sand designated extraction areas may nevertheless have qualitative values.

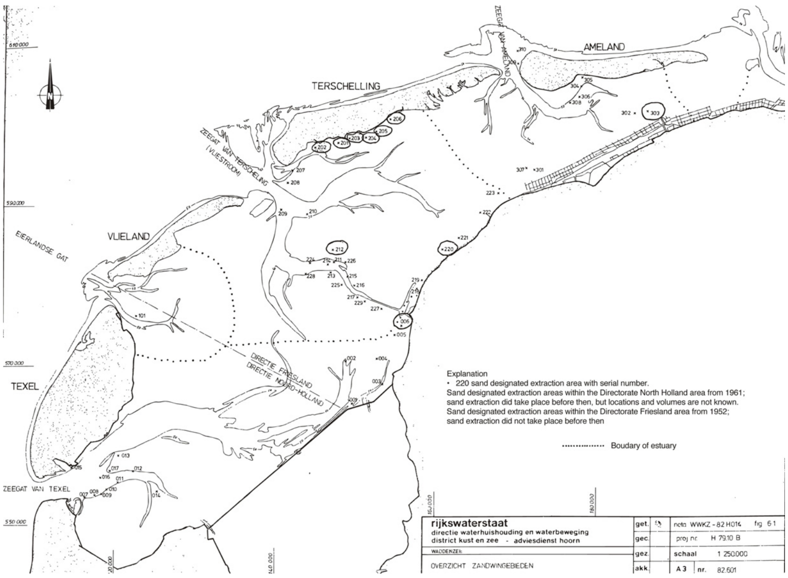


Figure 3.21:
EXPLANATION
• 220 Sand designated extraction area with serial number
Sand designated extraction areas within the Directorate North Holland area from 1961; sand extraction did take place before then, but locations and volumes are not known.
Sand designated extraction areas within the Directorate Friesland from 1952; sand extraction did not take place before then.

Figure 3.21 Overview of extraction locations in the western part of the Wadden Sea (up to the Ameland tidal divide, from **Rakhorst, 1982**. The morphological evolution of the circled sand pits has been studied.

An inventory of sand extraction in the western Wadden Sea (up to the Ameland tidal divide) is given for the period 1955 up to and including 1980 in **Rakhorst, 1982**. Over that period a total of approx. 58 million m^3 was extracted, spread over 57 different extraction sites (see Figure 3.21).

The volume evolution and sedimentation rates of four sand extraction pits (‘Griend’, ‘Boontjes-Harlingen’, ‘Oosterbierum’, ‘Kikkertgat’) and one group of sand pits (‘Terschelling’) have been determined over several years (**Rakhorst and Midderham, 1979**). The extraction pits varied in volume from approx. 120,000 to 700,000 m^3. The volume evolution shows that there are considerable differences in sedimentation rates (Figure 3.22). This is hardly surprising considering the many factors of local sediment transports.

Designated extraction area ‘Oosterbierum’ (no. 220) is located just off the coast of Friesland and has a high sedimentation rate. Of the initial volume of approx. 460,000 m^3, only 20,000 m^3 is left after 8 months, which means that the characteristic time scale for filling a sand pit is 2.5 months and the sedimentation rate is approx. 660,000 m^3/year. This extremely high backfilling rate can be attributed to sedimentation of silt.

The pit group ‘Terschelling’ (nos. 201-206), which is located just off the coast of the island of Terschelling and not far from the tidal divide, has a slow sedimentation rate. It will take at least 10 to 15 years to fill up six pits – varying in volume from 120,000 to 300,000 m^3. The average linear sedimentation rate varies from 6,000 to 16,000 m^3/year. In this area, which has low flow velocities and which is protected against waves, there is significantly less sediment transport than elsewhere in the Wadden Sea.

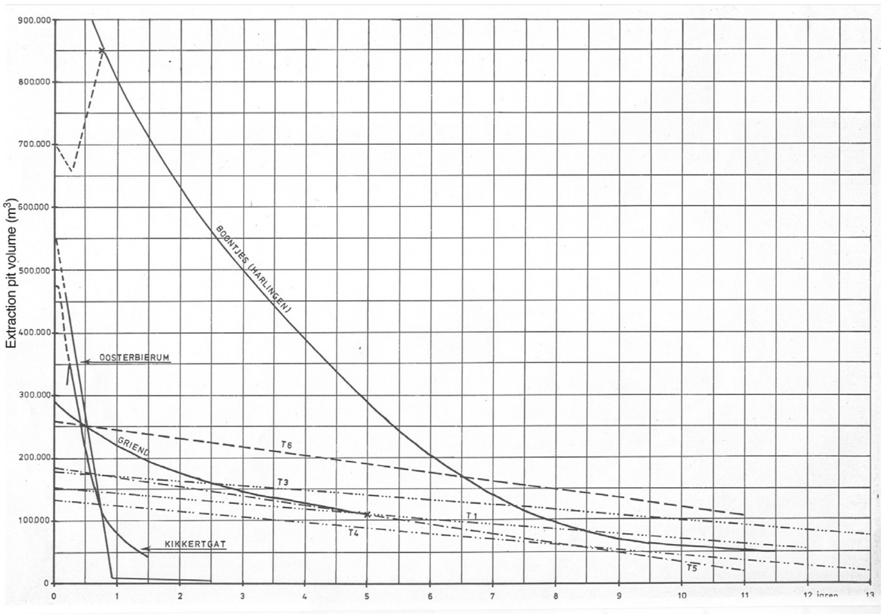


Figure 3.22 Sediment deposition in sand pits in the Wadden Sea, from **Rakhorst and Midderham, 1979.**

In the pits ‘Boontjes-Harlingen’ (no. 006) and ‘Kikkertgat’ (no. 303), the sedimentation rates decrease as the pit volumes decrease (see Figure 3.23).

This means that the pit volumes decrease exponentially through time. At the 'Griend' pit (no. 212), this only occurred in the first year; in the following years the sedimentation rate was practically constant and the pit volume decreased linearly through time.

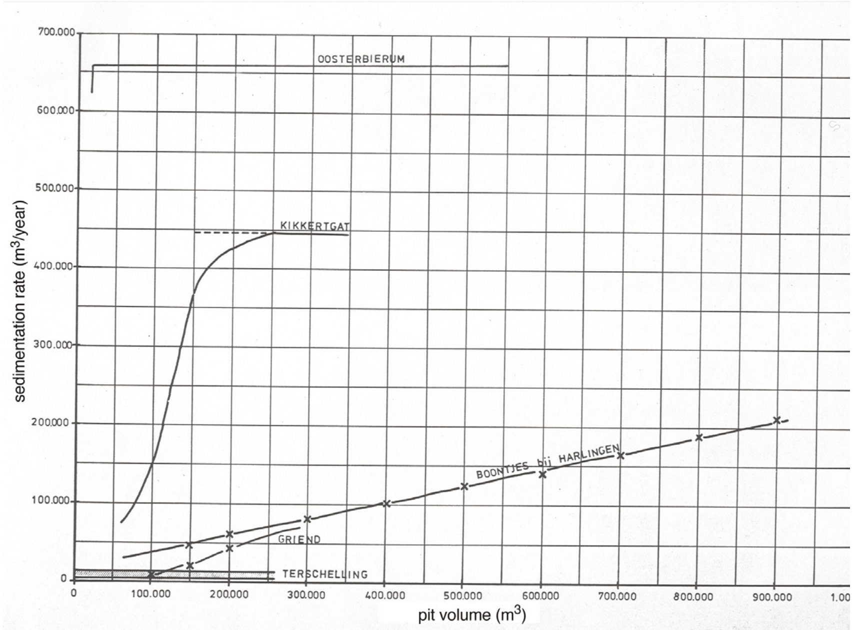


Figure 3.23 Relation between pit volume (m^3) and sedimentation rate (m^3/year)

Gerritsen, 1997, has made a theoretical estimate of the characteristic time scale of sedimentation for the above-mentioned former designated extraction areas in the Wadden Sea**.** His results are reasonably consistent with the time scales deduced from the observations (**Rakhorst and Midderham, 1979**).

3.4.3 Model calculations of the morphological evolution of a sand pit

Sedimentation in a sand pit can be calculated by means of simple or more complex numerical models. An example of a simple model for the calculation of sand pit sedimentation (in m^3/m) is given in **Eysink, 1979**. This model distinguishes between transport of sediment close to the bottom and transport of sediment in suspension higher up in the water column. This model describes that:

- The degree of sedimentation increases as the local natural sediment transports increase
- The amount of sedimentation is at a maximum equal to the local natural sediment transports
- Sedimentation increases as the pit surface area increases, thus as the pit is deeper or wider in relation to the dominant transport direction.

SUTRENCH (**Van Rijn and Tan, 1985**) is a more complex model. It is relatively effective for areas with a dominant tidal current and little variation in grain size distribution of the sediment (**Walstra et al, 1998**). Such a model does not only calculate sedimentation but also the entire change of a designated extraction area cross-section.

Of course the sedimentation time scale calculated by a numerical model strongly depends on the sand transport volumes defined as a boundary condition. For larger sand transports, sedimentation is also larger, which results in a smaller time scale of backfilling.

The available observations (Subsection 3.4.2) of the cross-section evolution of a sand pit in the nearshore coastal zone show that there is little influence on the cross-shore profile. No deduction can be made from this if the latter is also the case for sand pits at lower water depths and closer to the coast, or at other locations along the coast.

Scenario calculations were performed using the numerical model UNIBEST-TC **(Klomp, 1996)**. The cross-shore profile evolution of various locations along the Dutch coast was calculated over a period of 1 year for several extraction variants. The period of 1 year is amply sufficient, since in practice the temporary sand pit is often in use for a shorter period. The model results show, as do the observations of the Ameland pit, that the effect of the presence of the cross-shore profile is minor, with the exception of a sand pit off the coast of Zeeuws-Vlaanderen (see Figure 3.24).

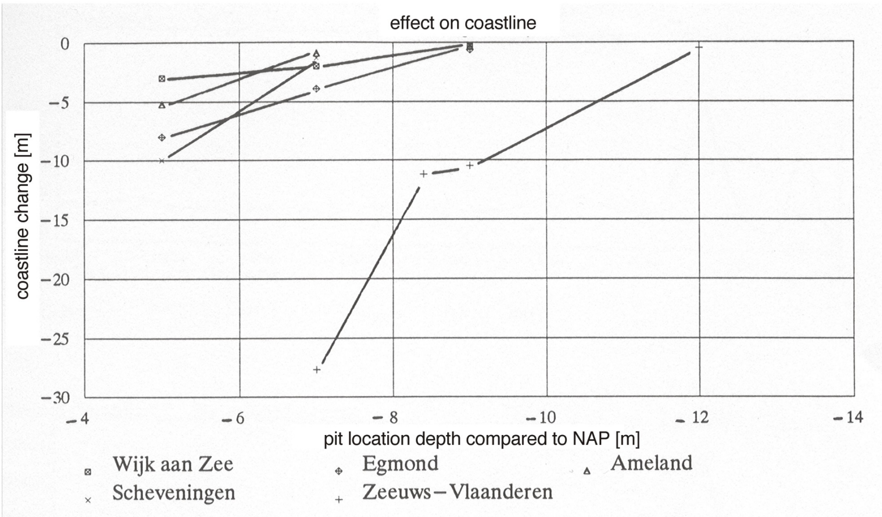


Figure 3.24 Effect of a temporary sand pit on the MCL as a result of a changed cross-shore bed profile, from **Klomp, 1996**.

3.5 Morphological evolution of the nearshore coastal zone

Coastline maintenance
As a result of the effect on the wave field, the wave-driven sand transports in the nearshore coastal zone change and morphological changes occur.

In the longer term, the change of the wave field – under ‘normal’ conditions – affects the **sand balance** of the nearshore coastal zone. A theoretically raised wave field shoreward of the pit results in a gradient in the longshore wave height distribution. As a result of the effect of the waves on the sediment transport, a gradient consequently also occurs in the longshore wave-driven sand transports, which results in erosion and sedimentation areas.

A striking example is found in America. Two sand pits were constructed just off the coast for carrying out a large sand nourishment operation (approx. 5.5 million m^3). As a consequence of the presence of these two extraction pits, a visible shoreline undulation occurred (**Combe et al, 1987**).

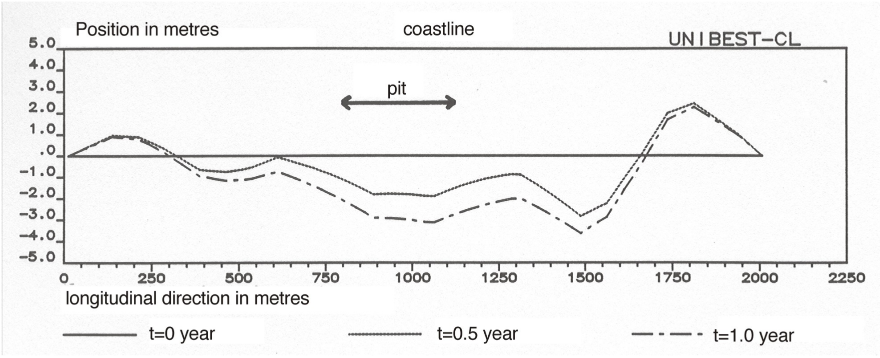


Figure 3.25 Effect of a temporary sand pit on the MCL, from **Klomp, 1996**. The change in the MCL position along the coast amounts to a maximum of several metres.

Such effects are considered extreme. If a temporary pit is used, a limited redistribution is expected at most. In **Klomp, 1996**, the effect on the cross-shore and longshore morphological evolution is calculated for a sand pit at NAP –7m off Wijk aan Zee. After one year the local receding of the MCL amounts to a few metres at most (see Figure 3.25). These results are considered representative for the entire Dutch coast, including the central parts of the Wadden Islands.

3.6 Dune erosion under storm conditions

Coastal safety

The presence of a temporary sand pit in the nearshore coastal zone can theoretically affect the wave field under extreme storm conditions. Dune erosion under storm conditions can be calculated with the numerical model DUROSTA. An example of a model calculation using DUROSTA is given in Figure 3.26. It gives the degree of dune erosion if extreme storm conditions, with a probability frequency of 1/10,000 per year, would have occurred during the 'Drawing Pin' test off Heemskerk. During these conditions, the maximum water level was NAP +5.7m, the significant wave height was 8.5m and the peak period 12.5 s. These calculations show that the temporary sand pit located at NAP –8m hardly affects dune erosion, while the dune erosion volume exceeding NAP +5m amounts to approx. 0.3%.

It can be concluded from these calculations, that as a result of the presence of a sand pit a slight increase in dune erosion is to be expected, which decreases as the surface area of the pit decreases and as it is further offshore. If a sand pit is used seaward of NAP –7m with a limited surface area (< 10 ha), the effects on dune erosion are not significant, ie in the order of 5%. These results are considered representative for the entire Dutch coast, including the central parts of the Wadden Islands.

The dune erosion model DUROSTA does not allow for wave refraction and wave reflection, which cause different distribution of wave energy over the shoreward-located zone. Allowing for these 2DH effects results in a redistribution of the increased wave energy.

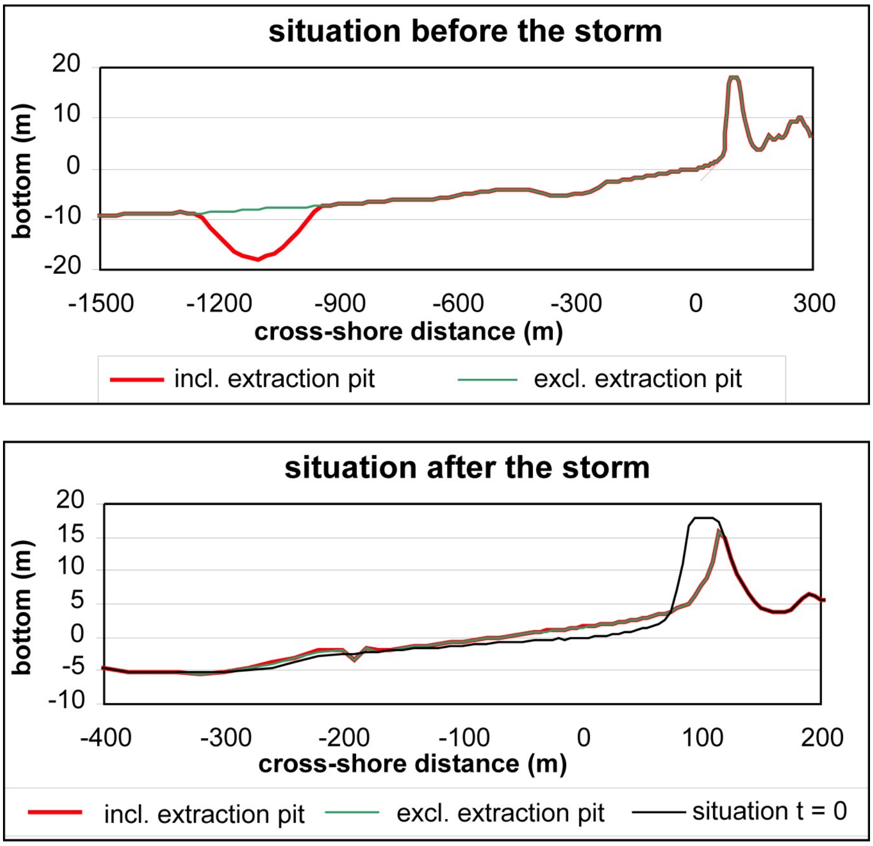


Figure 3.26 Dune erosion calculations with DUROSTA for the 'Drawing Pin' test off Heemskerk during extreme storm conditions

3.7 Conclusions: effects of temporary sand extraction in the nearshore coastal zone

The main questions in this chapter are:

> *What physical effects occur as a result of the use of a temporary sand pit in the nearshore coastal zone and what influence do these effects have on the user functions, coastal maintenance and coastal safety?*

Physical effects

At the site of a temporary sand pit, the water depth exceeds that of its immediate surroundings, which causes 'flow deceleration'. Furthermore, there is a reduced sediment suspension by wave action, which causes reduced sediment transport capacity. This causes sedimentation in the pit, as a result of which the pit becomes more shallow and eventually disappears. Part of the sediment deposited in the pit originates from the immediate surroundings. This allows erosion around the banks of the sand pit, causing gentler slope gradients. In addition to the sand pit backfilling, its centre of gravity could shift.

Observations of the bed evolution of temporary sand pits in the nearshore coastal zone of the North Sea show that the pits fill up over a relatively short period of time. There is hardly any evidence of shifting sand pits, with the exception of the temporary sand pit off the island of Ameland. Table 3.3 shows a summary of the location, volume and characteristic time scale of natural backfilling of the sand pits that were studied. The characteristic time scale of backfilling is 6 to 12 months. This time scale is considerably smaller than the time scale at which the 'RIACON' sand pit off the island of Terschelling is filling (water depth > 20m).

Location:	Volume (m^3)	Characteristic Time Scale (Days)
'Drawing Pin' test off Heemskerk	154000	222
Test trench off Scheveningen	20000	165
Ameland (I)	140000	365
Ameland (II)	257000	187
Simon Stevin pit	60000	204

Table 3.3 Summary of analysed sand pits in the nearshore coastal zone

Figure 3.27 gives the percentage of natural backfilling of a pit as a function of the time in months, taking a characteristic time scale of 6 to 12 months as a basis. The graph shows, for instance, that the percentage of natural backfilling varies between 8% and 15% after one month and between 15% and 28% after two months.

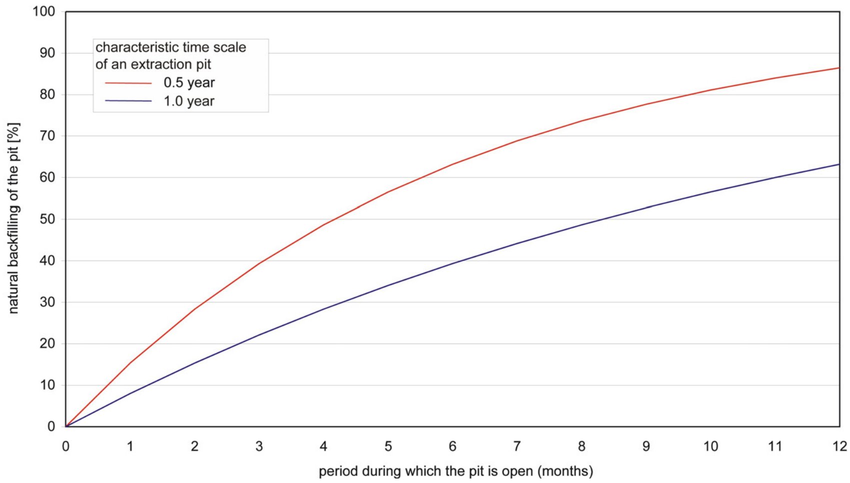


Figure 3.27 Natural backfilling of a temporary sand pit in time, depending on the characteristic time scale

A number of factors affect the characteristic time scale, such as the season during which the sand pit was constructed, the water depth at which it was constructed, its shape, the local tides and the grain size diameter of the sediment in the area. For instance, a short time scale is expected for a temporary sand pit constructed during the winter season at a shallow location with steep slopes, high tidal current velocities and a small grain size diameter.

Effect on coastal maintenance and coastal safety

The possible effect of the presence of a temporary sand pit on the coastline position or on the degree of dune erosion cannot be deduced from observations. Model calculations (UNIBEST-TC, UNIBEST-CL) show that the presence of a temporary sand pit in the nearshore coastal zone – along the Dutch coast or the central parts of the Wadden Islands – could result in a local receding of the coastline of several metres on a time scale of one year.

Model calculations for determining dune erosion (DUROSTA) indicate that the presence of a temporary sand pit in the nearshore coastal zone off Wijk aan Zee could cause slightly increased dune erosion under extreme storm conditions. If a temporary sand pit is constructed at a depth of around NAP – 7m or deeper, the increase in dune erosion is less than 5%. This is subject to the condition that the surface area of the temporary sand pit is limited: under 10 hectares. These results are considered representative for the entire Dutch coast, including the central parts of the Wadden Islands.

4 Sand Extraction by Navigation channel Overdimensioning

4.1 Introduction to navigation channel overdimensioning

4.1.1 Question: what are the effects of navigation channel overdimensioning?

Widening and deepening, ie overdimensioning, of the Euro-Maas Channel and the IJ Channel is considered one of the that in the long term would is able to meet the need for relatively cheap sand for the execution of sand nourishments or for use as filling sand. The sand could be used for future land reclamation or for concrete and masonry sand.

The main question in this chapter is:

> *What are the consequences of large-scale sand extraction in the navigation channels, ie overdimensioning, to the coastal system and relevant user functions?*

4.1.2 The present IJ Channel and Euro-Maas Channel

There are two large navigation channels off the Dutch coast, the IJ Channel and the Euro-Maas Channel. In fact, these two navigation channels are the only relatively large scale designated extraction areas near the Dutch coast (see box below).

The IJ Channel, which is the gateway to the port of IJmuiden, is located off the central part of the Dutch coast. The Euro-Maas Channel, which is the gateway to the port of Rotterdam, is located at the southern point of the Dutch coast (see Figure 4.1). Good access to the ports of IJmuiden and Rotterdam is of major economic importance.

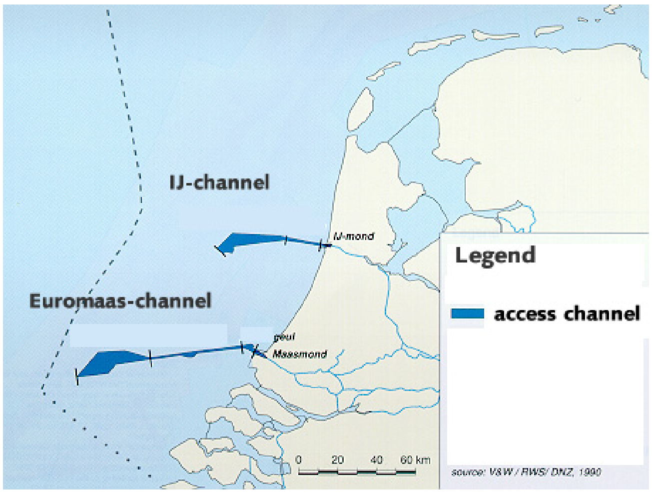


Figure 4.1 Locations of the IJ Channel and Euro-Maas Channel off the Dutch coast

Specifications of IJ Channel and Euro-Maas Channel

The IJ Channel is approximately 23 km long, 450 km wide and has a bottom target depth of NAP –19m. The 'approach area' further seaward is not discussed here. Since 1 October 1985 the IJ Channel gives access to vessels of 54 ft (16.5m) draught. The IJ Channel lies at an angle of approx. 80 degrees with the north. The total navigation channel volume is approximately 50 million m^3.

The Euro-Maas Channel is slightly larger in volume, ie 600m wide, and has a bottom target depth of 26 metres. This means that the navigation channel gives access to vessels of 75 ft (=22.9m) draught. The navigation channel consists of two parts. The Maas Channel, from the Noorderhavenhoofd to 11.5 km seaward, is situated at an angle of approx. 65 degrees with the north. The Euro navigation channel is situated further seaward, at an angle of 98 degrees with the north. On the northern side of the bend between Maas Channel and Euro navigation channel is an anchor area. This report deals only with the part of the navigation channel up to 20 km from the Maasmond, and does not discuss the 'approach area' situated further seaward. The total navigation channel volume is approximately 70 million m^3*. The Maas Channel was recently deepened to NAP –31m in the zone between 6 and 11 km from the Maasmond.*

4.2 System description of IJ Channel and Euro-Maas Channel

The most seaward part of the IJ Channel, which can in fact hardly be recognized as a navigation channel, is influenced morphologically by the presence of shoreface-connected ridges and sand waves (see Figure 4.2).

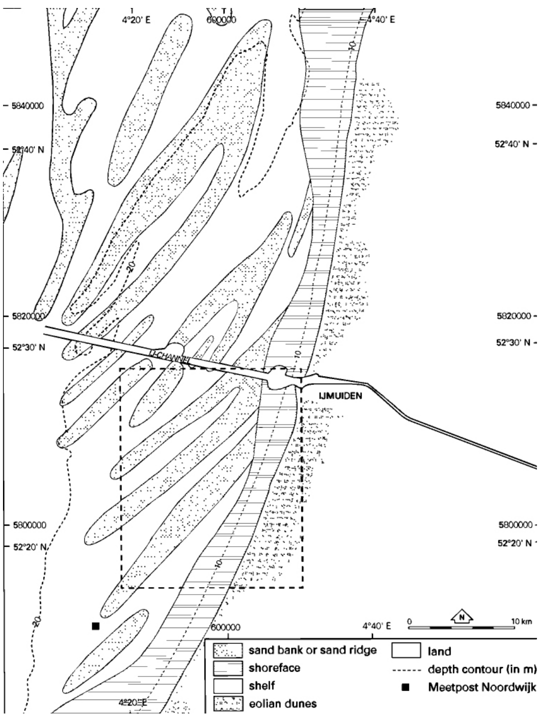


Figure 4.2 The sea bed around the IJ Channel is influenced morphologically by the presence of shoreface-connected ridges, from **Van de Meene, 1994.**

The most seaward part of the Euro navigation channel, which can in fact hardly be recognized as a navigation channel, is influenced morphologically by the presence of shoreface-connected ridges and mega ripples (see Figure 4.3).

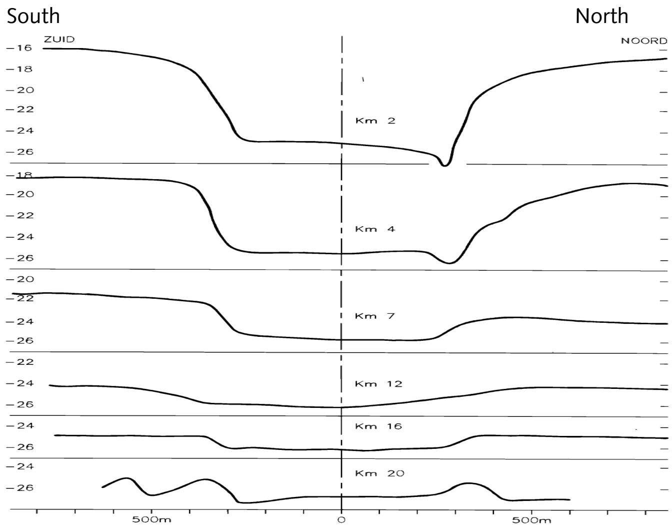


Figure 4.3 Cross-sections of the Euro-Maas Channel (period 1989-1991) for various distances in relation to the Noorderhavenhoofd, from **Allersma and Ribberink, 1992.**

The water movement in this area is dominated by the tide – the tidal current is practically perpendicular to both navigation channels, with the exception of the Euro navigation channel.

Fresh water transport from the rivers is another important factor. From the Scheldt, the New Waterway (Rhine/Maas) and the Haringvliet relatively fresh river water is transported to sea. As fresh water is lighter than salt water, an 'estuarine circulation' is created. Fresh water from the rivers flows seaward at the surface and mixes with the salty sea water (see Figure 4.4). Salt water flows coastward along the bottom. For a mean year, the shoreward flow velocity near the bottom of approx. 0.03 m/s was deduced from measurements (**De Ruijter et al, 1992**).The seaward component at the surface is weak.

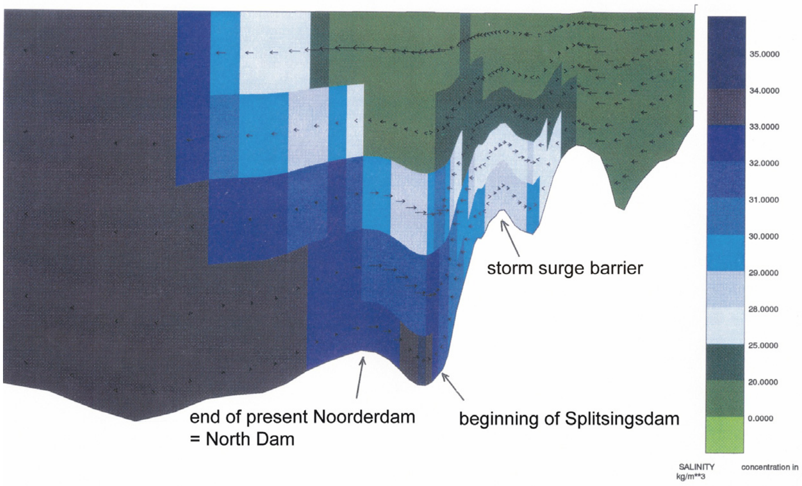


Figure 4.4 Estuarine circulation in the New Waterway (at slack water), from **De Looff et al, 1995.**

The shoreward residual flow near the bottom causes the sand and silt transport to be pushed against the shore in a narrow band. This is also known as the ‘coastal river’. An important part of sedimentation of the fine sand and silt occurs in the harbours. Another large part of sedimentation occurs in the Wadden Sea. Both areas have in common that the wave action effect is strongly reduced compared to the ‘open’ North Sea.

The presence of fresh water over salt water creates vertical density differences (‘stratification’). The area off the Dutch coast which is affected by stratification and the related estuarine circulation concerns the shoreward part of the uninterrupted Dutch coast and the tidal basins of the Delta coast.

In the area around the harbour estuaries, hydraulics are strongly affected by the presence of the breakwaters. The tidal current is forced away from the coast, which results in a tidal contraction zone directly in front of the breakwaters. Larger water level differences occur along the coast and consequently larger flow velocities, particularly around the navigation channel banks. In the case of the Euro-Maas Channel, tidal contraction is further increased by the presence of the Maasvlakte. This results in a local complex three-dimensional flow pattern (**Allersma and Ribberink, 1992**).

4.3 Effects of channels to user functions

4.3.1 Physical aspects and user functions of channels

The physical effects of a channel on user functions are divided into three physical aspects (see Table 4.1). First the effects of the channels in their present form are examined, after which the relative effects of overdimensioning in relation to the user functions are described (Section 4.7).

Physical Aspect	Relevant User Functions
Hydraulic aspects in the channels and their immediate surroundings (**Section 4.4**)	Shipping
II. Morphological evolution of the channels and their immediate surroundings (**Section 4.5**)	Channel maintenance operations, coastline maintenance and locations of cables and pipelines
III. Wave conditions in the coastal zone (**Section 4.6**)	Coastal safety and coastline maintenance

Table 4.1 Physical aspects in relation to relevant user functions of channels

4.3.2 Delineation: emphasis on Euro-Maas Channel and IJ Channel

In the study into the physical effects of the widening and deepening (overdimensioning) of the Euro-Maas Channel and IJ Channel, a link is made between the physical effects of both channels in their present dimensions. In Sections 4.4, 4.5 and 4.6 the study focuses on the effects of the channels in their original dimensions: a 70 million m^3 channel volume for the Euro-Maas Channel and a 50 million m^3 channel volume for the IJ Channel. Section 4.7 describes the effects of overdimensioning of both channels, in accordance with the Zero-Plus option in the present RON/MER. This option is based on a sand extraction volume of 320 million m^3 for the Euro-Maas Channel and 200 million m^3 for the IJ Channel.

In practice part of the overdimensioning has already been executed. Part of the Maas Channel now has a depth of approx. NAP –31m (see Figure 4.12). The Zero-Plus option seems to be insufficient to fill the future need for land reclamation, which is in the order of 500 million m^3.

4.3.3 Theory of the physics wit respect to channels

I. Hydraulics in the channels and their immediate surroundings
As explained in Section 3.3, 'flow deceleration' occurs at the site of a local deepening. This principle also applies to the IJ Channel and the Euro-Maas Channel, which are both practically perpendicular to the tidal current. The value of the depth-averaged velocity over the channel is inversely proportionate to the water depth: $u_0/u_1 = h_1/h_0$ (see Figure 3.8). The relative decrease in the depth-averaged flow velocity over the channel increases in a shoreward direction, which is caused by an increasing relative channel depth.

As a result of the velocity differences between the channel and its surroundings, minor differences in water level, being in the order of centimetres, could locally occur at the channel slopes.

The flow velocity directly in front of the harbour estuaries determines channel navigability and consequently shipping access of the IJmuiden and Rotterdam harbours. A depth-averaged approach is not applicable in this zone.

II. Morphological evolution of the channels and their immediate surroundings
As a result of the decreased depth-averaged tidal current velocities and the decreased effect of sediment suspension at greater water depths in the channel, the sediment transport capacity is smaller inside the channels than outside. During inflow into the channels sediment transports decrease and cause sedimentation, whereas sand transports increase during outflow and cause erosion. The distance across which sediment transport adapts to the changed conditions is also called the adaptation length. This adaptation length is several hundreds of metres.

The tide causes fluctuations in the sand transport direction and alternation of sedimentation and erosion. In the deeper parts of the channel, sand transports are presumed to be larger during flood than during ebb. This results in a net sand transport in the flood direction, ie northeast. As a consequence the south side and the channel bed silts, while the north side erodes (Figure 4.5). If no action is taken, the channel's centre of gravity shifts in a northeast direction.

We learn from the observations at the test pit off Heemskerk, the Scheveningen test trench and the sand pit off the island of Ameland, that the channels erode around the banks, which causes gentler slope gradients over a short period of time. The channel widens, in other words: the *morphological influence area* expands.

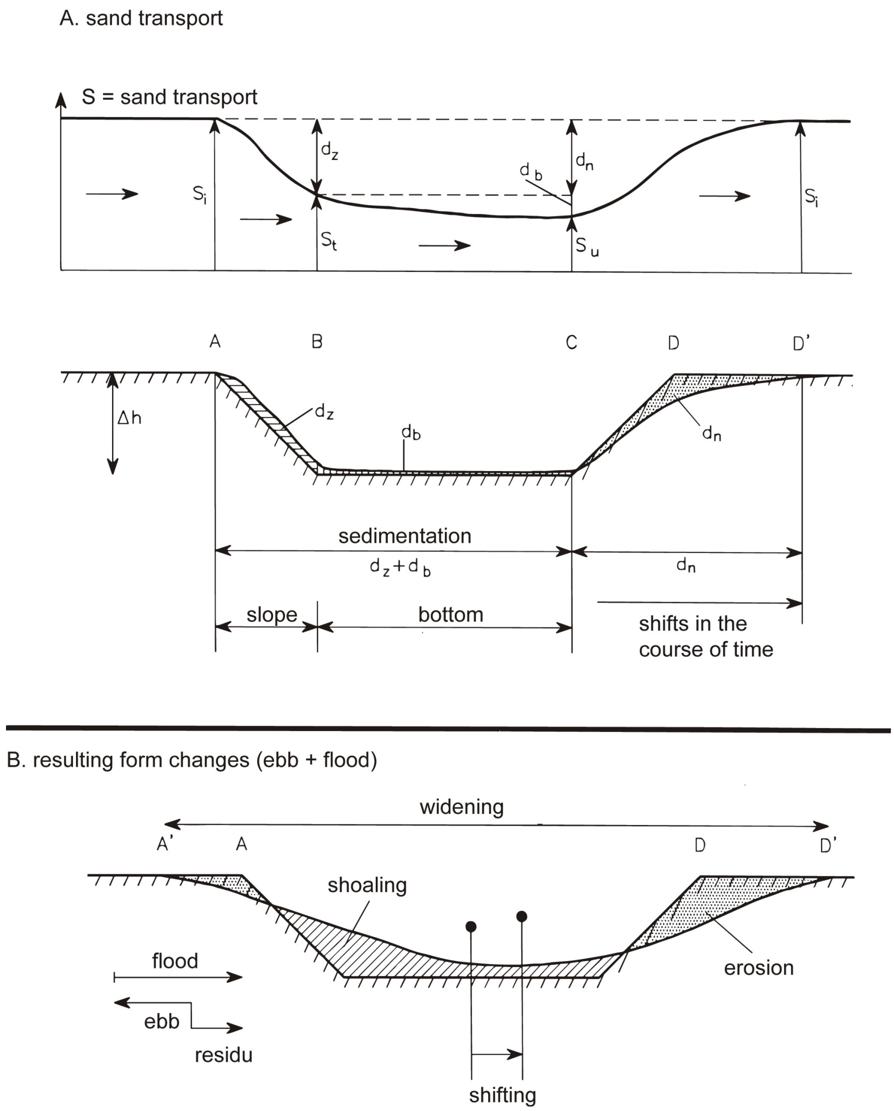


Figure 4.5 Sand transport and bed changes in a channel at low and high tides (A) and the resulting mean tide bed change (B), from **Allersma and Ribberink, 1992.** In this example the channel shifts in the flood direction.

Contrary to the behaviour in small-scale pits, channels only show a very slight decrease in channel volume, for which two reasons can be put forward:

- In small-scale designated extraction areas in the nearshore coastal zone more fine sand is probably deposited which originates from a wider surrounding area.
- The time scale of the morphological adaptation of the channels exceeds the time scale of the small-scale sand pits in the nearshore coastal zone, because:
  (1) the surface area of a channel cross-section – in a dominant tidal current direction –exceeds the surface area of the small-scale designated extraction areas examined, and
  (2) Sediment transports in the shallow nearshore coastal zone exceed those in deeper water.

Channel behaviour can be defined as a combination of shifting and widening (see Figure 4.6). In mathematical terms, channel bed evolution can be described as an advection-diffusion equation. The required coefficients could be obtained by means of a numerical model, such as SUTRENCH-2DV, or deduced from existing observations of the autonomous channel evolution. A similar advection-diffusion equation was deduced and applied for the IJ Channel (see Figure 4.7) by **Van de Kreeke et al** (**2001**).

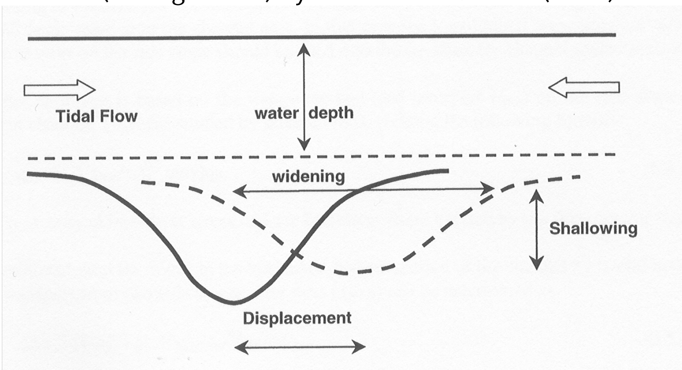


Figure 4.6 Diagram of channel bed evolution (**Van Rijn and Walstra, 2002**)

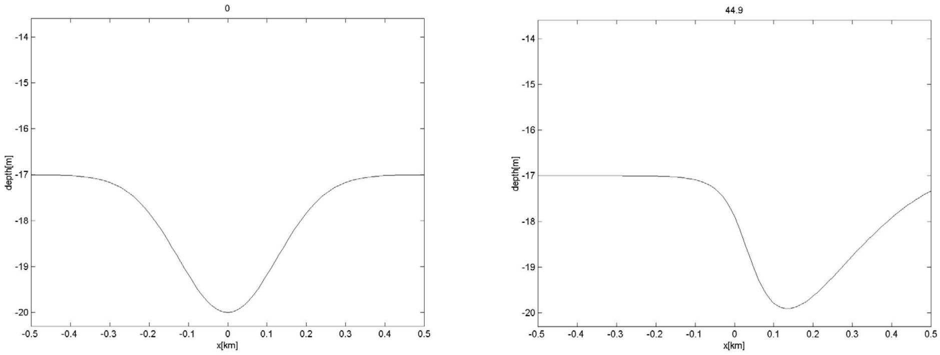


Figure 4.7 Theoretical change in an idealised cross-section of the IJ Channel (at 2.5 km from the south jetty) over a period of 50 years. The evolution calculated is based on simplified advection-diffusion equations (**Van de Kreeke et al, 2001**)

III. Wave conditions in the coastal zone

The presence of a channel affects the nearshore wave field (see Figure 4.8). Waves, propagating across the channel, are less high and move faster than waves outside the channel. At the channel banks channel refraction easily occurs, which causes a loss of wave energy in the channel.

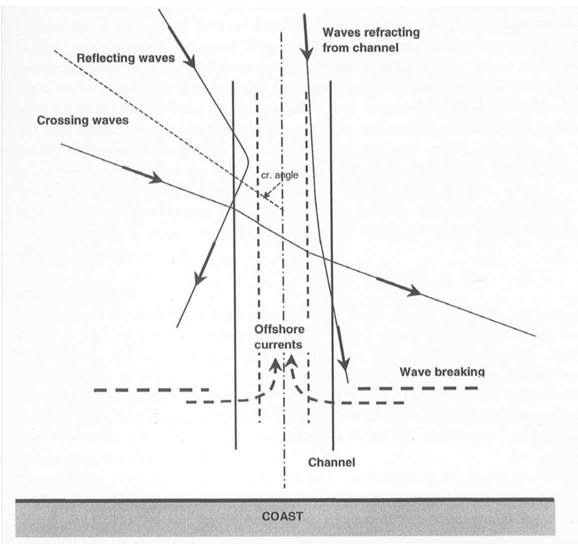


Figure 4.8 Principles of wave reflection and refraction around the channel (**Van Rijn and Walstra, 2002**)

Waves approaching the channel at a narrow angle with the channel can reflect if the channel slopes are steeper than 1:7. These waves can consequently become ‘trapped’ within the channel, which causes a complex wave pattern. If the angle between the channel axis and the wave direction exceeds approx. 30°, the waves will cross the channel.

4.4 Flow in the channels and their immediate surroundings

4.4.1 User function: shipping

Good access to the ports of IJmuiden and Rotterdam is of major economic importance. Channel depth, which is also called target depth, is the most important factor of access for the deepest-drawing vessels. A second access factor is formed by other hydrodynamic conditions, like flow velocities and waves, at the channel, particularly in the area directly seaward of the breakwaters.

For the deepest-drawing vessels, access to the harbour is only possible for a limited period, the ‘tidal window’, due to varying water levels during the tidal cycle. During storm conditions wave heights and flow velocities across the channel furthermore form a barrier to shipping traffic. This is particularly the case for stormy southwesterly winds, which involve relatively high transverse flow velocities. Access of harbours in combination with water levels, flow and waves can be tested by means of a navigation lane study (see box below).

Navigation lane study

*Harbour access can be tested by means of a ‘navigation lane study’. A fast-time navigation lane study determines a navigation lane beforehand, after which the various steering parameters required during the process of entering the port are evaluated. In a real-time navigation lane study, the captain carries out the manoeuvre manually in a bridge simulator; in that case the navigation lane is not predetermined (*__Marinesafety Rotterdam b.v., 1997__*).*

A good navigation lane study requires that the local hydrodynamic conditions (water level, flow velocity, wave height and wave period) around the harbour entrance are known and sufficiently reliable. For this purpose hydraulic models are essential.

Wave reflection on the channel banks may have an adverse effect on shipping. As the maximum slope gradients of the Euro-Maas Channel and IJ Channel are considerably gentler than 1:7, however, this problem does not occur.

4.4.2 Observations and model results: hydraulics around channels

The following information is also based on results of the *Rijkswaterstaat* Nautilus project (**Robaczewska, 1998**).

Tidal current

In theory the depth-averaged tidal current in the channels decreases. This theory is only valid for the seaward part of the channels, however. In the direct surroundings of the harbour mouth, ie the ‘connecting zone, a depth-averaged flow approach is definitely not justified. The presence of the jetties and the increased effect of density differences result in considerably more complicated flow patterns. A three-dimensional approach is required at this location.

Accurate information on channel flow velocities, particularly the cross-channel velocity component, is of major importance for navigation to the ports of Rotterdam and IJmuiden. Shipping traffic does not enable permanent measurements within the channel, although two measuring poles have been placed near the Maas and IJ Channels. The locally measured flow velocity and flow direction are subsequently translated into values applicable within the channel.

This translation has been carried out for the Maas Channel (see Figure 4.9). Flow velocities off the coast near Hook of Holland consist of an astronomical component and a residual velocity component. Water transport from the Rhine and the wind characteristics largely determine this residual velocity (eg see **Visser, 1998**). This hypothesis was tested by making use of flow velocities observed by means of a temporary measurement set-up in the channel. These are called the 'test trench measurements' and were carried out by the Noordzee Directorate.

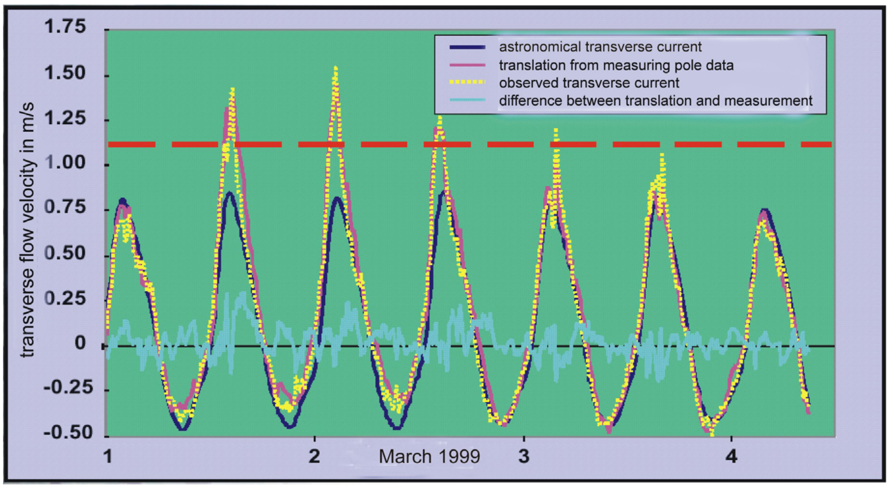


Figure 4.9 Example of a comparison of measured and calculated transverse flow velocities in the Maas Channel.

An operational instrument, called the 'Nostradamus', collects flow information which is translated for the channel, after which the results are presented on a monitor for support of navigation. The system operates in real-time at the hydro-meteo centre Rijnmond (HMR), and in 2000 a similar system was installed at IJmuiden.

Calculations of the flow velocities in and around the channels are available in the form of a electronic navigational chart (Figure 4.10).

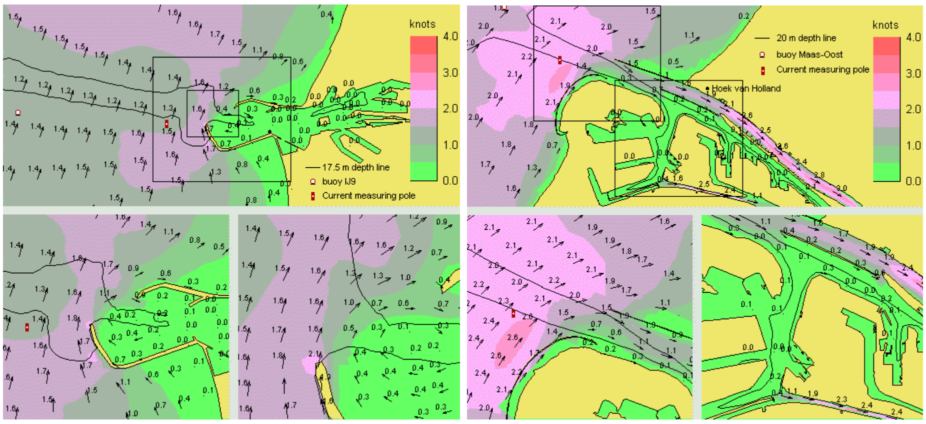


Figure 4.10 Digital navigational chart for shipping off the IJmond (a) and Maasmond (b).

Water levels
Measurements of possible water level differences in and next to the channel are not known to have been made. The channel effect on water levels along the coast – which in theory is a slight difference of several centimetres – is negligible compared to the effect of the tide and possible wind set-up.

4.5 Morphological evolution of the channels and their immediate surroundings

4.5.1 User functions: channel maintenance operations, cables and pipelines, coastline maintenance

User function: channel maintenance operations
Channel maintenance guarantees the channel target depth. As channel shoaling occurs in the course of time, as a precaution the construction channel depth exceeds the target depth by approx. 1 metre. This difference between construction depth and target depth is called the dredging margin.

Dredging operations keep the channel at the depth required and the southern slope in place. The northern slope is allowed to shift freely in a north-eastern direction. Figure 4.11 gives an overview of the dredged amounts in the Maas Channel.

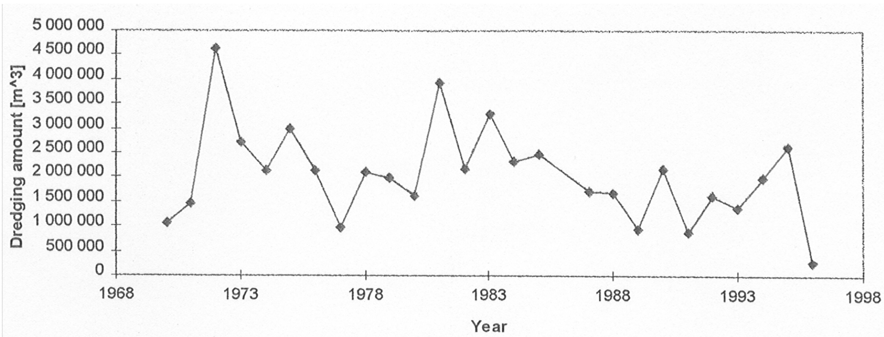


Figure 4.11 Annual dredging amounts (m3) in the Maas Channel (zone km 0-11.3 km, including anchor area) over the period 1970-1996, from **Hoitink 1997**. The peak in dredging amounts in the years 1972, 1981 and 1995 corresponds to a deepening of the Maas Channel.

Channel maintenance operations are also necessary in the harbour mouth and the harbours themselves, due to a large supply of silt through the channel in the direction of the harbour mouth and harbours (see box below).

Maintenance operations in Rotterdam ports and Maas Channel

Over the past decades much effort was put into developing more efficient maintenance alternatives, for instance within the working group MKO (for minimising the cost of maintenance dredging operations), the working group PSV (for spreading of silt) and as part of PROVA (a channel project), see **Van der Gouwe, 1990; Haksteen, 1993** *and* **Verlaan and Spanhoff, 1994.**

*Resulting alternatives are aimed at preventing silt sedimentation on the one hand and concentrating silt sedimentation in specific areas on the other hand. This led to a number of experiments, such as the sand dam near Hook of Holland (***Woudenberg, 1996***), the Simon Stevin pit (***Pluijm and Bossinade, 1986***) and the Trough in the Maas Channel. Partly on the basis of these experiments, the shifted Loswal Noord and the deep Loswal Noord have been taken in use as alternatives for the present Loswal Noord dumping site. Both alternatives were recorded in the EIA Loswal Noord (***Anonymous, 1995***).*

*Various studies were carried out into the morphodynamic behaviour of sand waves and mega ripples in the more seaward channel sections (***Jansen, 1981; Tafeiëff, 1982; Tobias, 1989; Scholl, 1999***). Insight into this behaviour allows a model-based approach (***Schipper, 1990 and 1991; Bosch et al, 1997***), as a result of which maintenance operations could be carried out more efficiently.*

As a result of recent deepening operations, a substantial part of the Maas Channel, ie a zone of 6-11 km, is much deeper than the required bottom target depth of NAP –26m (see Figure 4.12). The dredging margin in this area is several metres, so that maintenance operations are not necessary for some time.

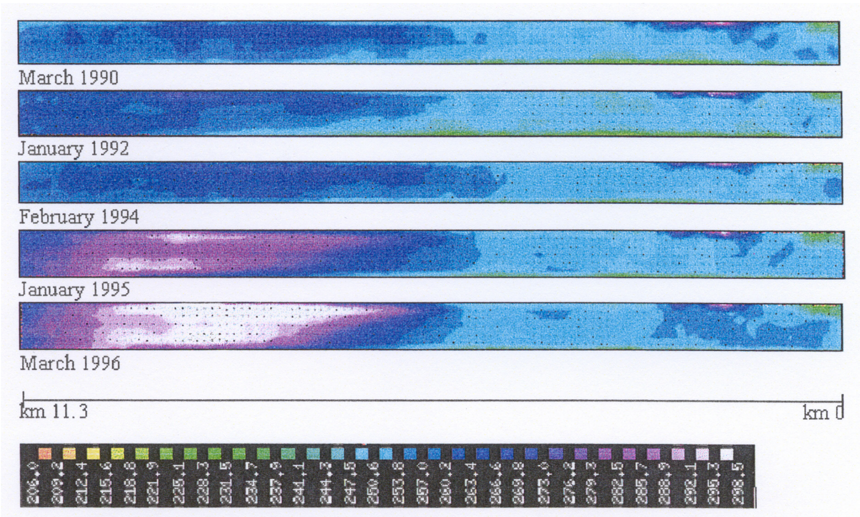


Figure 4.12 Bed elevation changes of the Maas Channel between 1990 and 1996, from **Hoitink, 1997.** The recent deepening of the seaward part is clearly visible.

The degree of natural channel maintenance varies according to the distance from the coast (see Figure 4.13). Maintenance is minor in the most seaward parts of both channels, where maintenance consists of dredging sand waves and mega ripples which rise above the required target depths. Maintenance in more shoreward areas mainly consists of dredging from the southern slopes and channel beds.

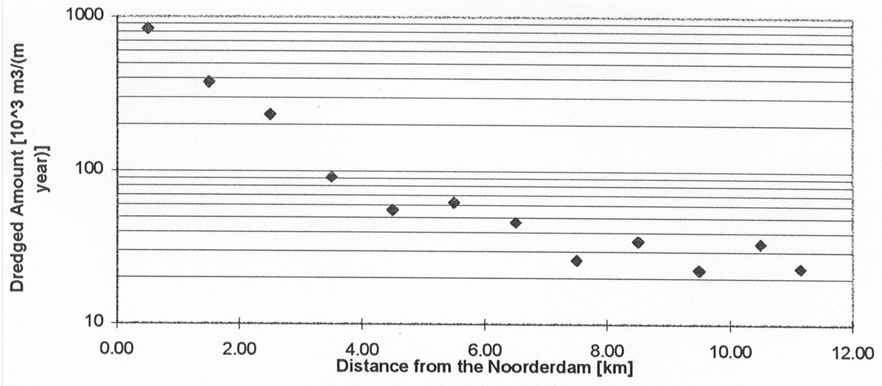


Figure 4.13 Dredging amounts per year for Maas Channel maintenance (period 1985-1987), from **Hoitink, 1997**. The dredging amounts decrease as the distance from the coast increases.

Dredging companies are paid for their services on the basis of tonnes dry solids. A conversion factor is applied to convert dredged volumes to tonnes dry solids. This conversion factor depends on the density of the dredged material. The density of pure sand (quartz) is approx. 2,650 kg/m^3. Based on a porosity of sand of 0.4 (= 40% empty space in between the grains), the conversion factor for pure sand is 1.59 ton/m^3.

Analysis of bed sediment in the Maas Channel shows that the sediment density decreases nearer to the Maas mouth as a result of the presence of silt. As silt has a lower density than sand, the conversion factor for the dredged sediment also decreases in this zone (see Figure 4.14).

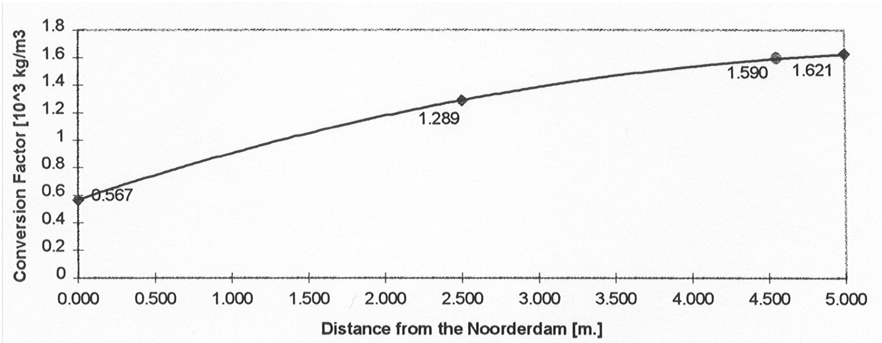


Figure 4.14 Conversion factor to convert volume to weight (Ton/m3) in the Maas Channel (zone 0-5 km), from **Hoitink, 1997**.

In the harbour mouths and harbours considerable sedimentation occurs of fine sediments, particularly silt. Neither the exact process of silt sedimentation in the harbours and harbour mouths, nor the influence of the channels, is well known. There are indications that a relationship exists between wave height and silt sedimentation (**Verlaan and Spanhoff, 1994),** and that large amounts of silt are deposited in the harbours and harbour mouth during or immediately after storm conditions. The channels function as a kind of silt conductor in the direction of the harbour mouth. Shoreward residual transport, which is caused by the estuarine circulation, takes the silt through the channel into the harbour mouth and harbours, where the silt settles. The stirring effect of waves in the 'open sea' prevents silt from settling within the channel.

User functions: cables and pipelines, and coastline maintenance
Human intervention, ie dredging, and natural processes cause the channels to change in volume and shape in the course of time. Bed elevation on both sides

of the channels is consequently affected over a distance which increases through time. Depending on the buffer zones surrounding the channels, the locations of nearby cables and pipelines and the sand balance of the coastal zone may be adversely affected.

4.5.2 Observations and model results: morphology around channels

Morphological evolution

As mentioned in the previous subsection, the south sides and the channel beds accrete whereas the north sides erode (see Figure 4.15). The channels' centres of gravity (without dredging operations) therefore shift in a northeast direction. Furthermore the southern slope gradients are steeper than the northern slope gradients. This difference is reinforced by the dredging operations in the channels. In due course the channel slopes become gentler, so that bed elevation on both sides of the channels is affected.

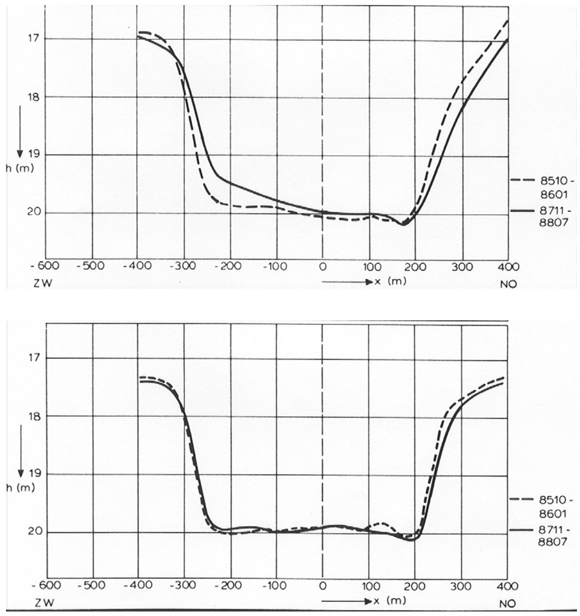


Figure 4.15 Morphological evolution of the IJ Channel (1985-1988) at 2.5 km (top) and 4.5 km (bottom) respectively from the Zuiderhavenhoofd; **Ribberink and Roelvink, 1989**.

By human intervention the channels were gradually deepened in the past to facilitate harbour access for increasingly deeper-drawing vessels. Regular maintenance operations cause the channel cross-section, ie channel volume, to widen even further in the course of time. Accretion on the south sides and on the channel beds is removed by dredging, while erosion on the north sides can freely take place. Cross-section widening enables a gradual increase of the morphological influence area.

Based on soundings (**Stive and Eysink, 1989**) the conclusion was drawn that on a time scale of several decades the morphological influence on both sides of the channels, ie in a longshore direction, at water depths between 10 and 20 metres varies between 3 and 10 km. Observations in the IJ Channel actually confirm that the channel behaviour in the long term can be approached as a combination of shifting and widening (**Van de Kreeke et al. 2001**).

At present there is no buffer zone between the channels and the coastal zones up to NAP –20m. This means that the deeper parts of the coastal zones lose sand in the course of time as a result of spatial extension of the channels.

In the long term – in the order of hundreds of years – it is unclear how the morphological channel evolution affects the evolution of the nearshore coastal zone, since other large-scale morphological evolutions are also of importance over such a long period of time. Evidently and in the long term, the breakwaters are continued to have a major effect on the local coastal evolution. A further study of morphological evolution around the breakwaters of IJmuiden is described in **Boutmy, 1998.**

4.6 Wave conditions in the coastal zone in the vicinity of channels

4.6.1 User functions: Coastal safety and coastline maintenance

Coastal safety is mainly determined by extreme wave boundary conditions. Wind direction and angle of wave approach are northwest under these conditions and at a small angle with the IJ Channel and Maas Channel axes, which are oriented in WNW direction.

In theory the present Euro-Maas Channel and IJ Channel have an effect on the wave-driven longshore transports through affecting the wave fields. In the long term this could possibly result in a redistribution of sand in the nearshore coastal zone.

4.6.2 Wave penetration in channels

Wave fields are affected at the channels. The greater water depth in the channels results in theory in a different distribution of wave energy by means of refraction and reflection. Owing to the specific channel orientation and the limitation on the coast, the wave-driven flow and sand transports are subsequently affected in the active zone along the coast. In **Ribberink and Roelvink, 1989** the principles of wave reflection and wave refraction are discussed and applied for the IJ Channel. In **Allersma and Ribberink, 1992** they are applied for the Euro-Maas Channel.

Both studies conclude that the theoretically possible effect of the channels is insignificant compared to the effect of the locally present breakwaters on the local morphological evolution in the nearshore coastal zone. In comparison with the effect of the breakwaters, the effect of the presence of the channels to coastal safety and coastline maintenance is negligible.

4.7 Effect of overdimensioning of IJ Channel and Euro-Maas Channel

4.7.1 Introduction to overdimensioning of Euro-Maas Channel and IJ Channel

This subsection examines how physical effects change as a result of overdimensioning of the existing channels. As a scenario the *Zero plus option* according to the present RON/MER is used.

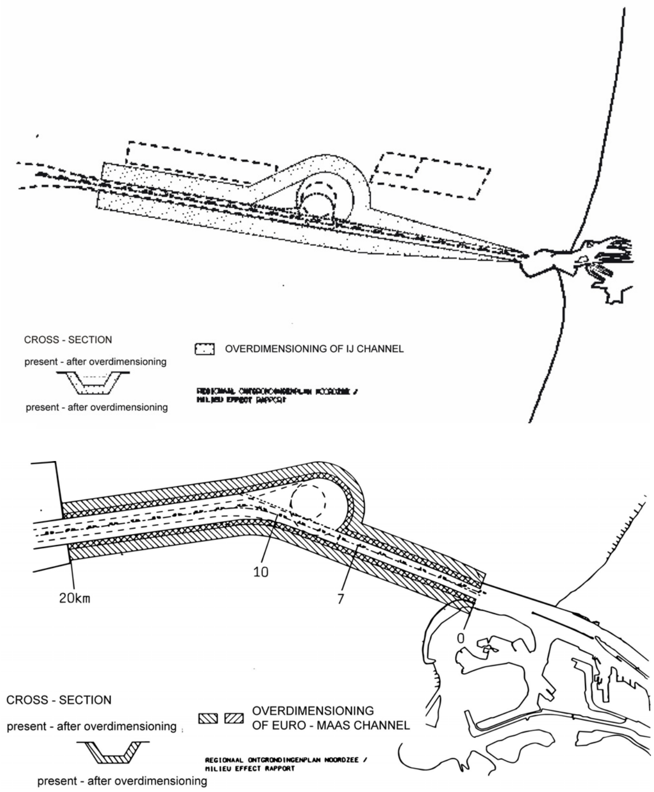


Figure 4.16 Zero plus option: maximum overdimensioning of the IJ Channel (top) and the Euro-Maas Channel (bottom), from **Rijkswaterstaat, 1991.**

Widening of the IJ Channel is possible to a maximum of 2,000m, whereas the Euro-Maas Channel can be widened to a maximum of 2,700m. Maximum deepening of the channels is 5m, which implies that the maximum construction depth of the IJ Channel is 24m and that of the Euro-Maas Channel 31m (see Figures 4.16 and 4.17).

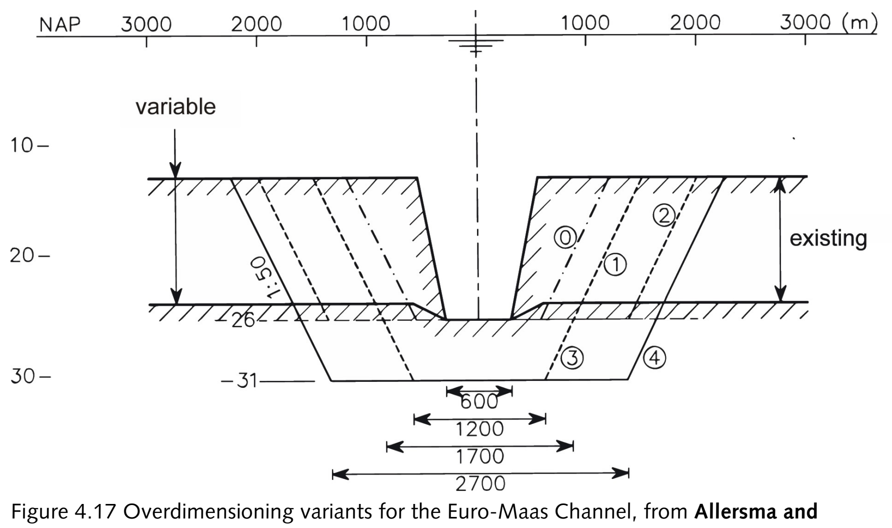


Figure 4.17 Overdimensioning variants for the Euro-Maas Channel, from **Allersma and Ribberink, 1992**. Variant 4 corresponds to a maximum overdimensioning.

In the case of maximum overdimensioning, approx. 200 million m^3 sand becomes available from the IJ Channel and approx. 320 million m^3 from the Euro-Maas Channel (**Allersma and Ribberink, 1992**).

4.7.2 User function: shipping

Area seaward of the connecting zone
An important boundary condition for harbour access is the extent of the transverse tidal current. Widening the channel increases the area in which flow velocities decrease. Deepening causes a further decrease in tidal current velocities in the channels. The relative increase in water depth is approx. 25% for the IJ Channel and approx. 20% for the Euro-Maas Channel. The tidal velocities in the channel decrease in theory almost proportionally. Overdimensioning in this zone has in principle a favourable effect on the channel's nautical access. Nautical access of the harbours, on the other hand, is determined by the flow directly in front of and within the harbour mouth.

Connecting zone
The theoretical view does not apply to the area directly in front of the harbour mouth. As a result of current contraction caused by the breakwaters – which for the Maas Channel is further reinforced by the presence of the Maasvlakte – the local transverse flow velocities can remain high. If the present Maasvlakte were extended, the increased tidal contraction could lead to design problems (**Kuijper, 1998 ; Van der Linden, 1998**).

It is recommended to use model calculations to determine which design of a connecting channel to a harbour mouth results in the smallest transverse tidal current velocities.

Wave conditions
According to the Zero-Plus option, the slopes are even gentler than the present slopes (Figure 4.17). This is to prevent that shipping traffic is hindered by waves reflecting on the channel banks.

4.7.3 User functions: maintenance operations, cables and pipelines

Morphological adaptations of overdimensioned channels
Widening the IJ Channel to 2,000m and the Euro-Maas Channel to 2,700m means a factual extension of the morphological influence area. The further extension of the influence area depends on the slope gradient of the widened channel. The steeper the slopes, the stronger the initial slope gradient decrease and the further the extension of the influence area.

The profile evolution has been calculated for several width and depth variants of the Maas Channel over a period of 50 years (**Walstra et al, 1998**). The calculations were carried out by means of the Sutrench (2DV) model, after calibration on the profile evolution observed at 4.6 km from the Noorderhavenhoofd. Figure 4.18 shows the model results of maximum relative depth evolution and the centre of gravity shifting through time.

If the channel is widened, a bigger distance develops between the southern and northern slopes. The sedimentation and erosion zones shift, while sediment transports get more space to adapt to the decreased transport capacity in the channel. Figure 4.19 gives the profile evolution calculated over 50 years for a widened Euro-Maas Channel (2,400m). The middle of the channel is further from the sedimented southern slope and is consequently to remain free from sedimentation for a longer period of time.

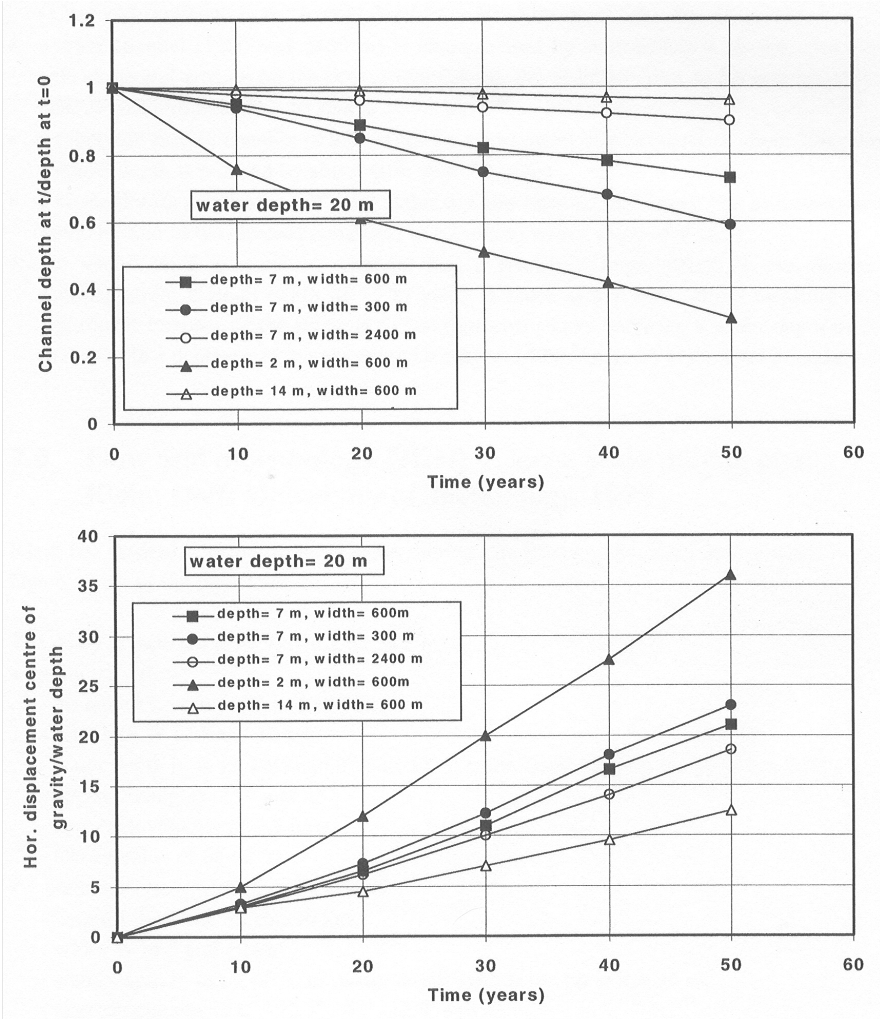


Figure 4.18 Evolution of the maximum relative channel depth and the centre of gravity over a period of 50 years, from **Walstra et al**, **1998.**

Deepening the channel results in smaller transport capacity in the channel. The relatively most significant change occurs in the seaward part of the channels, where the present channel depth is still low compared to the immediate surroundings. Channel deepening causes an increase in the gradient in sand transports over the channel banks, as well as an increase in erosion and sedimentation. A stronger slope gradient decrease, resulting in a larger horizontal extension of the influence area, is expected. The centre of gravity of the channel shifts at a slower rate. The decrease is roughly linear to the depth for a constant channel width (see Figure 4.18).

If the channel cross-section is deeper as well as wider, the slopes develop virtually autonomously. The southern slope remains considerably steeper than the northern slope (see Figure 4.19). It furthermore seems that the extension of the morphological influence area is much smaller in southern direction than in northern direction.

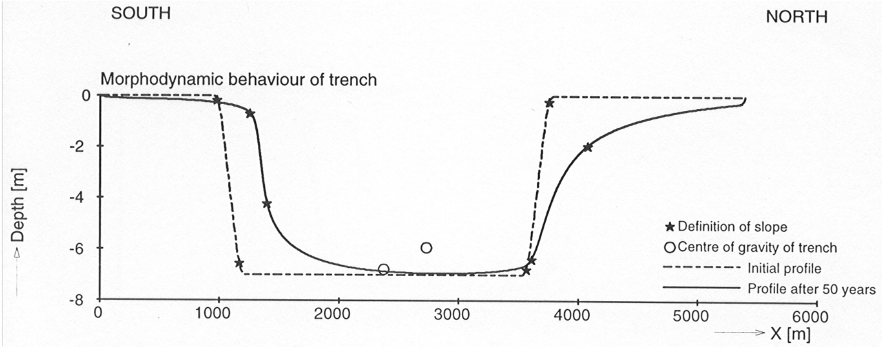


Figure 4.19 Profile evolution of a widened Maas Channel, calculated by means of numerical model Sutrench, from **Walstra et al, 1998.**

Generally speaking an enlargement, being a widening and/or deepening, causes an increase in the area which is morphologically affected by the presence of the channel. In the present situation, the influence areas on both sides of the channels are estimated at 3 to 10 km over a period of 50 years (see Subsection 4.5.2), which are larger in the case of channel enlargement. In **Stive et al, 1998** it is stated that a profile enlargement by a factor x results in an increase in the influence area by a factor √x. The assumption was made that the spatial extension of the influence area occurs as a result of diffusion. Overdimensioning according to the Zero-Plus option could cause the influence area to increase roughly by a factor 2. In the case of widening, the increase is fairly literal, whereas in the event of deepening it manifests itself in an increased levelling-off of the slopes.

A comparison of model calculations with various field and laboratory data (**Walstra et al, 1999**) shows that model calculations underestimate the levelling-off of slopes compared to reality. This was taken into account when the calculations were translated from theory into practice.

Maintenance operations: channel sedimentation
By widening the channel, maintenance operations can be postponed for an extended period of time, as the middle of the channel remains free from sedimentation for a longer period of time. By deepening the channel a profit may be made on maintenance even without adjusting the target depth – more sedimentation can occur without endangering the target depth.

Maintenance operations: sedimentation of connecting zone and harbours
In the area surrounding the harbour mouth, ie the 'connecting zone', a possible increase in silt and fine sand sedimentation in the channel needs to be taken into account. More importantly, increased silt sedimentation is to be expected in the harbour mouths and harbours after channel deepening (**Allersma and Ribberink, 1992**). Although this idea lacks a solid foundation, there are indications that channel deepening affects the estuarine circulation (see **Salden, 1995**). A possible increase in the shoreward residual flow causes an increase in silt transports to the harbour mouth and harbours. The eventual increase will depend to a considerable extent on the exact design of the channel connection to the harbour mouth.

Cables and pipelines
By overdimensioning the channels, existing cables and pipelines can become exposed, and can require new cables and pipelines to be installed further north or south of the channel. This is first of all a direct consequence of channel

widening. Another factor is that the morphological influence area increases by a factor 2 to 6-20 kilometres.

4.7.4 User function: coastline maintenance and coastal safety

Coastline maintenance: Sand loss in the coastal zone up to NAP –20 m
At the moment there are no buffer zones between the channels and the coastal zones up to NAP –20m. This means that sand directly disappears from the coastal zone if the channels were widened. Based on an expected increase in the influence area caused by morphological evolution, sand loss can also be expected to occur in the longer term in the deeper parts of the coastal zone. The extent of sand loss partly depends on the coastal zone definition.

Coastline maintenance: the coastline position
Overdimensioning results in steeper cross-shore bed profiles directly on both sides of the breakwaters. This effect occurs if the channel width exceeds the width of the breakwaters. This is the case, for instance, for overdimensioning of the Euro-Maas Channel according to the Zero-Plus option (see Figure 4.16). Even if there is no sand extraction on both sides of the breakwaters, this effect can occur in due course as a result of erosion directly seaward of the breakwaters caused by to tidal contraction.

At IJmuiden in particular, the coastline positions on both sides of the harbour mouth are significantly extended seaward as the jetties block wave-driven longshore transport. A steeper cross-section as a result of overdimensioning, however, could reduce a further extension or even partly reverse it. Increased wave intensity as a result of channel overdimensioning further reinforces this process.

Coastal safety: wave attack during extreme conditions
One of the effects of channel overdimensioning is that more wave energy can reach the coast. This effect occurs locally around the harbour mouth, however, and does not a factor for the major part of the Dutch coast. As far as known, no research has been conducted into the effect of overdimensioning on wave conditions during extreme conditions. The effect on coastal safety is probably slight, but it is recommended to conduct further research.

Channel overdimensioning affects wave-driven sediment transports. The presence of the jetties, however, has a far greater effect on the dimensions of the wave-driven sediment transports and resulting changes in bed elevation.

4.8 Conclusions: effects of sea sand extraction by channel overdimensioning

The main question in this chapter was:

> *What are the consequences of large-scale sand extraction in the channels, ie over-dimensioning, to the coastal system and relevant user functions?*

Effects on the coastal system of large-scale sand extraction in the channels, ie overdimensioning, according to the Zero-Plus option.

Hydraulics and sedimentation of silt and fine sand
As a result of the Euro-Maas Channel and IJ Channel being oriented practically perpendicular to the tidal current, 'flow deceleration' occurs as it does at the temporary sand pit. Channel widening results in a larger area in which flow

deceleration occurs. Channel deepening results in a stronger decrease in tidal current velocity.

In the shoreward part of both channels, which is referred to as 'connecting zone' and is in the order of 5 km, the water movement is strongly three-dimensional. The jetties cause contraction of the tidal current, while the inflow of fresh river water drives estuarine circulation: fresh river water flows seaward near the surface, while salty sea water flows shoreward near the bottom. Estuarine circulation causes silt and fine sand to be transported through the channel to the harbour mouth and harbours. It is assumed that particularly during or immediately after storm periods silt enters the harbour mouth. The disturbing sediment suspension effect of waves in the open North Sea results in silt hardly settling within the channel.

If overdimensioning were to be applied in this shoreward part of the channels, the specific design of the connection to the harbour mouth determines the effect on threedimensional flow. An increased estuarine circulation, causing more sedimentation in the harbour mouth, is one of the possible effects.

Morphological evolution
Sediment accrete in the channels, as does the temporary sand pit, which results in shoaling. At the same time erosion occurs around the channel banks, which causes the channels to widen. The areas on both sides of the channels which are morphologically affected over a period of 50 years is estimated at 3 to 10 kilometres. Channel deepening results in increased erosion on both sides of the channels, whereas channel widening results in an extension of the morphological influence area. As a result of overdimensioning the morphological influence areas on both sides of the channels increase by a factor 2, and over a period of 50 years the influence area measures 6-20 km.

Under the influence of a net sediment transport to the northeast, the channels' centres of gravity shift to the northeast direction, which measures 1 to 10 metres per year. Channel deepening results in a shift of the centre of gravity which is roughly proportional to the increased depth (at a constant width).

Contrary to the situation for temporary sand pits, the total channel volume hardly decreases in the channels. The natural morphological channel evolution in the longer term, ie in the order of decades, can be described as a combination of shifting, widening and shoaling, ie advection-diffusion.

Effect of overdimensioning on the user functions
Shipping
Channel deepening has a positive effect on shipping: vessels with deeper draughts can reach the harbour. Furthermore as a result of flow deceleration in the seaward part of the channel, the period during which deep-drawing vessels can enter the channel is extended. The complex flow patterns in the shoreward part of the channels distort the picture of the effects of widening and/or deepening on navigability.

It is expected that there are no wave reflections on the channel banks, which hinder shipping traffic, if the slopes of the overdimensioned channel banks are gentler than 1:7.

Maintenance operations
Widening and deepening the existing channels makes maintenance dredging operations in the channels unnecessary for a certain period of time as there is

sufficient overdepth and overwidth. Owing to a changed estuarine circulation, silt sedimentation in the harbour mouth is expected to increase, which also increases the need for maintenance operations.

Cables and pipelines
Channel widening reduces the distance from the present cables and pipelines to the channel. Overdimensioning furthermore results in an extended morphological influence area. Both aspects give an increased chance of bed erosion at the locations of cables and pipelines.

Coastline maintenance
Channel overdimensioning causes erosion in extended areas on both sides of the channels, so that the deeper part of the coastal zone loses sand. The extent of sand loss depends on the 'coastal zone definition'. As channel widening on both sides of the jetties can cause steepening of the cross-section, present coast accretion on both sides of the harbour mouth can be slowed down or even partially reversed.

Coastal safety
Channel overdimensioning could theoretically result in higher wave boundary conditions locally around the harbour mouth. This could affect the safety of the seawall around the jetties. An effect on the safety of the adjoining sandy dam is not expected. The jetties have a much more significant effect on wave action near the coast than the channels have.

5 Large-Scale Sea Sand Extraction in Designated extraction areas

5.1 Introduction to large-scale sea sand extraction in designated extraction areas

5.1.1 Question: what are the effects of large-scale sea sand extraction?

Over the past years several plans have been developed to reclaim land at the Dutch coast. Examples of potential coastal expansion are: Second Maasvlakte, Airport at Sea, Coastal Location Nieuw-Holland (see Figure 5.1). Possible future coastal expansion needs to be realised by means of sand and filling sand from the sea. The required amount of sand over a period of 5 to 10 years is 200 to 2,000 million m^3, depending on the expansion plans. Compared to the amount of approx. 25 million m^3 presently required for coastal maintenance and the market (see Section 2.3), this implies an additional sand demand of one to ten times the annual amount.

In addition to potential coastal expansion plans, sand needed for the concrete and bricklaying industries can also be a reason for large-scale sand extraction, for which an environmental effects report (EIA) is required (**RIKZ, 1999/2001**). The amount of sand needed over a period of 10 years is an estimated 40 million tons of suitable concrete and masonry sand and a maximum of approx. 320 million m^3 filling sand, which roughly correspond with the present sand extraction volume.

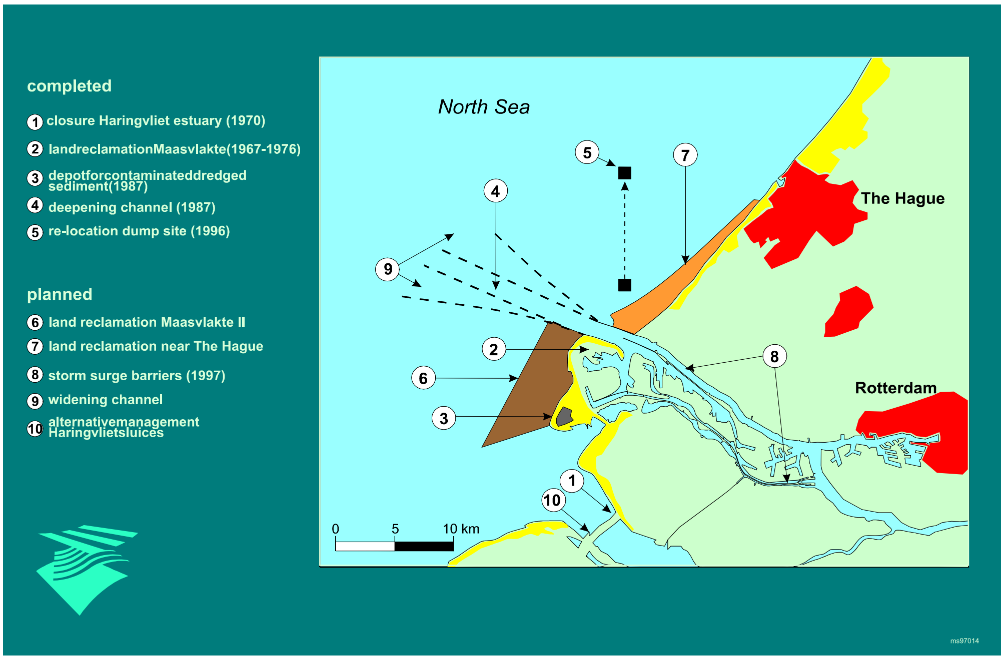


Figure 5.1 Plans for large-scale interventions in and around the Maasmond (situation 1997)

The following main questions are central in this chapter:

What physical effects occur as a result of large-scale sand extraction in designated extraction areas and what influence do these effects have on the relevant user functions?

With a view to large-scale sand extraction for the purpose of potential coastal expansion there is a demand to allow extraction at greater depths. By extraction at a greater depth than the maximum extraction depth of 2m in accordance with the RON/MER, the extraction surface area can be limited. Extraction at greater depths is also advisable for sand extraction for the concrete and bricklaying industries: preliminary research shows that sand suitable for this purpose is found either at the crests of sand waves, or in sedimentary layers at a depth of at least 5m underneath the sea bed.

5.2 Brief system description of the Dutch coast

Three subsystems can be identified for the Dutch coastal system: the Wadden coast, the straight Dutch coast and the Delta of Zeeland and South-Holland. Bed elevation and flow in the Dutch coastal area is subject to continuous change, both naturally and by human intervention. These changes occur at different spatial and temporal scales. In the medium term of 10-100 years, flow, waves and wind are the major moving forces of the natural processes.

Sediment properties

The North Sea bed mainly consists of sand – the silt content is generally less than 5%.

Tidal motion

As a result of changing hydrodynamic conditions along the Dutch coast, the location of a designated extraction area affects the extent of water motion adaptation. The direction and amplitude of the tidal current vary along the coast. The same applies to the asymmetry of the tidal current, which determines the tidal average sediment transports, and the tidal average residual flow.

<u>Tidal current direction</u>

The tidal current direction along the straight Dutch coast has mainly one component, ie the longshore component. In the Delta area or around the Wadden Sea tidal outlets, this is combined with another component, ie the cross-shore component. The same occurs at a greater distance from the Dutch coast, which means that the cross-shore flow velocity component increases.

<u>Tidal current amplitude</u>

The tidal current amplitude also varies along the coast. In the south, where the 'tidal wave' enters the Dutch coastal area, the amplitude is highest. It subsequently decreases along the Dutch coast and slightly increases again near the Wadden Sea.

In the coastal zone, the amplitude is highest in the tidal navigation channels of the tidal outlets and estuaries. This area is however not discussed in this report, as sand extraction is carried out outside the coastal zone.

<u>Tidal current asymmetry</u>

Also tidal current asymmetry varies along the Dutch coast. The asymmetry is low in the south – ebb and flood phases are practically equal. Along the Dutch coast the tidal velocity asymmetry increases further north, as well as the mean year transports (**Van Rijn, 1997**). A characteristic extent of the tidal current velocities during ebb and flood is approx. 0.8 m/s, where the flood velocity slightly exceeds the ebb velocity.

<u>Mean tide residual flow</u>
Mean tide residual displacement occurs in north-eastern flood direction in the order of 2.5 km, or approx. 0.05 m/s. Near jetties and coastal inlets, however, the extent and direction may differ locally.

River transport and wind
The flow pattern is not only affected by tide but also by wind and freshwater transport from the rivers. The wind field has a mean year resultant from westerly to south-westerly direction. It was deduced from measurements along the straight Dutch coast that as a result of wind effects a north-easterly flow occurs in the *upper layer* of the water column of 0.07 to 0.11 m/s (**De Ruijter et al, 1992**). Section 4.2 gives a description of the effect of river transport on flow and sediment transports.

Sediment transport and bed changes
Tidal asymmetry and residual displacement cause mean tide sand transport to occur in the flood direction. An estimate of the extent and direction of the mean year sand transport in deeper water along the Dutch coast is given in **Van Rijn, 1997.** At a water depth of 20m the mean year sand transport is minor. Along the coast mean year sand transport is towards the northeast: from 15 m^3/m/year off Scheveningen to 45 m^3/m/year off Callantsoog. In a cross-shore direction mean year transport at a water depth of 20m is even more minor, up to a maximum of 10 m^3/m/year and coastward. As there is a lack of field data, the transport values are subject to wide uncertainty margins. Considering the fact that mean year transport is minor, bed changes in deep water occur at a much lower rate than in the shallow coastal zone. Adaptation of the bed elevation after large-scale sand extraction takes at least several decades.

A more detailed system description is given in the EIA for the extraction of concrete and masonry sand, **RIKZ, 1999/2001**.

5.3 Effects of large-scale designated extraction areas and user functions

5.3.1 Physical aspects and user functions of large-scale designated extraction areas

Table 5.1 gives the relevant user functions which are affected by large-scale sand extraction. It also lists the physical aspects in which this effect takes shape.

Physical Aspect	Relevant User Functions
I. Hydraulics at the designated extraction area and its immediate surroundings (**Section 5.4**)	Ecology
II. Morphological evolution of the designated extraction area and its immediate surroundings (**Section 5.5**)	Coastline maintenance and locations of cables and pipelines
III. Hydrodynamic conditions in the coastal zone (**Section 5.6**)	Coastal safety and coastline maintenance

Table 5.1 Physical aspects in relation to relevant user functions of large-scale sand extraction in designated extraction areas

5.3.2 Delineation of the study into the effects of large-scale sea sand extraction

Scenarios for large-scale sand extraction
The following basic assumptions were defined:
- Sand extraction takes place in one continuous designated extraction area
- The designated extraction area is seaward of the NAP –20m depth contour
- The sand extraction volume is in the order of > 100 million m^3
- The sand extraction depth is deeper than 2 metres
- The examined time scale of effects lies between 1 and 100 years

The designated extraction area *geometry*, which is determined by the extraction depth, the length/width ratio and the orientation of the longitudinal axis towards the dominant flow direction, was not pre-set, but functions as a variable. Furthermore, the *slope gradients* and *location* of the designated extraction area are also variables.

Starting points for description of effects
The starting points described in Subsection 3.3.2 apply here as well.

5.3.3 Physics wit respect to large-scale designated extraction areas

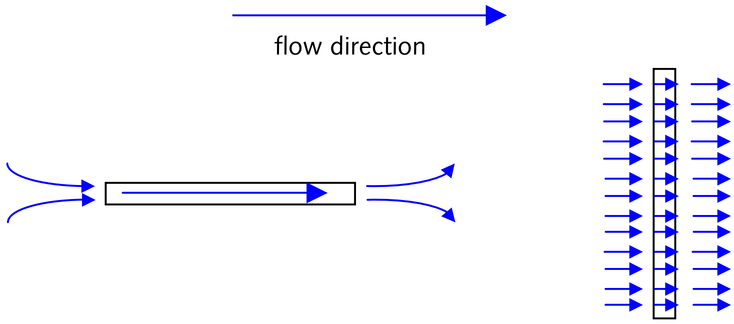
I. Local hydraulics in the designated extraction area and its immediate surroundings
The geometry of the designated extraction area strongly affects the flow patterns. The adaptation of a fictitious stationary flow is described first to explain this.

<u>Stationary flow at the designated extraction area</u>
As explained with respect to the situation of temporary sand pits (Chapter 3) and the navigation channels (Chapter 4), the principle of preservation of water mass results in a 'flow deceleration' over a local deepening. The flow velocity over the designated extraction area is determined by the measure of deepening: $u_1 = u_0 * h_0/h_1$ (see Subsection 3.3.3).

In the case of large-scale sand extraction – for which the precise location and geometry are still variable – another principle is important as well. At a greater water depth the flow slows down less because of friction with the bottom. Consequently more water can be transported through the designated extraction area – the discharge per metre increases. If this increase is significant, the depth-averaged flow velocity – locally around the centre of the designated extraction area – can in theory even *exceed* that of the undisturbed situation before the extraction. The maximum flow velocity for a stationary flow is given by $u_E \approx u_0 * \sqrt{(h_1/h_0)}$ (**Svašek, 1998**). In the case of a limited increase of the discharge per metre, the depth-average flow velocity in the designated extraction area often nevertheless decreases as a result of the increased water depth.

Depending on the flow rate increase, the flow velocity in the designated extraction area (**u_1**) varies therefore between $\mathbf{u_0 * h_0/h_1 \le u_1 \le u_0 * \sqrt{(h_1/h_0)}}$. The relative designated extraction area depth (h_1/h_0) determines the theoretically possible minimum and maximum of the flow velocity. For this reason, the relative depth is a *quantitative* determinative factor. The possibility of flow acceleration is determined by the length/width ratio in combination with the orientation of the designated extraction area towards the flow direction. These variables are *qualitative* determinative factors.

Two extremes are conceivable, in which the length(L)/width(W) ratio in both cases strongly exceeds 1. A maximum flow acceleration occurs in case of an elongated designated extraction area situated parallel to the flow direction. The other extreme, ie no increase of the discharge per metre and consequently 'flow deceleration', occurs for a similar elongated designated extraction area, yet situated perpendicular to the flow direction (see Figure 5.2). The latter is more or less comparable to the navigation channels off the Dutch coast. Every other extraction variant, with a smaller length/width ratio and/or a different orientation, results in a certain small or large flow rate increase. The depth-averaged flow velocity may either decrease or increase.



a) longitudinal axis parallel to the flow direction

b) longitudinal axis perpendicular to the flow

Figure 5.2: Diagram of two designated extraction area variants with an extreme adaptation of the flow velocity (Length/Width >> 1). Maximum flow acceleration occurs in variant (a), while complete flow deceleration occurs in variant (b).

In the extreme situation of a *maximum flow rate increase*, additional flow is not just supplied over the inflow edge, but also over the side edges of the designated extraction area. As a result, the depth-averaged flow velocity increases as the distance from the inflow edge increases (see Figure 5.3). This adaptation occurs exponentially over a characteristic adaptation length λ in the order or 4 km. The uniform velocity (u_E) is achieved after 3 to 4 times distance λ (**Svašek, 1998**).

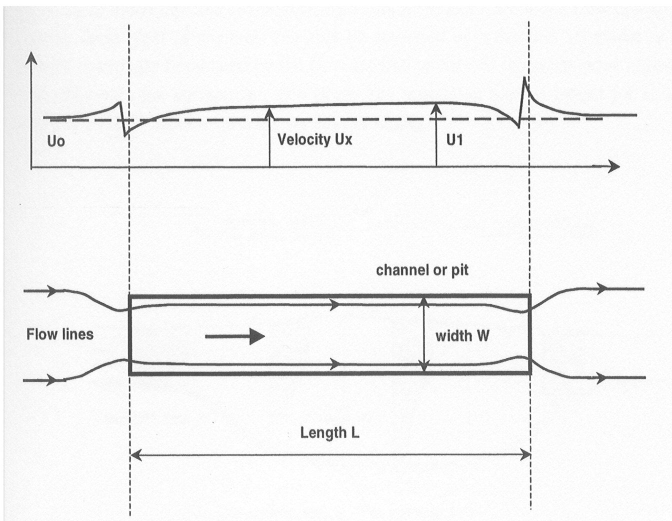


Figure 5.3 Flow velocity adaptation in an elongated designated extraction area parallel to the tidal curent, from **Van Rijn and Walstra** (**2002**)

Tidal current at the designated extraction area
The flow deceleration and flow acceleration processes described above are based on a situation with stationary flow. As regards tidal current, in which case the flow velocity and the flow direction are a function of time, the situation is slightly more complicated. The time scale of adaptation is also a factor for tidal current. Theoretical approaches of flow adaptation, by means of a ‘quasi-stationary approach’ or a ‘local approach’, are nevertheless still possible (**Svašek, 1998**).

In accordance with the stationary flow, for the extraction variants a and b of Figure 5.2 an ‘magnification’ or a ‘attenuation’ of the flow velocity amplitude are expected. The values achieved, however, are less extreme than for stationary flow. Moreover for a tidal current a small phase difference occurs, in the local approach, between the velocity changes within and outside the designated extraction area. The maximum flow velocity within the designated extraction area is reached slightly later than outside it.

Tidal current in the immediate surroundings
If a certain degree of flow acceleration occurs in the designated extraction area, this affects the tidal current in the immediate surroundings of the designated extraction area. The increased tidal discharge through the designated extraction area needs to be supplied and transported through the surrounding area. An increased tidal discharge, resulting in higher flow velocities, occurs at the inflow and outflow areas. Redistribution of the tidal discharge results in a decrease in tidal discharge and flow velocities in the immediate surroundings.

Tidal average residual flow in and around the designated extraction area
Redistribution of the tidal discharge also affects the residual flow pattern and the refreshment of water masses in and around the designated extraction area. Water refreshment determines the supply of oxygen, which is vitally important to the bottom fauna.

Further details can be found in Section **5.4**.

II. Morphological evolution of the designated extraction area and its immediate surroundings
If the flow velocities in the designated extraction area decrease, there is an increased chance of silt or fine sand sedimentation originating from a wider area around the designated extraction area.

Along the Dutch coast, slightly increased sedimentation is to be expected in the case of a extraction location along the coast of the South Holland or Zeeland islands. The presence of stratification suppresses sediment suspension, whereas it increases sediment concentrations near the bottom. The relatively best chance of sedimentation is expected in the vicinity of silt sources, including the dump locations north of the Maas Channel and IJ Channel.

Apart form location, designated extraction area geometry also has an effect. The relatively best chance of sedimentation occurs in an elongated designated extraction area (L/B >> 1) situated perpendicular to the tidal current, a situation comparable to those of the navigation channels, with a relatively large depth.

Long-term morphological evolution within the designated extraction area

Unlike a small-scale temporary sand pit in the nearshore coastal zone (Chapter 3) or a navigation channel (Chapter 4), the morphological evolution of a designated extraction area *strongly depends on the geometry* of this designated extraction area.

In the extreme situation of an elongated designated extraction area (L/W >> 1) situated perpendicular to the dominant tidal current direction, the morphological effects expected are comparable to those of the present navigation channels:

- The greatest changes in the bed elevation occur around the inflow and outflow zones of the designated extraction area – the slope gradients become gentler and the morphological influence area expands.
- In the case of steeper slopes the levelling-off is stronger and consequently the expansion of the influence area is greater.
- As a result of flow deceleration over the designated extraction area the central part is subjected to mild sedimentation.
- The centre of gravity of the designated extraction area shifts in the direction of net sand transport. In the situation of the Euro-Maas Channel and the IJ Channel this concerned the northeast flood direction.

For a different designated extraction area geometry, which involves a flow rate increase to a greater or lesser extent, the morphological evolution is different:

- The exact geometry of the designated extraction area determines the degree of flow rate increase over the inflow and outflow edges, and possibly the side edges.
- Increased flow velocities as a result of the flow rate increase over the inflow and outflow edges of the designated extraction area, leads to increased sediment transports (see Figure 5.3), resulting in:
  (1) the levelling-off of the slopes, ie the inflow and outflow edges as well as the side edges, occurs at a higher rate, and
  (2) an expected increased residual transport, causing the centre of gravity of the designated extraction area to shift at a higher rate.
- when additional flow is supplied over the side edges as well, the tidal flow discharge through the designated extraction area increases as the distance to the inflow edge increases. In this situation a mild erosion of the central part of the designated extraction area is to be expected. This certainly applies to the extreme situation of an elongated designated extraction area with the longitudinal axis parallel to the tidal current direction.

<u>Long-term morphological evolution of the immediate surroundings</u>
The morphological evolution in the immediate surroundings of the designated extraction area, outside the effect of the slopes, is affected by the presence of a designated extraction area. If a designated extraction area attracts additional tidal discharge, this must be at the expense of the tidal discharge in the surrounding area, which also causes a decrease in tidal current velocity. Consequently sediment transports in the surrounding area of the designated extraction area change, resulting in erosion and sedimentation.

<u>Long-term morphological evolution of the nearshore coastal zone</u>
The sand balance of the nearshore coastal zone, and consequently the coastline position, may be affected in the very long term, ie over centuries or longer, as a result of the morphological evolution of the designated extraction area. This occurs if the designated extraction area stretches out in a cross-shore direction into the nearshore coastal zone.

Further details can be found in Section **5.5**.

III. Hydrodynamic conditions in the coastal zone
A designated extraction area can affect the wave field approaching the shore in various ways. Higher waves can occur at the designated extraction area and on the shoreward side. This effect can in theory reach the coast, as most of the wave energy is dissipated only just off coast. As the wave field is affected, the wave boundary conditions can increase under extreme storm conditions, in the longer term necessitating sand redistribution in the nearshore coastal zone.

Further details can be found in Section **5.6**.

5.4 Hydraulics in the designated extraction area and its immediate surroundings

5.4.1 Function: ecology
Sand extraction destroys the bottom fauna, which is found mainly in the bed top layer with a thickness of several centimetres. Recovery of the bottom fauna in the designated extraction area is desirable. The initial recovery depends on the structure and sediment composition of the new bed top layer, the increased water depth and the altered flow regime.

<u>Sediment composition in the bed top layer</u>
The sediment composition at the bottom of the designated extraction area depends in the first place on its original sediment. The composition is furthermore affected by the nature and quantity of sediment deposited in the designated extraction area. Silt deposition in particular can present risks to the bottom fauna if deposition and erosion occur alternately, causing the bottom fauna to be buried periodically. Silt deposition depends on the supply of silt from the surrounding area, such as natural sources, dredging spoil and other sand extraction operations, and the flow velocity in the designated extraction area. The higher the flow velocity, the less risk that this process occurs.

Silt deposit calculations have not been carried out within the context of this report. As indicated in Section 4.5, sedimentation of silt and fine sand occurs to a certain extent in the most shoreward part of the Euro-Maas Channel. Local deepening in that part is on the order of 10 metres. In view of the specific conditions in the vicinity of silt sources and the outflow of fresh river water under which this sedimentation occurs, it is to be expected that silt sedimentation in a large-scale designated extraction area with a comparable or relatively lesser deepening is minor.

<u>Water depth increase</u>
If the water depth strongly increases in the case of a deep extraction operation, such as 20m or deeper, the light climate near the bottom changes to such an extent that the new bottom population is expected to be different from the original population.

<u>Oxygen deficiency</u>
Oxygen deficiency can in theory occur near the bottom of the designated extraction area. Such a situation occurs under a combination of high oxygen use due to algal growth and of limited water refreshment. This report is restricted to the physical aspect, ie insufficient water refreshment in the designated extraction area. A water residence time near the bottom exceeding 10 days should be avoided. A long residence time can be caused by vortices at the bottom of the slope, which may be reinforced by stratification in the designated extraction area underneath the original sea bed surface (Figure 5.4).

Vortices can occur if the slope gradient of the designated extraction area becomes too steep. This phenomenon occurs with slope gradients steeper than approximately 1:6. Strong stratification mainly occurs around the Rijn/Maas mouth, as a result of density differences between fresh water and salt water. In most cases, however, this salt stratification is limited to the top ten metres of the water column. Other causes of stratification are the occurrence of vertical temperature differences or high silt concentrations, eg resulting from heavy storm or dredge spoil.

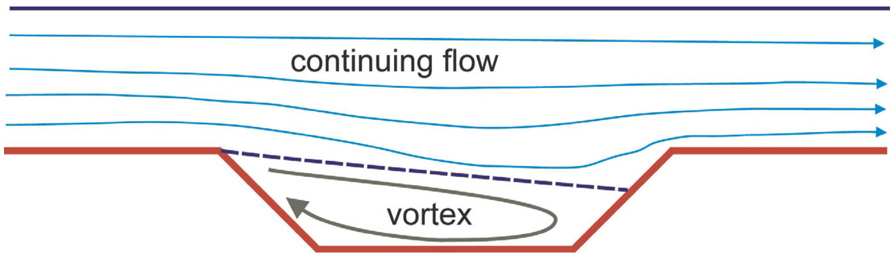


Figure 5.4 There can be insufficient water refreshment of water at the bottom of the designated extraction area due to vortices or stratification. This can cause oxygen depletion.

5.4.2 Flow velocity model calculations

As measuring data of flow velocities in large-scale designated extraction areas are hardly available, insight into designated extraction area flow is mainly derived from model calculations. These are often based on a depth-averaged flow approach (see previous hypotheses) which is acceptable for deeper water. In addition to model calculations, qualitative information on longshore hydrodynamic and sediment transport conditions was applied. Expert judgement was also used.

Tidal current
Subsection 5.3.3 explained that a flow rate increase can be expected at a designated extraction area, while the depth-averaged flow velocity can either increase or decrease. By means of model calculations, it was examined at which length/width ratio the transition in the changing flow velocity can occur, depending on the orientation of the designated extraction area towards the main direction of the tidal current.

Svašek, 1998 and **Klein, 1999** carried out idealised model calculations of the depth-averaged tidal current in and around a rectangular large-scale designated extraction area, at an ambient depth of 20m (flat bottom). It can be deduced from these model calculations that the velocity amplitude increases, which is tidal current ‘magnification’, if the L/W ratio is ≥ 5 and if the designated extraction area location is parallel to the direction of the tidal current. If the L/W ratio is < 5, the velocity amplitude remains lower than outside the designated extraction area (tidal current ‘attenuation’).

In the case of an elongated designated extraction area (L/W >>1), the sand extraction depth determines the extent of velocity amplitude. The deeper the sand extraction the stronger the ‘magnification’ or ‘attenuation’, depending on the orientation of the designated extraction area. In an elongated designated extraction area parallel to the tidal current direction, ‘magnification’ of the velocity amplitude occurs as well as an increase in the phase difference. In the case of a designated extraction area with a lower length/width ratio, the effect of the width on the velocity amplitude also becomes noticeable.

The following can be concluded from a comparison of model results with theory (**Svašek, 1998**):

- In the case of high L/W ratios, the time scale effect dominates the length scale effect on the designated extraction area flow. The velocity amplitude and phase lag compared to the surrounding area can then be determined in good order with the 'local approach'.
- In the case of decreasing L/B ratios, the flow can be approached as increasingly 'quasi stationary', still taking into account the effect of width.

Within the context of a study into the possible construction of a Second Maasvlakte, model calculations were carried out by means of a hydraulic models which covers the nearshore zone of the Dutch coast[12] (**Kuijper, 1997b**) of the threedimensional hydraulics for various sand extraction variants, in combination with overdimensioning of the Euro-Maas Channel. The vertical water column was represented schematically in the calculations by means of six layers.

The model results show that in a shallow designated extraction area (2m) the tidal current does not change. In a designated extraction area with a extraction depth of 5m and 10m respectively, the maximum flow velocities in the top layers decrease during flood tide by 20% and 25% respectively. At the bottom the changes in flow velocity are minor. These minor differences could nevertheless have been caused by the method of schematisation of the bottom layer and the calibration applied.

Tidal current in the immediate surroundings
An increase in tidal discharge per metre through the designated extraction area causes a decrease in discharge per metre parallel to the designated extraction area. Higher flow velocities occur in the running-in areas where the increase of discharge per metre is already present. Both effects are represented in Figure 5.5.

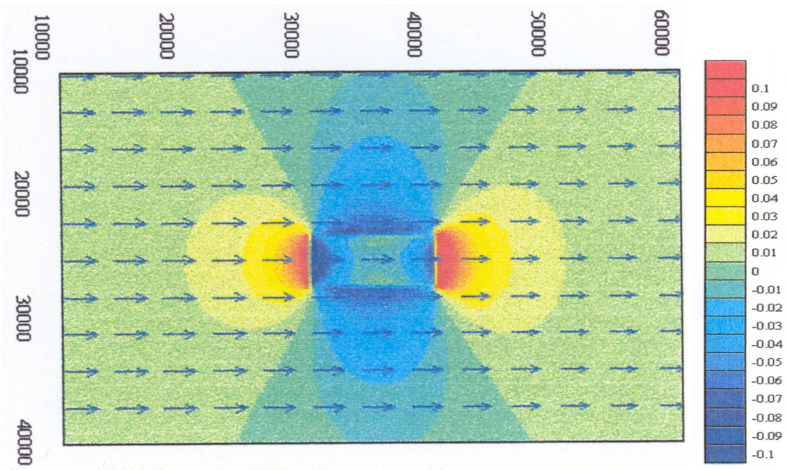


Figure 5.5 Flow velocity differences in a situation with a designated extraction area (length 20 km, width 4 km and depth 10m, parallel to the tidal current) and a flat bottom, during maximum flood tide, from **Svašek, 1998**.

[12] Also known as 'Kuststrookmodel'

Mean tide residual)flow in and around the designated extraction area
Klein, 1999 paid particular attention to the mean tide velocity field including the earth rotation effect, resulting in the 'Coriolis apparent force'. As a basic scenario, a designated extraction area of 40 km in length, 5 km in width and 10m in depth was examined. The velocity amplitude outside the designated extraction area is 0.5 m/s.

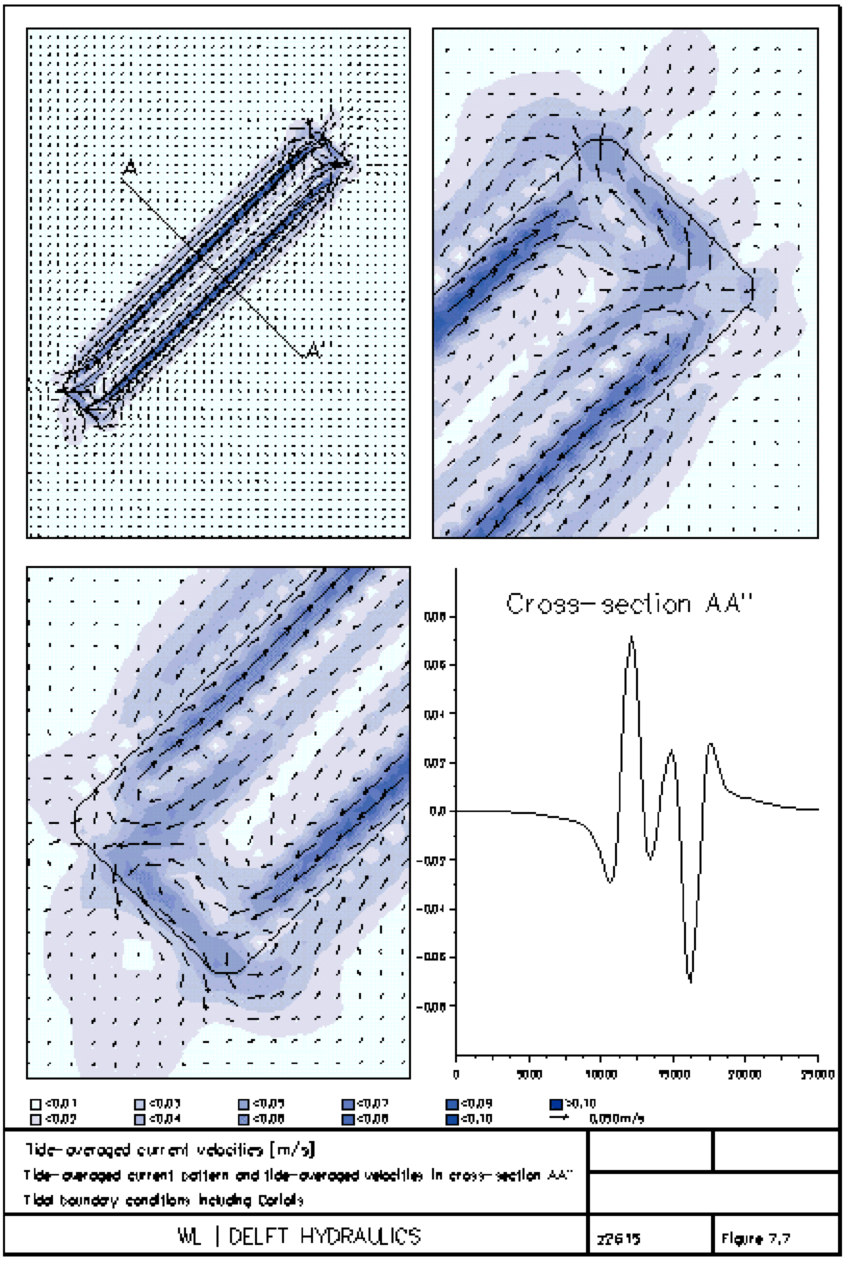


Figure 5.6: Calculated mean tide velocity field around a designated extraction area, 45 degrees anti-clockwise compared to the tidal current (flood direction is to the right). The designated extraction area dimensions are: length 40 km, width 5 km and depth 10m, from **Klein, 1999**.

In a designated extraction area situated in the direction of the tidal current, higher residual velocities in the order of 1 cm/s occur near the lateral edges within the designated extraction area than around the central part of the designated extraction area. The direction of the residual velocity on one side is opposite to the direction on the other side. In addition the direction of the residual velocity directly outside the designated extraction area – along the lateral edges – is opposite to the direction directly inside the designated extraction area. One could say that two large circulation cells can be identified.

If the designated extraction area is rotated anticlockwise compared to the tidal current direction, the two circulation cells become considerably stronger (see Figure 5.6). If the designated extraction area is rotated in the opposite, clockwise direction the circulation is also considerably stronger, but the direction of the circulation cells is reversed. If the tidal velocity amplitude outside the designated extraction area is greater, the positions of the two circulation cells shift. If the velocity amplitude is very high, ie in the order of 2 m/s, one large circulation cell remains, which extends to a zone around the designated extraction area.

The designated extraction area outflow is concentrated around two angular points, to the left of the outflow direction, in a narrow zone with relatively high velocities in the order of 10 cm/s.

5.4.3 Refreshment of water masses in the designated extraction area

Model calculations of the residence time of water masses in a designated extraction area were not made. To form a picture, nevertheless, of the effect of the presence of a large-scale designated extraction area on the residence time of water masses and consequently the measure of refreshment, theoretical calculations were carried out (**RIKZ, 1999/2001**).

It can be deduced from a conservative estimate of the flow velocity near the bottom in a large-scale designated extraction area, that refreshment of water masses in the designated extraction area hardly decreases. Depending on the geometry it may even increase. The chance that oxygen depletion of the water column near the bottom occurs in a large-scale designated extraction area – under extraordinary conditions – is nearly as small as the chance that it occurs without the designated extraction area, in the natural situation.

5.5 Morphological evolution of the designated extraction area and surroundings

5.5.1 User functions: coastline maintenance and locations of cables and pipelines

The morphological evolution of the designated extraction area and its immediate surroundings is relevant to the sand balance of the coastal zone and to the locations of cables and pipelines. Both are adversely affected if the morphological evolution extends to the coastal zone or to the location of cables and pipelines. If this in fact occurs is determined on the one hand by the initial distance to the designated extraction area, ie the *buffer zone*, and on the other hand by the long-term morphological evolution of the designated extraction area and its immediate surroundings.

<u>Coastal buffer zone</u>

The RON/MER allows sand extraction immediately seaward of the NAP –20m depth contour. As this NAP –20m depth contour also forms the seaward boundary for the coastal zone, there is basically no buffer zone between the designated extraction area and the coastal zone.

<u>Cable and pipeline buffer zone</u>

With respect to sand extraction operations, the present RON/MER prescribes that a minimum distance of 500m is kept between designated extraction areas and cable and pipeline locations present on the North Sea bed. Overstressing, particularly in pipelines, due to erosion at the locations of cables and pipelines, with the risk of pipeline breakage, should be prevented.

5.5.2 Model calculations of the morphological behaviour of the designated extraction area

Long-term morphological evolution of the designated extraction area
Little is known about the possible morphological behaviour of large-scale deepening in the North Sea, as measuring data are not available. The previous chapters focused on onedimensional calculations. Longshore evolution was calculated separately from cross-shore evolution. The separate approaches does not consider the effect of large-scale designated extraction area geometry to the morphological evolution.

Klein, 1999 carried out model calculations for an idealised situation for the long-term morphological evolution, in the order of 1,000 years, of a large-scale designated extraction area and for various extraction variants.

Morphological evolution within the designated extraction area: further deepening
The model results show that deepening of the central part may occur. Erosion of the central part was already calculated in **Ribberink and Roelvink, 1989**, which calculation was based on L/W = 20. From their theoretical approach of the morphological evolution, it followed that in a designated extraction area parallel to the flow with a length (L) exceeding 5,000m, erosion of the central part can occur if L/W ≥ 3. This is a lower value than the length/width ratio at which an increase in the depth-averaged flow velocity occurs (L/W ≥ 5).

At the upstream edge of the designated extraction area, the transport capacity decreases as a result of a decrease in flow velocity and in the suspension effect, after which it gradually increases owing to a gradual flow rate increase (increase in flow velocity). This results in local erosion areas around the centre of the designated extraction area. It follows from **Klein, 1999** that even at L/B ≥ 1 erosion of the central part can occur.

Although the model calculations did not show it explicitly (**Klein, 1999**), it is expected that the increased discharge inflow and outflow over the edges results in a greater transport gradient over the slopes and consequently a higher rate of morphological adaptation of the slopes **(Stive et al 1998).** The same applies to the side slopes.

To conclude, the designated extraction area orientation is also a factor. On physical grounds it can be proven that a preferential orientation exists, in which erosion of the central part occurs (**Zimmerman, 1981**). **Nemeth, 1998** confirms this in his study, in which this principle is worked out theoretically and compared to numerical calculations of bed changes on a short time scale. The designated extraction area rotates anticlockwise compared to the dominant flow direction, to arrive at its preferential orientation. The model results of **Klein, 1999** are qualitatively in line with this. In designated extraction areas which rotated in an anticlockwise direction, erosion of the central part occurs, whereas sedimentation of the central part mainly occurs for a clockwise rotation.

There is great uncertainty about the long-term morphological evolution. The erosion of the central part can clearly not continue unhindered. Neither the central part's maximum attainable depth is known, nor the time scale on which the maximum depth is achieved. Moreover the maximum depth is not necessarily a stationary depth. There is a real possibility that shoaling occurs after reaching the maximum depth. In **Klein, 1999** a local deepening of the central part of 2 metres maximum was calculated over a period of 1,000 years. However, the model results did not produce an indication of a possible stationary depth, nor of the time scale on which the maximum depth is reached. The model results should therefore be treated very carefully when translated into practice.

Morphological evolution outside the designated extraction area: new bed forms?

The morphological evolution in the immediate surroundings of the designated extraction area, outside the effect of the slopes, is also affected by the presence of a designated extraction area. If a designated extraction area attracts additional tidal discharge, the tidal current in the surrounding area is affected. Small differences in flow velocities and residual transports in the long term induce bed changes stretching over a larger zone. Bed elevation disturbance with a favourable length scale can initiate dynamic bed forms comparable to existing dynamic bed forms, such as the tidal banks or sand waves (**Nemeth, 1998**). In theory it is possible that a large-scale designated extraction area initiates new dynamic bed forms in a large zone around the designated extraction area. It is however not known if these forms actually would occur, what they would look like and how far around the designated extraction area they could stretch.

In view of the large spatial scale on which the possible dynamic bed forms can extend, the impact to, for instance, the sand balance of the coastal zone and the location of cables and pipelines can be significant. As there are also great uncertainties about the possible effects, it is recommended to conduct further studies into the possible long-term evolution of dynamic bed forms.

Buffer zone between designated extraction area, and cable and pipeline locations: greater distance

The morphological influence area on a time scale of 50 years is a minimum of several kilometres (**Stive et al, 1998**). This area exceeds the presently defined safe zone. Depending on the life span of cables and pipelines, eg 30 years, and the extent of the expected erosion in the area, a wider safe zone may be advisable. Future designated extraction areas should therefore be projected at a greater distance from the location of cables and pipelines.

Consequences for the nearshore coastal zone: sand loss in the long term

The sand balance of the nearshore coastal zone and consequently the coastline position, can be affected in the very long term, in the order of centuries or longer, due to the morphological evolution of the designated extraction area. This occurs if the designated extraction area migrates in a cross-shore direction into the nearshore coastal zone. In this situation the cross-shore morphological influence area increases proportionate to the extent of the disturbance in a cross-shore direction. Over a period of 50 years, the upper limit for the dimensions of the cross-shore morphological influence area is several kilometres (**Stive et al, 1998**).

The greatest cross-shore effect is to be expected at a relatively high cross-shore component of the tidal current around tidal outlets and estuaries or further offshore. The observation can furthermore be made that the seaward boundary for sea sand extraction varies along the Dutch coast (eg max. 20 km for the central part of the Dutch coast). Consequently, the morphological influence on the shoreward zone also varies relatively speaking. This raises the question if a less variable depth limit could be applied, eg the established NAP –20m line.

The tidal variation along the Dutch coast affects the morphological changes of the designated extraction areas. The highest tidal current velocities occur along the Delta coast. This is where the greatest morphological changes of the designated extraction area are expected. The slight tidal asymmetry translates into a virtually symmetric evolution of the designated extraction area slopes. Tide-averaged residual transport increases further north along the Dutch coast under the influence of an increasing tidal asymmetry. As a result there is also an increased shift towards the north of the centre of gravity of a designated extraction area. The difference between the gradients of the south and north slopes of the designated extraction area furthermore increase. In the area off the Wadden Sea the tidal current velocities increase further, which means that the morphological influence area, such as along the Delta, exceeds that of the more northern part of the Dutch coast (**Stive et al, 1998**).

In view of the large temporal and spatial scales involved in the morphological influence of a designated extraction area, a study of a local coastline effect does not suffice. Coastal evolution should preferably be studied in a wider context, ie of larger coastal sections in longshore and cross-shore direction. Effects of possible interaction with land reclamation and the effect of the sea level rise should also be taken into consideration.

5.6 Hydrodynamic conditions in the coastal zone

5.6.1 User functions: Coastal safety and coastline maintenance

A sizeable part of the sea dykes and dunes of the Dutch coast must be able to withstand an extreme storm occurring once every 10,000 years. In theory the presence of a large-scale designated extraction area in deep water can affect the wave field and water levels during extreme storm conditions. Both aspects are explained below.

In theory the presence of a large-scale designated extraction area has an effect on the wave-driven longshore transports through its effect on the wave field. In the long term this may possibly result in redistribution of sand in the nearshore coastal zone.

5.6.2 Model calculations for coastal safety and coastline maintenance

Water levels

Within the context of studies into the possible construction of a Second Maasvlakte, model calculations were carried out to study the effect on water levels (**Kuijper and Philippart, 1997**), for various reclamation and accompanying sand extraction variants. It is concluded from the calculations that the presence of a designated extraction area with a maximum depth of 10m and a volume of 300 million m^3 has a negligible effect in the order of 1 cm on the astronomical high tide level (mean tide) and the base levels over the designated extraction area or along the coast. On the basis of this result, the conclusion seems justified that the geometry and location outside the coastal zone of a large-scale designated extraction area are of minor importance to the effect on the base levels.

Wave field: wave height and wave period
Within the context of studies into the possible construction of a Second Maasvlakte, calculations of the effects on the wave field during extreme storm conditions were carried out by means of the HISWA wave model (**Kuijper, 1997a**). The following effects occur in the case of a 10m deep designated extraction area with a volume of 300 million m^3:

- A wave height increase is visible at the western edge of a 10m deep sand designated extraction area, caused by refraction.
- Along a cross-shore profile off Delfland, a wave height increase seaward of the designated extraction area as a result of refraction as well as a decrease over the pit and shoaling shoreward of the designated extraction area are visible.

It is concluded that the raised wave field is not noticeable up to the coastline.

As regards the wave period, measurements near Petten showed that the peak period of the wave field during storm conditions hardly changes during its propagation towards the coast (**Andorka, 1996**). When a large-scale designated extraction area causes an increase in the peak period as a result of wave generation, this is possibly be noticeable up to the coastline.

The HISWA calculations (**Kuijper, 1997a**) as yet do not show any shift of the peak period in the case of the presence of a 10m deep sand designated extraction area.

As the above-mentioned calculations concerned only one sand extraction variant, as the SWAN wave model is better validated than the HISWA model applied, and as knowledge is gained in the field of the occurrence of long waves with large wave periods during storm conditions, it is recommended to include this aspect explicitly in the design of a large-scale designated extraction area.

Sediment transports and morphology in the nearshore coastal zone
The presence of a large-scale designated extraction area in theory affects the wave field approaching the shore, and consequently also the wave-driven flow and sand transports in the nearshore coastal zone. As part of studies into the possible construction of a Second Maasvlakte, calculations were carried out with the numerical model UNIBEST of the possible effect of the location of the MCL (**Steijn, 1997**). It follows from the model results that in the short term, ie 5 years, the effect on the MCL position is minimal and insignificant.

This does not give a conclusive answer to the question of the effects in the longer term or of the effects in the case of a different location or geometry of the designated extraction area. Additional calculations, if possible in combination with field measurements into the effect of the wave field should provide an answer to this.

5.7 Conclusions: effects of large-scale sea sand extraction in designated extraction areas

The main questions in this chapter were:

> *What physical effects occur as a result of large-scale sand extraction in designated extraction areas and what influence do these effects have on the relevant user functions?*

Physical effects

Hydraulics
The geometry of the designated extraction area determines the manner in which flow patterns change. Depending on the orientation and the length(L)/width(W) ratio of the designated extraction area, an increase in the tidal discharge through the designated extraction area occurs. Model calculations show that for an elongated designated extraction area ($L/W \geq 5$) situated parallel to the tidal current, the increase of the discharge per metre is so extensive that the depth-averaged flow velocity is higher within than outside the designated extraction area. In the case of an elongated designated extraction area situated perpendicular to the tidal current, the increase of the discharge per metre is minimal and flow deceleration occurs. Such a situation is characteristic of the Euro-Maas Channel and the IJ Channel. The relative depth of the designated extraction area determines the degree of flow deceleration or flow acceleration.

Silt and fine sand sedimentation
Measuring data of silt and fine sand sedimentation in a large-scale designated extraction area are only available for the navigation channels in the 5 km-long connection zone with the harbour mouth. It is assumed that the chance of silt and fine sand sedimentation in a large-scale designated extraction area of the same relative depth is comparable or possibly slightly smaller. The chance of sedimentation in the designated extraction area theoretically increases in the case of a geometry involving flow deceleration, and further increases as the relative depth increases. In addition the chance of silt sedimentation is bigger if the designated extraction area is in the vicinity of silt sources, eg the deep extraction pits.

Morphological evolution
As for the hydraulics, the geometry of a large-scale designated extraction area determines the morphological evolution. Model calculations involving a designated extraction area with $L/W \geq 1$ situated parallel to the tidal current, show that mild erosion occurs in the central part of the designated extraction area. This effect is expected to be maximal in the case of an elongated designated extraction area situated parallel to the flow or at a small angle to the flow (rotated anticlockwise). Neither the maximum depth eventually reached is known, nor if shoaling re-occurs after that or if a stable equilibrium elevation occurs. In the situation of an elongated designated extraction area situated perpendicular to the flow, the morphological behaviour is comparable to the behaviour of overdimensioned navigation channels.

Effect on the user functions
Ecology
Ecology, in particular bottom fauna, is an important value. A prolonged negative effect on ecology due to the construction of large-scale designated extraction areas is undesirable. Ecological recovery can only occur, however, if the water in the designated extraction area is regularly refreshed, keeping the oxygen concentration at a sufficient level. Situations of practically stagnant water have shown that under extraordinary conditions, such as prolonged warm weather, slight mixing of water masses and high oxygen use after a period of algal growth, oxygen deficiency may occur if the water residence time in the area exceeds 10 days. In the case of an elongated designated extraction area situated perpendicular to the flow (comparable to navigation channels), flow deceleration occurs and is the residence time, and the chance of a possible oxygen deficiency, larger than of an elongated designated extraction area situated parallel to the flow direction. In the latter case, the flow velocity in the designated extraction area can even increase, as a result of

which the residence time of the water in the designated extraction area and consequently the chance of oxygen deficiency is very slight. In addition the slope gradient is important with a view to possible 'vortex formation' in the flow.

Cables and pipelines
Due to the morphological evolution of a large-scale designated extraction area, erosion can occur over a period of 50 years and over a distance of several kilometres around the designated extraction area. This erosion is caused by the leveling of the slopes and the shift in the centre of gravity of the designated extraction area. Any cables and pipelines in this zone could become exposed due to erosion.

Sand balance
If a large-scale designated extraction area is situated close to the NAP –20m line, erosion on the shoreward side of the designated extraction area adversely affects the sand balance of the coastal zone. Whether this could affect the coastline position in the very long term was not investigated.

Coastline position and coastal safety
The effect of a large-scale designated extraction area on coastal safety immediately after construction of the designated extraction area seems limited. Model results indicate that such a designated extraction area has a negligible effect on the hydraulic boundary conditions as for water level and wave parameters. The effect of a large-scale designated extraction area on the coastline position is limited. Model results indicate that a large-scale sand designated extraction area affects the wave field and consequently sediment transports to a limited degree. In the short term, ie 5 years, this does not result in an appreciable change of the coastline position. However, the long-term effect on the coastline position has as yet not been clearly investigated.

6 Sea Sand Extraction Recommendations

6.1 Temporary sand extraction in the near-shore coastal zone

Temporary sand extraction in the nearshore coastal zone can be an attractive option for an efficient execution of, for instance, a dune or beach nourishment. Concessions should be granted on the condition however that this method does not result in any sand loss in the nearshore coastal zone.

Backfilling the temporary sand pit after the nourishment to the level of the original bed elevation is a prerequisite for fulfilling this condition. It should furthermore be realised that during the presence of the pit, sand is eroded from the immediate surroundings. This sand loss also needs to be compensated, for example by overdimensioning of the sand nourishment or by leaving a small sand buffer over the temporary sand pit.

The volume of sand loss to be compensated from the surrounding area to the temporary sand pit can be calculated with the following formula:

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

where:

V_c	[m^3]	: Volume of sand loss to be compensated
V_0	[m^3]	: Volume of the temporary sand pit
t	[months]	: Period during which the temporary sand pit is open
T_k	[months]	: Characteristic time scale of the temporary sand pit

The analysis of temporary sand pits in this report shows that the time scale varies between 6 months and 12 months. It is assumed that the time scale is small, ie that the pit fills quickly. The table below gives a recommendations for the time scales to be applied.

Characteristic Time Scale [months]	Winter	Summer
Shallower than NAP –10m	6	9
Deeper than NAP –10m	9	12

Table 6.1 Choice for the time scale to be applied for the calculation of sand volume to be compensated

Figure 6.1 can be applied to determine the sand volume to be compensated. It is expressly mentioned that the period during which the pit is open starts at the moment of the first extraction.

The use of a temporary sand pit along the straight Dutch coast and the central parts of the Wadden Islands for the execution of beach nourishments does not have any adverse consequences for the coastal safety if:

- extraction is carried out seaward of the NAP –7m line, and
- if the surface area of the extraction pit is under 10 ha.

If the use of a temporary sand pit for the purpose of beach nourishment is considered in the nearshore coastal zone along the Zeeland or South-Holland islands or along the heads of the Wadden Islands, it is recommended that a further specification be given for the conditions under which temporary sand extraction is to be executed.

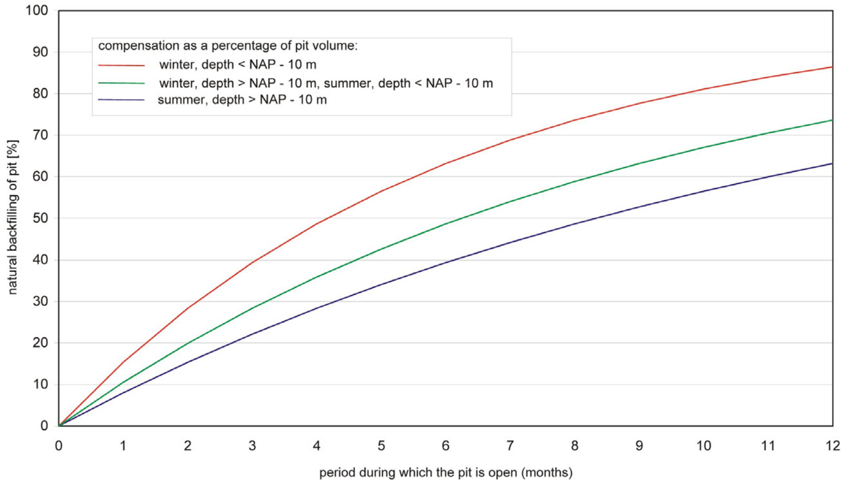


Figure 6.1: Diagram showing the compensation for sand loss as a result of a temporary sand pit in the nearshore coastal zone

6.2 Large-scale sand extraction in navigation channels

Shipping and maintenance operations

Large-scale sand extraction in navigation channels to shipping has the positive effects of an increased depth and a lower transverse flow velocity. Around the jetty heads a complex flow pattern can occur, however. It is recommended to investigate this further by means of hydraulic model calculations in the case of a further widening and/or deepening of navigation channels.

It is recommended to make the slope navigation channels gentler than 1:7 to prevent wave reflection on the navigation channel banks, so as to prevent possible hindrance to shipping due to reflecting waves. The Zero-Plus option of the present RON/MER already takes a slope gradient of 1:10 as a basis.

Through estuarine circulation, silt is transported from the sea to the harbour basins. Navigation channel overdimensioning can affect this estuarine circulation. It is therefore recommended to examine beforehand by means of a hydraulic/silt model if navigation channel overdimensioning causes increased silting of the harbours.

Cables and pipelines

The RON/MER provides for a buffer zone of 500m between the navigation channels and the cable and pipeline locations. When overdimensioning of the present navigation channels is planned, the distance of this buffer zone is to be reconsidered. Studies show that the influence zone is 6 to 20 kilometres over a period of 50 years. This can be anticipated by taking the following measures:

- Widening the buffer zone, eg to 1,000m
- Deeper digging in of cables and pipelines in the seabed
- Periodical checks for possibly exposed cables and pipelines, followed by mitigating measures if necessary

Coastline maintenance and coastal safety

The presence of navigation channels causes erosion of the deeper parts of the nearshore coastal zone adjoining the navigation channels, which has an adverse effect on the sand budget in that area. The presence of jetties, on the other hand, makes a positive contribution to the sand budget by accretion of the coastline. It is recommended to investigate both the positive and the negative effects in the influence area and subsequently decide if mitigating measures are necessary.

It is recommended to carry out a study into the navigation channel effect on wave conditions in the nearshore coastal zone and to examine how navigation channel overdimensioning affects wave conditions during extreme conditions.

Connection between large-scale interventions
It is recommended to consider the effects of navigation channel overdimensioning in connection with effects of other large-scale interventions.

6.3 Large-scale sand extraction in sand designated extraction areas

General
Large-scale sand extraction operations exceeding 100 million m^3 in volume will be few in number, as opposed to regular sand extraction operations. This report does not recommend any quantitative guidelines regarding pit geometry, such as length, width, extraction depth, orientation towards tidal current and slope gradients. Instead it recommends extraction of the effects of large-scale sand extraction on all relevant user functions in an Environmental Impact Assessment. The knowledge in this report and the recommendations given below can be used for that purpose.

Ecology
Recovery of bottom fauna in the designated extraction area at least requires a sufficiently high level of the minimum oxygen concentration. To achieve this, it is important that the water in the designated extraction area is refreshed within a period of approximately 10 days. If there are doubts as to the refreshing rate of the water in a future designated extraction area, eg because the design involves steep slope gradients and/or deep extraction depths, it is recommended to carry out a study by means of hydrodynamic model calculations, including a calculation of oxygen concentration by means of a water quality model.

Cables and pipelines
In the case of an elongated designated extraction area along the coast, the tidal current is directed through the designated extraction area with maximum effect. This causes an increase in the gross sand transports during ebb and flood, and in the net mean year transport. This results in a greater slope gradient decrease and in shifting slopes. Over a time scale of 50 years, an influence area of several kilometres is to be taken into account. This can be anticipated by taking the following measures:

- Widening the buffer zone, eg to 1,000m
- Deeper digging in of cables and pipelines in the seabed
- Periodical checks for possibly exposed cables and pipelines, followed by mitigating measures if necessary.

Maintaining the coastline and the sand budget in the coastal zone
Large-scale sand extraction in a designated extraction area causes sand loss at the area's shoreward side. Sand loss in the coastal zone, which in the long tem

affects the coastline position, is to be prevented. Partly for this reason it is recommended that a buffer zone of several kilometres be created between the large-scale sand designated extraction area and the coastal zone to be maintained, of which the seaward boundary is currently formed by the established NAP –20m depth contour.

Coastal safety
Large-scale sand extraction in a designated extraction area outside the coastal zone, seaward of the NAP –20m depth contour, does not seem to have a significant adverse effect on coastal safety, on the condition that the coastline position and the sand budget of the coastal zone are maintained. On the basis of model calculations for several extraction scenarios it is concluded that the wave boundary conditions and the basic levels during extreme storm conditions are affected to a very limited extent. It is nevertheless recommended always to include this aspect in the evaluation of the design for a large-scale sand extraction operation.

Connection between large-scale interventions
It is recommended to examine the effects of large-scale sand extraction in designated extraction areas in connection with the effects of other large-scale interventions in the North Sea.

Bibliography

References

Allersma, E. and Ribberink, J.S., 1992. *"Zeezandwinning. Analyse van de morfologische effecten van zandwinning in de Euro-Maasgeul"*, report WL, H 1258.

Andorka Gal, J.H. 1996. *"Verification set Petten"*, work document RIKZ/OS-96.137x.

Anonymous, 1995. *"Milieu-effectrapport over een nieuwe Loswal Noord. Voor baggerspecie uit het Rijnmondgebied die in de Noordzee wordt verspreid"*, Project group MER Loswal Noord.

Bestuurlijk Overleg Voordelta, 1993. *"Integraal beleidsplan Voordelta : vastgesteld door het Bestuurlijk Overleg Voordelta op 3 mei 1993"*, ed. J. van Alphen and R. Molendijk. – Rijswijk, 75 p.

Bosch, R. , E. Heeringa, P. Laloli, M. van de Ploeg, I. Ranzijn, J.Sytema, E. Veer and R. Vos., 1997. *"Baggeren van zandgolven in de Eurogeul. Op zoek naar de optimale baggerstrategie. Multidisciplinaire Ontwerp-opdracht"***,** Twente University, June 1997.

Boutmy, A.E.G., 1998. "Morphological Impact of IJmuiden Harbour. Validation of Delft3D 1968 - 1996", Dissertation (Delft University of Technology), WL report no. Z2321.

Combe, A.J. and C.W. Soileau, 1987. "Behavior of Man-Made Beach and Dune Grand Isle, Louisiana", Coastal Sediments 1987, pp 1232 - 1242.

De Looff, A.P. and F.P. Hallie, 1995. *"Effecten van zandoverslag in de kustzone; proefsuppletie m.b.v. de 'Punaise' - interim evaluatieverslag"*, report RIKZ/AB-95.125x.

De Looff, A.P., F.C. Groenendijk, R.M. Salden and A.C. Smaal, 1995. *"Met maasvlakte II in zee. Zeewaartse uitbreiding van de Maasvlakte: Hydraulische, morfologische en ecologische gevolgen voor het zeegebied"*, National Institute for Coastal and Marine Management, report RIKZ-95.047.

De Ruijter, W.P.M., A. van der Giessen, F.C. Groenendijk, 1992. "Current and Density Structure in the Netherlands Coastal Zone", From: Dynamics and Exchanges in Estuaries and the Coastal zone, 1992; D. Prandle, ed.

Dunsbergen, D.W., 2001. *"Programmaplan KUST2005. Deel 1, 2 en 3"*, work document RIKZ/OS/2001.106x, March 2001.

Eysink, W., 1979. *"Morfologie van de Waddenzee, gevolgen van zand- en schelpenwinning. Verslag literatuuronderzoek"*, Hydrodynamic Laboratory, report R1336, May 1979.

Gerritsen, F., 1997. *"Voorstudie naar een vakindeling van de zandbalans van het zeegat van Texel, inclusief buitendelta en kombergingsgebied, door middel van een tijdschalen analyse"*, KUST*2000 report, November 1997.

Haksteen, A.M.,1993. "*Onderzoek naar de mogelijkheid tot het verder reduceren van bagger- en lodingswerk in de Maasgeul*", draft, October 1993.

Hoitink, A.J.F., 1997. "Morphological Impact of Large Scale Marine Sand Extraction", Dissertation, Twente University, Z2268.

Hoogewoning, S.E., 1996. "*Tijdelijke zandwinputten. Advies over de morfologische effecten bij het gebruik van tijdelijke zandwinputten landwaarts van de NAP -20 m dieptelijn*", work document RIKZ/OS-96.161X.

Hoogewoning, S.E., 1997. "*Effecten van grootschalige zandwinning. Verkennend advies ten dienste van globale richtlijnen voor grootschalige zeezandwinning*", report RIKZ-97.033.

Jansen, S.E.A., 1981. "*Analyse van het gedrag van zandgolven in een baggerproefvak*", Directorate North Sea, no. NZ-N-81.25 (S).

Jetten, P. and Lei, C., 1998. "Collection and Analysis of Bathymetric Data of Sand Extraction Areas", report IHE.

Klein, M.D., 1999. "Large-Scale Sandpits. Hydrodynamic and Modelling of Large-Scale Sandpits", MSc Thesis Delft University of Technology, WL report Z2615, June 1999.

Klomp, W.H.G., 1996. "*Modelstudie zandwinputten*", *DHV milieu en infrastcructuur*, report no. IS-NW962244.

Kuijper, E.V.L., 1997a. "*Veiligheid van de waterkeringen in relatie tot Maasvlakte2: Extreme golfklimaat*", work document RIKZ/AB-97.102X.

Kuijper, E.V.L., 1997a. "*Maasvlakte2: De beïnvloeding van waterbeweging en stoftransport langs de Nederlandse kust*", report RIKZ-97.010.

Kuijper, E.V.L. and M.E. Philippart, 1997. "*Veiligheid van de waterkeringen in relatie tot Maasvlakte2: Basispeilen*", work document RIKZ/AB-97.103X.

Kuijper, E.V.L., 1998. "*Het effect van een zandwinkuil op de stroomcontractie door Maasvlakte2*", RIKZ work document AB-98.107x.

MarineSafety Rotterdam b.v., 1997. "*Fast-time vaarbaanonderzoek Maasvlakte2*", Final Report.

Ministry of Agriculture, Nature Management and Fisheries, 1995. "*Structuurschema Groene Ruimte*".

Ministry of Transport, Public Works and Water Management, 1998. "*Vierde Nota waterhuishouding. Regeringsbeslissing*", December 1998.

Németh, A.A., 1998. "Modelling the Dynamic Behaviour of Sand Extraction Pits and Tidal Sand Banks", Dissertation, Twente University.

NOURTEC, 1997. "Innovative Nourishment Techniques Evaluation, Final Report", Coord. *Rijkswaterstaat*, National Institute for Coastal and Marine Management/RIKZ, May 1997.

Pluijm, M. and J. Bossinade, 1986. "*Morfologisch onderzoek specieberging in de zeebodem (Simon Stevin put)*", Tidal Waters Department, policy document GWWS-86.007.

Pluijm, M., 1994. "*Onderzoek naar de civiel-technische aspecten van een verdiepte loswal op de Noordzee*", Frederic R. Harris, report H7218.

Rakhorst, H.D. and Midderham, 1979. "*Zandwinning Waddenzee; aanzanding zandwinputten*", Advisory Department Hoorn, Memorandum 79H203.

Rakhorst, H.D., 1982. "*Inventarisatie zandwinning*", Directorate Water Management, District Coast and Sea, Advisory Department Hoorn, Memorandum wwkz-82.H014.

Rakhorst, H.D. and P. Mens, 1995. "*Rapportage suppletie Bloemendaal/Zandvoort 1993/1994, PUNAISE*", Memorandum NH-ANV 95.115.

Rakhorst, H.D. and P. Mens, 1997. "*Zandsuppletie Heemskerk 1996. Uitvoeringstechnische evaluatie tijdelijke overslagput/PUNAISE*", Directorate North Holland.

Ribberink, J.S. and Roelvink, J.A., 1989. "*Zeezandwinning. Onderbouwende notitie*", report WL, H825.

Rijkswaterstaat, 1985. "*Beheersplan ontgrondingen Waddenzee : beheersplannen Waddenzee*", Ministry of Transport, Public Works and Water Management, *Rijkswaterstaat*, Directorate Friesland, 51 pp.

Rijkswaterstaat,1990. "*Kustverdediging na 1990; Beleidskeuzenota*", Ministry of Transport, Public Works and Water Management, The Hague.

Rijkswaterstaat, 1991. "*Regionaal Ontgrondingenplan Noordzee/ Milieu Effect Rapport (RON/MER)*", Directorate North Sea.

RIKZ, 1999/2001. "*Milieu-effectrapport voor de winning van Beton- en metselzand op de Noordzee*", report RIKZ/1999.014. A revised version is to appear in 2002 under the same title, with report no. RIKZ/2001.047.

Robaczewska, K.B., 1998. "*Projektplan NAUTILUS*", National Institute for Coastal and Marine Management, Draft, February 1998.

Salden, R.M., 1995. "*Gevolgen van uitbreiding van de Maasvlakte voor de hydrodynamica en de daaraan gerelateerde transportverschijnselen*", work document RIKZ/OS-95.128X.

Schipper, L.C., 1990. "*Bodemontwikkeling in de Eurogeul*", Directorate North Sea, November 1990.

Schipper, L.C., 1991. "*Zandgolven en megaribbels in de Eurogeul*", Directorate North Sea, April 1991.

Scholl, O., 1999. "Estimating Amplitude Evolution of Sandwaves", Dissertation, Twente University.

SOD, 1996. "*Structuurschema Oppervlaktedelfstoffen. Deel 4: Planologische kernbeslissing*", Ministry of Transport, Public Works and Water Management and Ministry of Housing, Spatial Planning and Environment, Sdu Publishers, The Hague, 49 pp.

Steijn, 1997. "*Invloed van MV2-varianten op het kustonderhoud van Delfland en Goeree*", Alkyon Hydraulic Consultancy & Research, report A168, Draft, May 1997.

Stive, M.J.F. and W.D. Eysink, 1989. "*Voorspelling ontwikkeling kustlijn 1990-2090, Fase 3. Deeelrapport 3.1.: Dynamisch model van het Nederlandse kustsysteem*", Hydrodynamic Laboratory l wl, report H825.

Stive, M.J.F., A. van der Weck, E. van Meerendonk, D.J.R. Walstra, L.C. van Rijn and J.A. Roelvink, 1998. "*Expert judgement morfologische ontwikkeling grootschalige zandwinning*", report WL/Delft Hydraulics, Z2566.

Svasek, J.N., 1965. "*Gedrag van een proefsleuf in de bodem van de Noordzee te Scheveningen*", *Rijkswaterstaat* – Delta Service, Hydrodynamic Department, policy document K-272.

Svasek, b.v. 1998. "*Waterbeweging in wingebieden. t.b.v. produkt K2000*ZW*", report Svasek, 98454/1081.

Tafeiëff, L., 1982. "*Ontwikkeling zuigvak baggerproef 1974. Een onderzoek naar de eventuele heropbouw van afgebaggerde zandgolven*", RIKZ, report WWKZ-82G.001.

TAW, 1995. "*Basisrapport zandige kust. Behorende bij de leidraad zandige kust*".

Tobias, F.C., 1989. "Morphology of Sandwaves in Relation to Current, Sediment and Wave Data Along the Eurogeul, North Sea", Utrecht University, 1989, 98 pp.

Van Dalfsen, J.A. and K. Essink, 1997. "Risk Analysis of Coastal Nourishment Techniques (RIACON)", National evaluation report (The Netherlands). National Institute for Coastal and Marine Management Report RIKZ-97.022 (in print).

Van Dalfsen, J.A., 1997. "*Effecten op de bodemfauna van het gebruik van een tijdelijke zandwin/overslagput in de kustzone ter hoogte van Heemskerk. PUNAISE 2: uitgangssituatie T0, mei 1996*", Koeman and Bijkerk, no. 97-14.

Van Dalfsen, J.A. 1998 a. "*Ecologische effecten van grootschalige zandwinning*", work document for vision development regarding coastal plans, RIKZ/AB-98.105x.

Van Dalfsen, J.A., 1998 b. "Long-Term Effects of Subaqueous Sand Extraction North of the Island of Terschelling", report RIKZ-98.034, project RIACON*2.

Van Dalfsen, J.A. and B. Storm, 1998 a. "*Effecten op de bodemfauna van het gebruik van een tijdelijke zandwin/overslagput in de kustzone ter hoogte van Heemskerk. Punaise 2: T1 bemonstering, januari 1997*", Koeman and Bijkerk, no. 98-07.

Van Dalfsen, J.A. and B. Storm, 1998 b. "*Effecten op de bodemfauna van het gebruik van een tijdelijke zandwin/overslagput in de kustzone ter hoogte van Heemskerk. Punaise 2: T2 bemonstering, mei 1997*", Koeman and Bijkerk, no. 98-44.

Van Dalfsen, J.A., O.W.M. Duijts and B. Storm, 1999. "*Effecten op de bodemfauna van het gebruik van een tijdelijke zandwin/overslagput in de kustzone ter hoogte van Heemskerk. Eindrapport Punaise 2*", Koeman and Bijkerk, no. 99-13, May 1999.

Van Dalfsen, J.A., 2000. "*Ecologische effecten van zandwinning op zee*", Koeman and Bijkerk, report no. 2000-16.

Van de Kreeke, J., S.E. Hoogewoning and M. Verlaan, 2001. "An Analytical Model for the Morphodynamics of a Trench in the Presence of Tidal Currents", accepted for publication in Continental Shelf Research.

Van de Meene, J.W.H., 1994. "The Shoreface-Connected Ridges Along the Central Dutch Coast", Royal Netherlands Geographical Society / Faculty of Spatial Sciences, Utrecht University, no. 174.

Van der Gouwe, J., 1990. "*Inventarisatie maatregelen reductie onderhoudsbaggerkosten in de Maasgeul en de Maasmond*", Directorate North Sea, May 1990.

Van der Linden, J., 1998. "*Het beïnvloeden van de stroomcontractie bij Maasvlakte2 door een stroomverlammingskui*l", National Institute for Coastal and Marine Management, work document
RIKZ/AB-98.128X.

Van der Woude, G., 1992. "O*nderwateroeversuppletie Noord-Ameland*", Dissertation, Delft University of Technology, Civil Engineering.

Van Moorsel, G.W.N.M, 1994. "*Samenstelling van sediment en macrobenthos bij Bloemendaal-Zandvoort in 1993*", Bureau Waardenburg bv., no. 94.01.

Van Rijn,L.C. and G.L. Tan, 1985. "*Sutrench model. 2DV mathematisch model voor de sedimentatie in vaargeulen onder stroming en golven*", *Rijkswaterstaat* communications, no. 41.

Van Rijn, L.C., 1993. "Principle of Sediment Transport in Rivers, Estuaries and Coastal Seas", Aqua Publications.

Van Rijn, L.C., 1997. "Sediment Transport and Budget of the Central Coastal Zone of Holland", Coastal Engineering 32, 1997, pp 61-90.

Van Rijn, L.C. and D.J.R. Walstra, 2002. "Morphology of Pits, Channels and Trenches. Part I: Literature Review and Suggested Study Approach", Delft Hydraulics, report Z3223.

Verhagen, H.J. and Kosgoda, K.M.S.K., 1998. "Analysis of Bathymetric Data of the Heemskerk Dredge Pit (*Punaise* Pit)", report IHE.

Verlaan, P.A.J. and Spanhoff, R., 1994. "*Sedimentatie in de Maasmond. Inventarisatie en heranalyse*", RIKZ, July 1994.

Visser, R. 1998. "*Stroming in de Maasgeul. Presentatie van stroming in Maasgeul als afgeleidevan actueel gemeten stromingbij meetpunt Maasmond*", work document RIKZ/OS-98.165X.

Walhout, T., R. Kalf, L. Walburg, 2000. "*Evaluatie zandsuppleties na 1990, deel 1 en deel 2 (appendix)*", work document RIKZ/AB/2000.824x

Walstra, D.J.R., L.C. van Rijn and S.G.J. Aarninkhof, 1998. "Sand Transport at the Middle and Lower Shoreface of the Dutch Coast", WL/Delft Hydraulics report Z2378.

Walstra, D.J.R., L.C. van Rijn, S.E. Hoogewoning and S.G.J. Aarninkhof, 1999. "Morphodynamic Modelling of Dredged Trenches and Channels", Coastal Sediments '99, pp 2355 - 2370.

Waltmans, M., 1994. "*Stremmingen door stromingen in de IJgeul?*", Report of the Channel Project, report RIKZ-94.039.

Woudenberg, C.C. van, 1996. "*De onderwater zanddam bij Loswal Noord: gedrag en zandtransport*", Directorate North Sea.

Zimmerman, J.T.F., 1981. "Dynamics, Diffusion and Geomorphological Significance of Tidal Residual Eddies", Nature, 290: 549-555.

Other literature consulted

Anonymus, 1999. "*Beheersvisie Noordzee 2010*", Steering Committee *Beheersvisie Noordzee 2010* (Ministry of Transport, Public Works and Water Management; Ministry of Agriculture, Nature Management and Fisheries; Ministry of Housing, Spatial Planning and Environment and Ministry of Economic Affairs), 64 pp.

De Jong, H., 1982. "*Sedimentatie in de trog welke is ontstaan rondom het scheepswrak 'Zamosc' in het pas van Terneuzen*", report wwkz-82.V007.

De Kok, J.M., J.M. Lourens and J.H.M. de Ruig, 1992. "*Baggerspecie, van Waterweg tot Waddenzee. Fysisch en milieukundig onderzoek naar alternatieven voor loswal Noord*", report DGW-92.030.

De Kok, J.M. and R.M. Salden, 1994. "*Resuspensie van baggerspecie uit een verdiepte loswal op zee*", work document RIKZ/OS-94.120X.

De Ronde, J.G., J.G.A. van Marle, A.P. Roskam and J.H. Andorka Gal, 1995. "*Golfrandvoorwaarden langs de Nederlandse kust op relatief diep water*", report RIKZ-95.024.

De Ruig, J.H.M. and A.P. de Looff, 1993. "*Effecten van kleine tijdelijke zandwinkuilen binnen de NAP -20 m lijn*", work document RWS-DGW; GWWS-93.127.

De Vriend, H.J., 1987. "Analysis of Horizontally Two-Dimensional Morphological Evolutions in Shallow Water", Journal of Geophysical Research, vol. 92, pp3877-3893.

Dijkman, M.J., B.S. Wiersum and T.J. Zitman, 1999. "*Risico-analyse morfologische effecten Maasvlakte2 en gerelateerde zandwinning*", *Rijkswaterstaat*, Directorate South Holland, report MEMV2-5-99029.

Fluit, C.C.J.M and S.J.M.H. Hulscher, 2000. "Morphological Response to a Gas-Mining Induced Bed Depression in the North Sea", Twente University, report no. 2000W-008 / MICS-016.

Hillen, P. et al, 1991. "*De basiskustlijn, een technisch/morfologische uitwerking*", GWWS-91.006, DGW

Hoornstra, D.R. and van der Hout, G., 1998. "*Berekeningen stroomverlammingskuil*", Public Works Department Rotterdam, harbour works engineering section.

Hoogewoning, S.E., 2000. "PUTMOR-field Measurements; a Six Months Measuring Campaign at a Lowered Dumping Pit near Hoek van Holland (The Netherlands)", National Institute for Coastal and Marine Management, work document RIKZ/OS-2000.132x.

Hulscher, S.J.M.H., 1996. "Formation and Migration of Large-Scale, Rhythmic Sea-Bed Patterns: a Stability Approach", Dissertation, Utrecht University.

Idskes, R., 1981. "*Zandwinput bij Ameland – z.w. kust*", *Rijkswaterstaat* Directorate Friesland, report WWKZ-81.H202.

Kuijper, E.V.L., 1998. "*Het effect van een zandwinkuil op de stroomcontractie door Maasvlakte2*", RIKZ, work document RIKZ/AB-98.107X.

Ministry of Transport, Public Works and Water Management, 1981. "*Zandwinning in de Waddenzee. Resultaten van een hydrografisch-sedimentologisch en biologisch-ecologisch onderzoek*", Directorate Friesland

North Sea Task Force, 1993. "Quality Status Report of the North Sea, Subregion 4".

Peters, B., 2000. "Large Scale Sand Extraction Offshore", Dissertation, Twente University.

Philippart, M.E., D. Dillingh and S.T. Pwa, 1995. "*De basispeilen langs de Nederlandse kust. De ruimtelijke verdeling en overschrijdingslijnen*", National Institute for Coastal and Marine Management, report RIKZ-95.008.

Projectgroep MER Loswal Noord, 1995. "*Milieu-effectraport over een nieuwe Loswal Noord. Voor baggerspecie uit het Rijnmondgebied die in de Noordzee wordt verspreid*"

Rakhorst, H.D. and E.R.F. van der Goes, 1978. "*Invloed zandwinning Kikkertgat op bodemligging aangrenzenden platen*", RWS, Study Department Hoorn, memorandum 78H246.

Rijkswaterstaat, 1991; "*Watersysteemplan Noordzee 1991-1995*", Draft plan 17 May 1991, Ministry of Transport, Public Works and Water Management, The Hague.

Rijkswaterstaat, 1995. "*Kustbalans, de 2^e^ kustnota*", Ministry of Transport, Public Works and Water Management, The Hague.

Roelvink, J.A. 1997. "*Ontgrondingen t.g.v. Maasvlakte-2. Modelberekeningen m.b.v. SCOUR*", Hydrodynamic Laboratory, report H3059.70, April 1997.

Roelvink, J.A., G. van Holland and J. Bosboom, 1998. "*Kleinschalig morfologisch onderzoek MV2*", Hydrodynamic Laboratory, report Z2428.

Roskam, A.P. and J. Hoekema, 1996. "*Randvoorwaarden voor golfperioden langs de Nederlandse kust*", report RIKZ-96.019.

RIKZ, 2000. "*Getijtafels voor Nederland 2000*", Sdu Publishers, The Hague, 1999.

Salden, R.M. and J.M. de Kok, 1994. "*Afregeling van het 3D-KUSTSTROOK model ten behoeve van slibtransport*", *Rijkswaterstaat* National Institute for Coastal and Marine Management , report RIKZ/OS-94.105X.

Salden, R.M., 1998. "*Een model voor het transport van slib in de Nederlandse kustzone - een hulpmiddel bij scenario studies naar kustuitbreidingsplannen*", work document RIKZ/OS-98.119X, report SILTMAN, subprojects 11 & 14.

Speekenbrink, H., 1982. "*Toekomstig onderhoud Maas- en Eurogeul (prognose voor het te verwachten onderhoud bij verdieping tot 72' en 75')*", WWKZ-82G.002, February 1982

Steetzel, H.J., 1993. "Cross-Shore Transport During Storm Surges". PhD thesis, Delft University of Technology.

Steijn, 1996. "*Grootschalig morfodynamisch modelonderzoek. Invloed van de vormgeving van Maasvlakte-2 op de grootschalige morfodynamica van de Nederlandse kust; Deel 1 tekst*", Hydrodynamic Laboratory, report H3059.

Svasek, b.v., 2001 a. "PUTMOR, Field Measurements at a Temporary Sand Pit. Part 1: Processing and Validation", report 01037/1177, June `2001.

Svasek, b.v., 2001 b. "PUTMOR, Field Measurements at a Temporary Sand Pit. Part 2: Data Analysis", report 01244/1177, June 2001.

Svasek, b.v., 2001 c. "PUTMOR, Field Measurements at a Temporary Sand Pit. Part 3: Final Report", report 01453/1177, June 2001.

Van den Heuvel, E.A. and K.G. Visser, 1988. "*Aanzanding B.P.-geul nabij wijk aan Zee*", J.G. Nelis, no. KGV03602.883.

Van der Giessen, A., W.P.M. de Ruijter and J.C. Borst, 1990. "Three-Dimensional Current Structure in the Dutch Coastal Zone", Netherlands Journal of Sea Research 25 (1/2): pp 45-55.

Van der Goes, E.R.F., 1979. "*De mate waaarin de zuigput in het Kikkertgat stroom onttrekt van de doorgaande waterbeweging*", RWS Study Department Hoorn, memorandum 79H202.

Van Rijn, L.C., A. Reniers, T. Zitman and J.S. Ribberink, 1995. "Yearly-Averaged Sand Transport at the -20 m and -8 m NAP Depth Contours of the JARKUS-Profiles 14, 40, 76 and 103", Delft Hydraulics, report H1887, Project Coastal Genesis.

Walstra et al, 1997. "*Grootschalige lange-termijn effecten van Maasvlakte-2 en gerelateerde zandwinningsvarianten*", Hydrodynamic Laboratory, report Z2255.

Winterwerp, J.C. and R.E. Uittenboogaard, 1997. "Sediment Transport and Fluid Mud Flow", Hydrodynamic Laboratory, report Z2005.