Delft Cluster

Eco-morphodynamics of the seafloor

Progress report 2000

Datum

July, 2001

Auteur(s)

M.J. Baptist (WL | Delft Hydraulics)
C.N. van Bergen Henegouw (Oceanographic Company of the Netherlands)
M. Boers (RWS - National Institute for Coastal and Marine Management/RIKZ)
J. van Dalfsen (TNO Institute of Environmental Sciences, Energy Research and Process Innovation)
S. van Heteren (Netherlands Institute of Applied Geoscience TNO)
S. Hoogewoning (RWS - National Institute for Coastal and Marine Management/RIKZ)
S.J.M.H. Hulscher (University of Twente)
J.J. Jacobse (RWS - National Institute for Coastal and Marine Management/RIKZ)
N.H.B.M. Kaag (TNO Institute of Environmental Sciences, Energy Research and Process Innovation)
M.A.F. Knaapen (University of Twente)
J.P.M. Mulder (RWS - National Institute for Coastal and Marine Management/RIKZ)
S. Passchier (Netherlands Institute of Applied Geoscience TNO)
A.J.F. van der Spek (Netherlands Institute of Applied Geoscience TNO)
F. Storbeck (Netherlands Institute for Fisheries Research)

Opdrachtgever

Delft Cluster

Projectleider

C. Laban (Netherlands Institute of Applied Geoscience TNO)

Contents

List of figures

List of tables

1 Introduction

1.1 Nature and scope of the problem

Ecologically and socially justified management and use of the North Sea requires proper integration of field measurements and knowledge regarding the ecomorphodynamics of the North Sea. Such an integration has not yet been accomplished, owing to a lack of reliable, high-quality data. Currently, there is no consensus on dominant mechanisms. Also, few suitable measurements have been made on the actual morphodynamics of the seafloor, neither under natural circumstances, nor after human intervention. In addition, the relationship of this morphodynamic behavior to sediment transport and the interaction of morphodynamic processes with macrozoobenthos on the seafloor has been subject to very little research.

This lack of accurate measurements and a lack of clarity about the relative importance of different natural processes hampers evaluation of existing models that suggest a strong interaction between human interventions and natural processes on the same scale. The project “Ecomorphodynamics of the North Sea floor” aims at a process-based approach of the dynamics of small- and large-scale phenomena on the sea floor, both in the short term and in the long term.

1.2 History of the project

This proposal for the project “Ecomorphodynamics of the North Sea floor” was submitted to Delft Cluster by C. Laban (TNO-NITG - National Geological Survey) in the spring of 2000, on behalf of participants from TNO-NITG, TNO-MEP, RIVO (Netherlands Institute for Fisheries Research), WL (Delft Hydraulics), the University of Twente, OCN (Oceanographic Company of The Netherlands), and RWS - RIKZ (National Institute for Coastal and Marine Management). On September 22, 2000, the scientific director of Delft Cluster (Prof. dr. ir. J. Blaauwendraad) approved the proposal “Ecomorphodynamics of the North Sea floor”. Activities, which had taken place for some time before the time of approval, intensified soon after this date.

The project, which covers the period 2000-2002, has a total budget of *f* 2.131.000,-. Delft Cluster contributes *f* 735.000,- from ICES/KIS means, RIKZ contributes *f* 766.000,- in the form of related projects, and the other participants contribute *f* 630.000,-. These funds will be used to:

- measure and analyze the morphodynamics at three locations in the North Sea under natural circumstances (middle to lower shoreface, shoreface-connected ridges, and sand waves), during a year and in the course of several years;

- initiate the quantification and modeling of morphodynamic processes, on the basis of both measurements and idealized models;
- initiate the determination of the role of zoobenthos with regard to ecomorphodynamic processes and sediment characteristics;
- create a database that allows modeling of sediment transport and ecomorphodynamics under natural circumstances.

1.3 Progress report

In this progress report, we present the results of activities carried out in 2000. Although the report is the product of collaborative research, various co-authors were responsible for subsections discussing their own expertise. M. Baptist, J. van Dalfsen, and K. Kaag focus on the relationship between the benthic community on the seafloor and hydro- and morphological parameters (Chapter 5), C.N. van Bergen Henegouw discusses the results of current and sediment-transport measurements (Chapter 4), S.J.M.H. Hulscher and M.A.F. Knaapen provide a brief overview of model-related issues (Chapters 4 and 5), and A.J.F. van der Spek and F. Storbeck present descriptions of methods and procedures (Chapter 3), as well as some results (Chapter 4). In addition to these subsections, S. Passchier and S. van Heteren provide summaries of various reports written by researchers with the National Institute for Coastal and Marine Management (Chapter 6): Sand extraction on offshore tidal ridges (M. Boers and J.J. Jacobse), PUTMOR field experiments (S. Hoogewoning), and Feasibility study large-scale sand extraction and construction (J.P.M. Mulder). S. van Heteren gives the overall framework of the project (Chapters 1, 2, and 4), discusses the implications of the results achieved in 2000, (Chapter 7) and presents the project plan for 2001-2002 (Chapter 7).

1.4 Acknowledgement

Sevaral people with the Directorate-General of Public Works and Water Management, North Sea Directorate, have been instrumental in data acquisition and data processing. In particular, we would like to thank C. Bijleveld for coordinating data acquisition, S.L. Bicknese for processing multibeam data, R.C. Lambij for processing side-scan-sonar data, and P. Pronk for supervising data acquisition aboard the m.s. Zirfaea.

2 Site descriptions

Three North Sea sites were chosen on the basis of the morphological map of the Dutch shoreface and adjacent part of the continental shelf (Van Alphen and Damoiseaux, 1987), representing various prominent morphological units on the seafloor (Figure 1). These three areas were selected because they are representative of large areas of the North Sea floor. Therefore, results of the present study are expected to be relevant to other similar areas in the North Sea, and may be a main source of (t_0) information when man-made structures are planned in such areas in the future.

Area A: Margin of sand-wave area on shoreface-connected ridge. This area was chosen for two reasons: 1) observing migration of the margin of a sand-wave field, and 2) monitoring long-term behavior of a shoreface-connected ridge.

Area B: Transition from lower shoreface to inner continental shelf. This area was chosen for two reasons: 1) providing data supporting current regulations banning sand and gravel extraction from the North Sea floor at depths less than 20 m, and 2) filling a knowledge gap on cross-shore sediment transport between the inner shelf and the upper shoreface and beach.

Area C: Sand-wave area on the inner shelf. This area was chosen for two reasons: 1) monitoring a spatial sequence of many sand-wave crests that form part of a short-wavelength sand-wave field, and 2) linking morphodynamics, macrozoobenthos, and fish.

2.1.1 Margin of sand-wave area on shoreface-connected ridge

Area A (Figure 1) measures 1 km x 2.5 km and is oriented approximately perpendicular to the present coastline. It is located about 5-10 km offshore Zandvoort, about 10 km south of the IJ Geul, and includes four geomorphological units. On its landward side, the area is dominated by a flat seafloor, without major bedforms. This seafloor has a slope of less than 1:1000. On its seaward side, it is characterized by sand waves that are 2-4 m in height, which are superimposed on seafloor sloping at less than 1:1000. These sand waves have wavelengths of tens to hundreds of m. Most of the area, however, is occupied by a shoreface-connected ridge. This ridge, covered by sand waves on its seaward side, forms an angle of about 30 degrees with the coast. It is several m high, several km wide, and several tens of km long.

2.1.2 Transition from lower shoreface to inner continental shelf

Area B (Figure 1) measures 1 km x 2.5 km and is oriented approximately perpendicular to the present coastline. It is located about 5-10 km offshore Noordwijk aan Zee, in water depths between 15 and 20 m. Area B includes one geomorphological unit. The area is dominated by a flat seafloor, without major bedforms. This seafloor has a slope of less than 1:1000 and continues landward as the toe of the lower shoreface.

2.1.3 Sand-wave area on the inner continental shelf

Area C (Figure 1) measures 1 km x 5 km and is oriented approximately parallel to the present coastline. It is located 55 km offshore Bergen aan Zee, in water depths between 25 and 30 m, and includes only one geomorphological unit. It is characterized by sand waves that are 2-4 m in height, which are superimposed on a flat seafloor sloping at less than 1:1000. These sand waves have wavelengths of tens to hundreds of m. The sand waves are covered by megaripples.

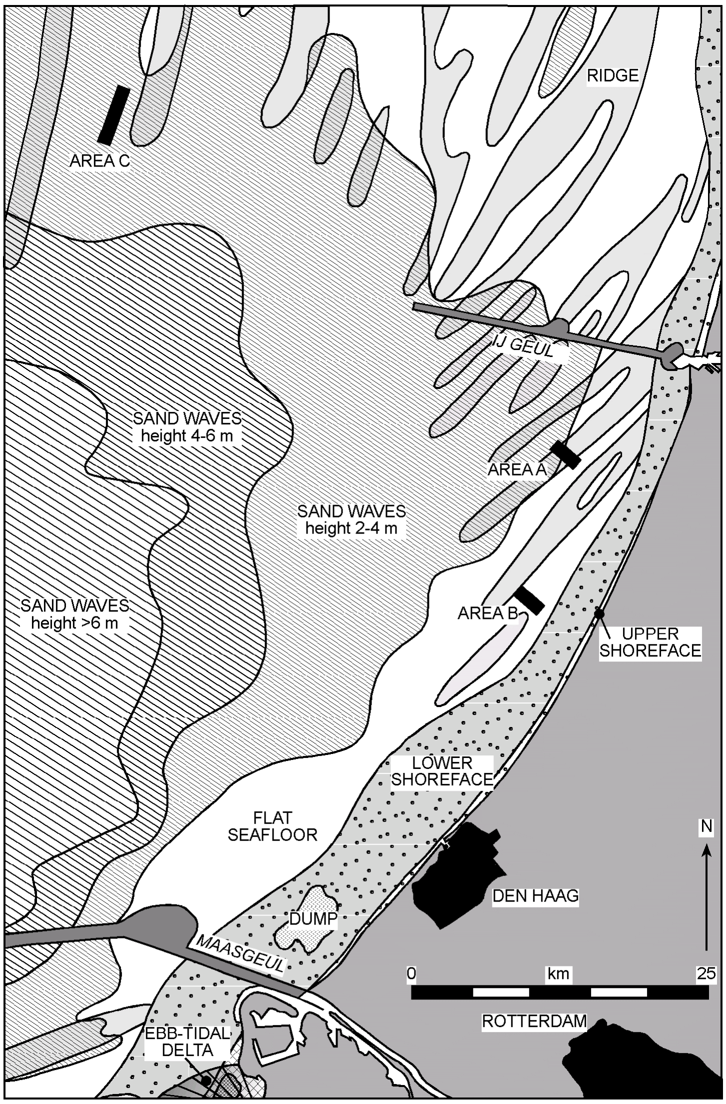


Figure 1 Location of study areas and primary geomorphological units (Van Alphen and Damoiseaux, 1987).

3 Methods and Procedures

In 2000, measurements were conducted in weeks 34 (m.s. Tridens), 35 and 38 (m.s. Zirfaea) and 36 (m.s. Isis) (Table 1).

Table 1 Field measurements

Week	multibeam	side-scan	box core	frame with sensors	beam trawl
34					x
35	x	x			
36					x
38	x		x	x	

A multibeam echo sounder was used to collect data for digital terrain maps of the research sites at a horizontal resolution of 1 x 1 m. A side-scan sonar was used to couple these coarse-resolution images to smaller-scale seafloor features indicative of morphodynamic processes. Box cores were taken to collect macrozoobenthos samples and samples for textural analyses. A frame with current meters and sediment-transport meters was used to collect real-time data on two processes that are important in explaining morphodynamic change as observed on subsequent multibeam images from the same site. Finally, beam trawls were used to sample the demersal fish and benthos living on the seafloor.

3.1.1 Multibeam echo sounder

The records were collected using the Kongsberg Simrad 100 system, installed aboard the m.s. Zirfaea. This hull-mounted system operates at a central frequency of 95 kHz (wavelength of 1.6 cm) and has a bandwidth of 10 kHz. It uses 32 beams with widths of 2/2.5°. The emitted signal covers 150°, resulted in a path width of 7.4 times the water depth. The vertical accuracy of the system is up to 0.3% of the water depth, or 0.15 m

Before and after each multibeam measurement, velocity profiles of the water column were obtained for corrections during processing. The multibeam data for areas A and B were obtained using 20 and 25 m track-line spacing, respectively, creating a minimal overlap. Owing to dominant shore-parallel currents, the data had to be collected in 1-km tracks along the width of the areas, rather than 2.5-km tracks along the length, which would have been more time effective. Reliable multibeam records cannot be collected perpendicular to strong currents. According to this shore-parallel collection pattern, 100-125 tracks were needed for each area, along with an equal number of turns. The multibeam data for area C were obtained using 40-m track-line spacing. The data could be collected in 5-km tracks along the length of the area, requiring 25 tracks.

The multibeam measurements are calibrated using a MORS tide gauge at the Eveline buoy and permanent tide stations IJmuiden and/or Measuring Platform Noordwijk (MPN) (area A), the permanent tide station at MPN (area B), and the MORS tide gauge at the location MO12 buoy and the permanent tide station at IJmuiden (area C).

3.1.2 Side-scan sonar

The records were collected using a Dowty system, type 310. This system can be operated at two frequencies. A low frequency of 100 kHz produces poor results. A higher frequency of 325 kHz, on the other hand, produces a very detailed image of the seafloor. When operated in this latter mode, the side-scan sonar has a narrower range, necessitating a track-line spacing of 50 m. The position-fix distance is 100 m. Side-scan-sonar data must be collected at speeds of no more than 4-5 knots. They cannot be collected simultaneously with the multibeam data, because of interference.

The side-scan-sonar data for areas A and B were obtained using a 50-m track-line spacing. As with the multibeam echo sounder, the data had to be collected in 1-km tracks along the width of the areas. According to this shore-parallel collection pattern, about 50 tracks were needed for each area. The side-scan-sonar data for area C were obtained using a 100-m track-line spacing. The data could be collected in 5-km tracks along the length of the area, requiring 10 tracks.

The sonar data were stored on an ISIS optical disk and printed on paper.

3.1.3 Box corer

Bottom samples were obtained using a cylinder-shaped box corer. Penetration varied between 0.2 and 0.3 m. In each area, 33 samples were collected using a strategy suggested by TNO-MEP ecologists (Figure 2). At one central location, nine cores were taken to be able to assess variability across very short distances. At eight other locations, three cores were taken, primarily to assess both small-scale and large-scale variability.

Each box core was subsampled for later sedimentological analyses using either a 5-cm-diameter or a 10-cm-diameter plastic pipe. The pipes were capped and stored in a rack before transfer to the core-description facilities at TNO-NITG.

The remainder of each box core was carefully transferred onto a 1-mm sieve, and gently wet-sieved using a deck wash. Owing to the sandy nature of the sediment, this procedure worked rapidly and without problems. Using a spatula, the coarse fraction (including macrobenthos, shell hash, etc.) was placed into plastic jars filled with a solution of 6% buffered formaldehyde. All jars were taken to TNO-MEP for later description.

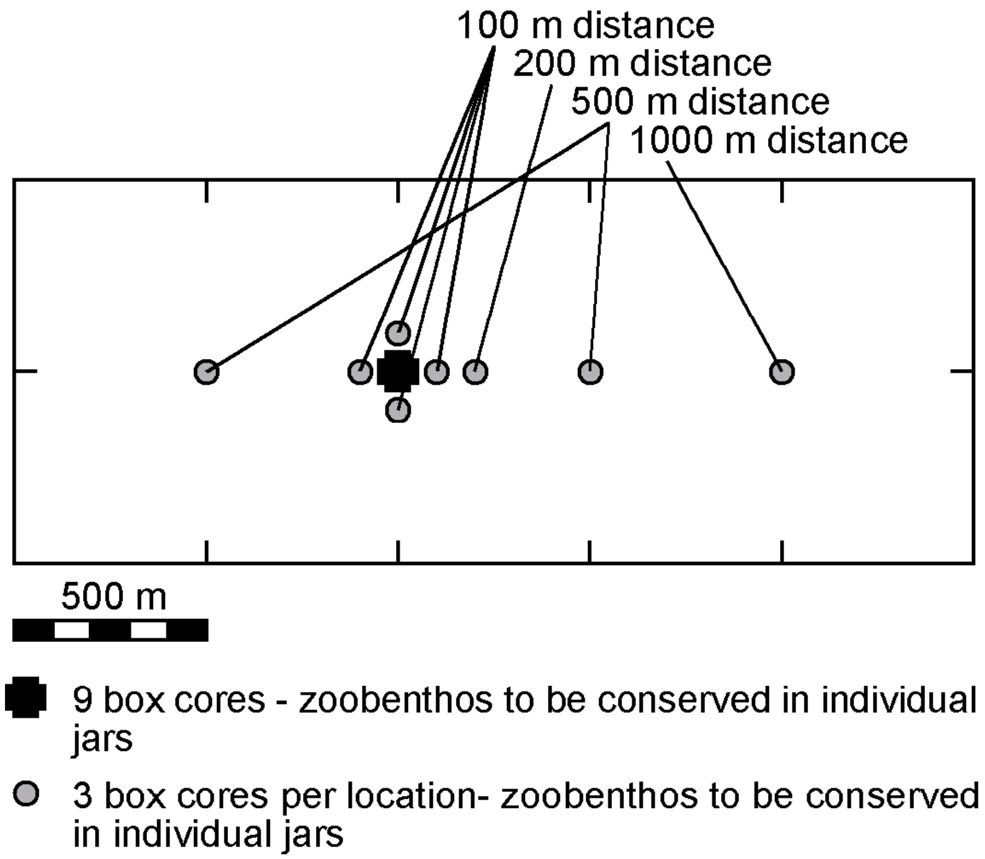


Figure 2 Sampling strategy.

3.1.4 Frame with sensors

At one location in each research area, we used a Sonar Work Station (SWS) to measure the migration of small-scale current ripples on the seafloor (Figure 3). We positioned a frame with four sensors on the seafloor. In areas A and B, the seafloor was flat; in area C, the frame was positioned on the lee side of a megaripple. A sonar sensor, a current-velocity sensor, a tilt sensor, and a pressure sensor were connected to computers on the ship via a cable (Figure 4). All measurements were stored digitally. A vane forced the frame into the current. The sensors were positioned in such a way as to minimize the disturbance of measurements by the frame.

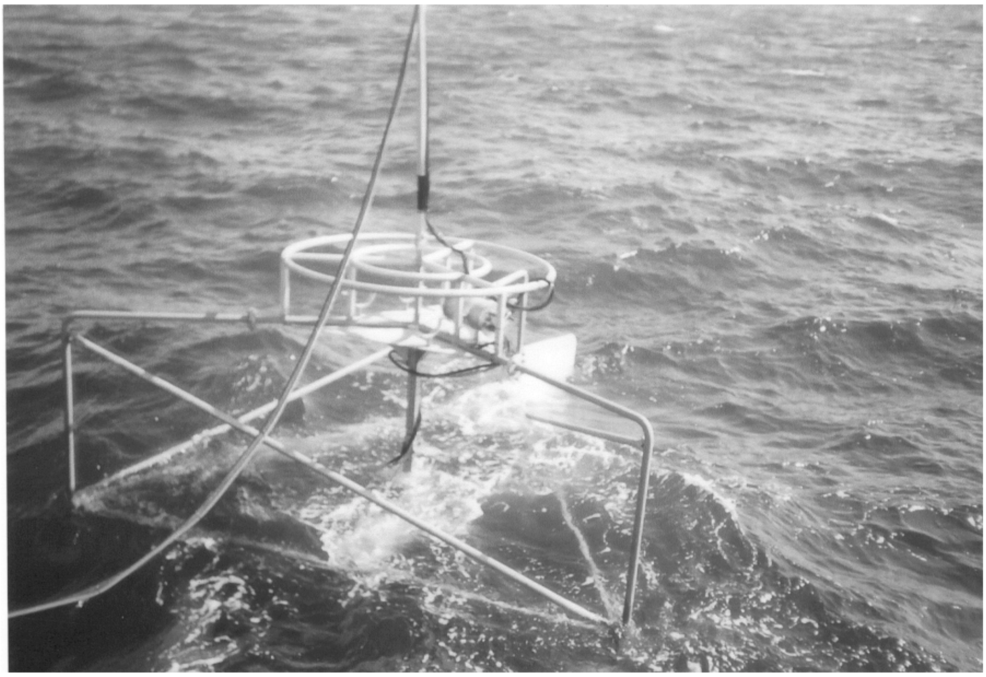


Figure 3 Employment of the frame.

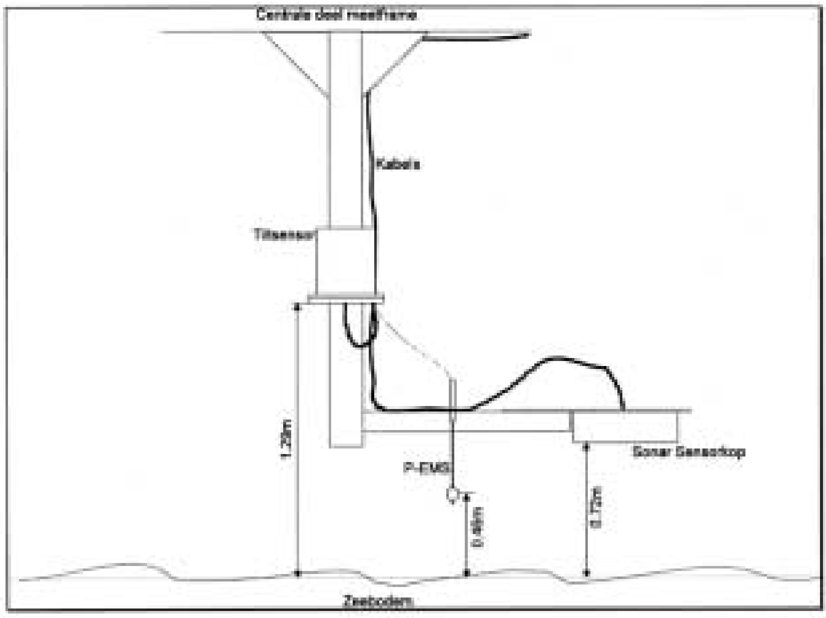


Figure 4 Sensor positions on the frame.

The sonar sensor was positioned about 0.7 m above the seabed (Figure 4). Its four transducers emitted 400-MHz pulses with a frequency of 5 Hz. Owing to the high intensity of the signals reflected from the seabed, the two-way travel time between sensor and seabed could be determined very accurately. These two-way travel times are easily converted to distances. The theoretical accuracy, about 0.002 m, is governed by the salinity and temperature of the water and by the pressure (Van Unen et al., 1997). In practice, the accuracy is also affected by the stability of the frame, including vibrations and movement of the frame relative to the seabed. By conducting measurements in time, we expected to document the migration of possibly present current ripples.

The current-velocity sensor was an S-type four-quadrant electromagnetic flow-current meter with a P-EMS measuring unit. The accuracy of this instrument, when optimally placed in the current, is about 0.01 m/s or 3% of the measured value. The range of this meter is 0 to 2.5 m/s. Measurements were made at 1-s intervals.

The horizontal and vertical movements of the frame were monitored by a SEATEC tilt sensor and by a pressure sensor, both mounted on the frame. The tilt sensor measured the heading, pitch, and roll of the frame. The pressure sensor measured the depth of the sensor below sea level. These last measurements were corrected for tidal influence using the tide-gauge measurements.

In addition to these measurements, a tide gauge was employed and sea-water temperature and air pressure were registered, to provide data for calibration purposes. For all measurement sites, a seafloor-sediment sample was analyzed for density and grain-size distribution.

3.1.5 Beam trawl

A 2-m beam trawl (BTS2-M20 – maze 4 cm) and an 8-m beam trawl (BT8 – maze 4 cm) were used to collect fish and macrozoobenthos along 12 profiles. Activities were limited to areas A and B.

4 Results

4.1.1 Mult-beam echo sounder

4.1.1.1 Introduction

The first multibeam images allow overall bathymetric characterization of the three research areas and provide a useful frame of reference for the box cores. Yet, the image quality achieved is too low for analyses of morphodynamics from time series. So-called asparagus fields, apparent ridge-and-swale topography along the length of the images, dominate the records, leaving intact the main morphological structures, but introducing significant errors in calculated water depth. Data processors with the North Sea Directorate have requested that the images not be published at this time.

4.1.1.2 Area A: Margin of sand-wave area on shoreface-connected ridge

The multibeam image does not contain any evidence of sand waves. The margin of the field may be located just outside the research area. Interestingly, the imaged shoreface-connected ridge (and the associated swales) is compartmentalized by approximately shore-perpendicular bathymetric lows that give it a bead-like appearance. The elevation differnce along the length of the ridge, traversing both highs and lows, is about 1-2 m. Across the ridge, the elevation difference is 3-5 m. The beads have a gentle updrift (southwest) slope and a steeper downdrift (northeast) slope. The seaward half of the area is marked by abundant shore-perpendicular megaripples. These bedforms are clearly linked to the dominant shore-parallel tidal current.

4.1.1.3 Area B: Transition from lower shoreface to inner continental shelf

The quality of the multibeam image is poor. The only morphological feature that can be identified is a shoreface-connected ridge. Future measurements will have to be made with an instrument that enables imaging of shallower water where the shoreface, rather than a shoreface-connected ridge, dominated the morphology. Therefore, area B has been shifted landward by about 2 km.

4.1.1.4 Area C: Sand-wave area on the inner continental shelf

The multibeam image shows about 25 sand waves, spaced 200 m apart. Generally, the sand waves are subparallel, but some crests are seen to merge. They have an amplitude of about 2 m, and appear to increase in depth from south to north.

4.1.2 Side-scan sonar

4.1.2.1 Introduction

Upon examination of the side-scan-sonar images, it became clear that interference mars the data collected thus far. Nevertheless, some good-quality images have been obtained, and these images provide reliable characterizations of the three research areas.

4.1.2.2 Area A: Margin of sand-wave area on shoreface-connected ridge

Much of this area is characterized by only few, small-scale bedforms. Faint 2-D megaripples are overshadowed by very clear tracks produced by beam-trawl fishing (Figure 5).

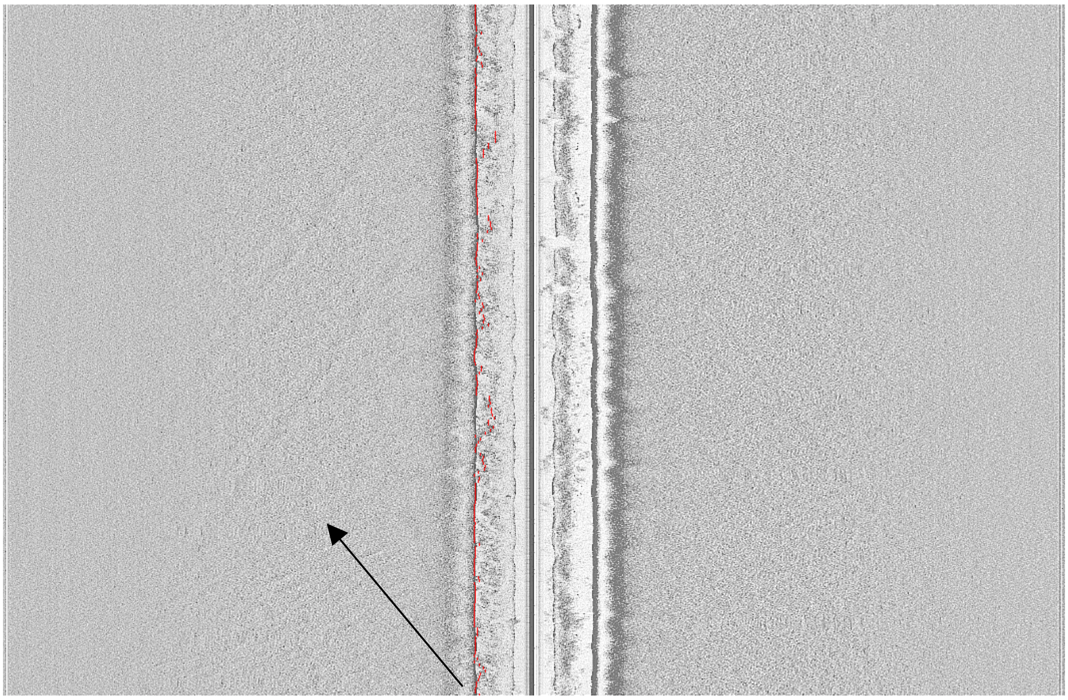


Figure 5 Beam-trawl fishing tracks and faint megaripples in area A. Arrow denotes North. Width of image represents 100 m.

More complex, 3-D megaripples are much less common. They cover limited areas on the margins of the sand-wave field (Figure 6). The orientation of these megaripples is approximately parallel to the present coastline, reflecting dominant longshore tidal currents.

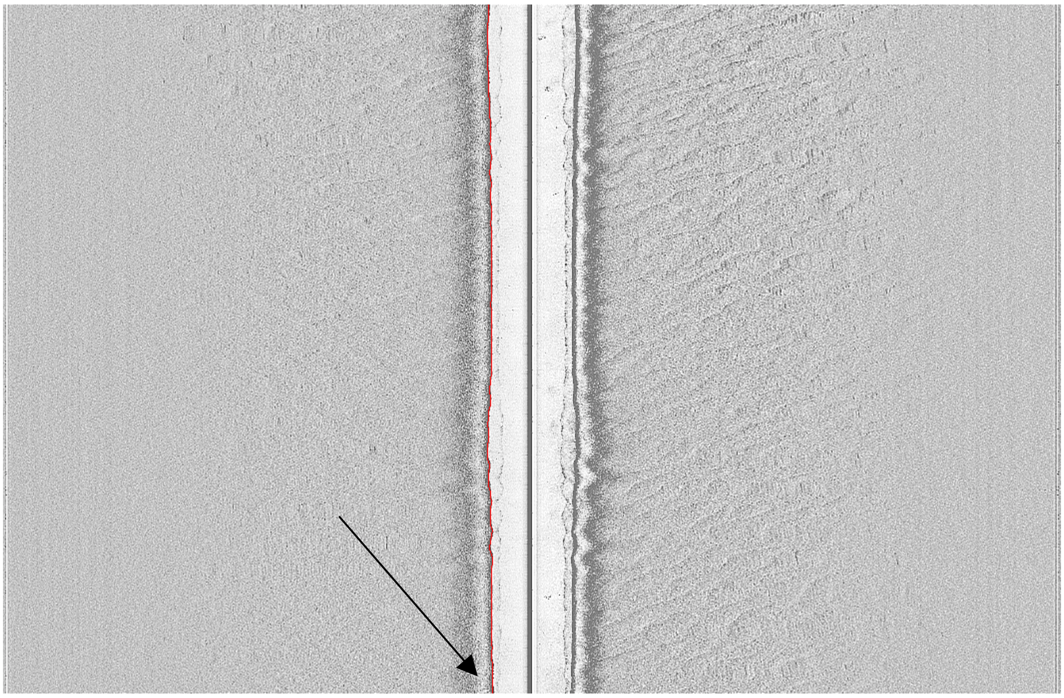


Figure 6 Complex megaripples formed by shore-parallel tidal currents in area A. Arrow denotes North. Width of image represents 100 m.

4.1.2.3 Area B: Transition from lower shoreface to inner continental shelf

For the most part, this area appears virtually featureless, except for abundant beam-trawl scars. Upon closer inspection, very faint, shore-parallel megaripples can be identified on some of the images (Figure 7). Though poorly developed, these bedforms are very significant, as they may reflect shore-perpendicular sediment transport. Locally, small features of unknown origin dot the seafloor in large quantities. These features may be bedforms, which would indicate sediment transport. They form linear patterns and appear to be linked to beam-trawl scars. Conceivable, sediment disturbed by fishing activities is reworked into low, but distinct morphological elements. At this time, it is uncertain whether or not they are ephemeral.

4.1.2.4 Area C: Sand-wave area on the inner continental shelf

Morphologically, the sand-wave area is rather uniform. The side-scan images show 2-2.5-m-high sand waves with wavelengths of about 250 m. They are oriented approximately east-west. Superimposed on these sandwaves are megaripples with amplitudes of 0.2-0.4 m and wavelengths of about 5 m. The migaripples do not have the same orientation as the sand waves. Their crests suggest sediment transport to the north-northeast, at a 20-30°-angle to the sand waves (Figure 8). Most of the megaripples form 2-D patterns, but some 3-D forms were observed as well (Figure 9).

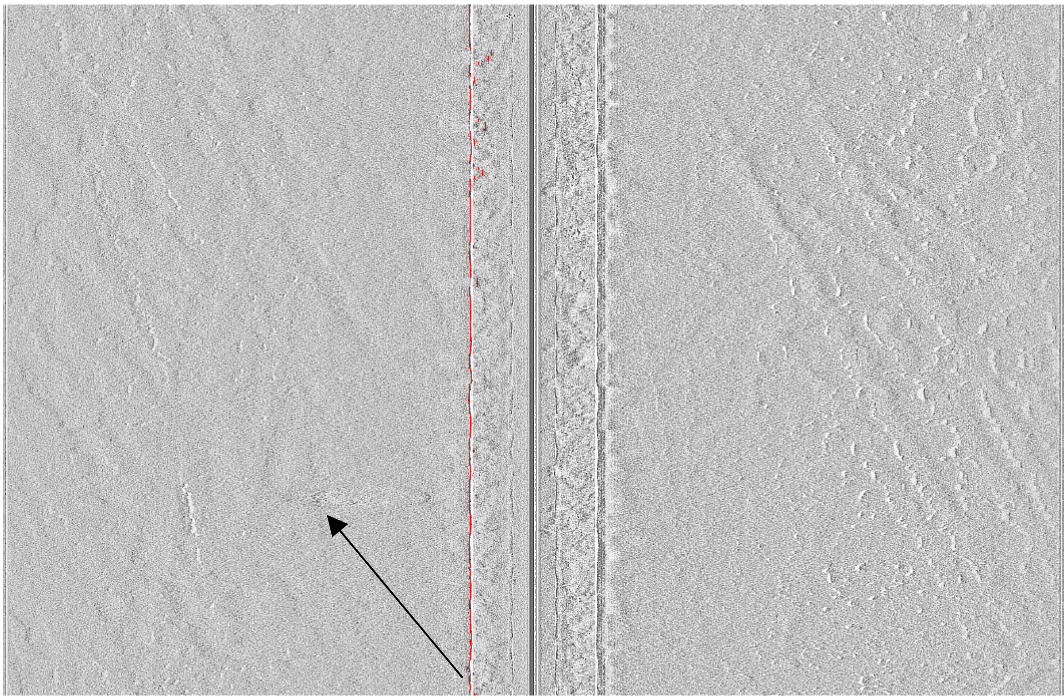


Figure 7 Poorly developed megaripples, beam-trawl scars, and unidentified m-scale objects in area B. Arrow denotes North. Width of image represents 100 m.

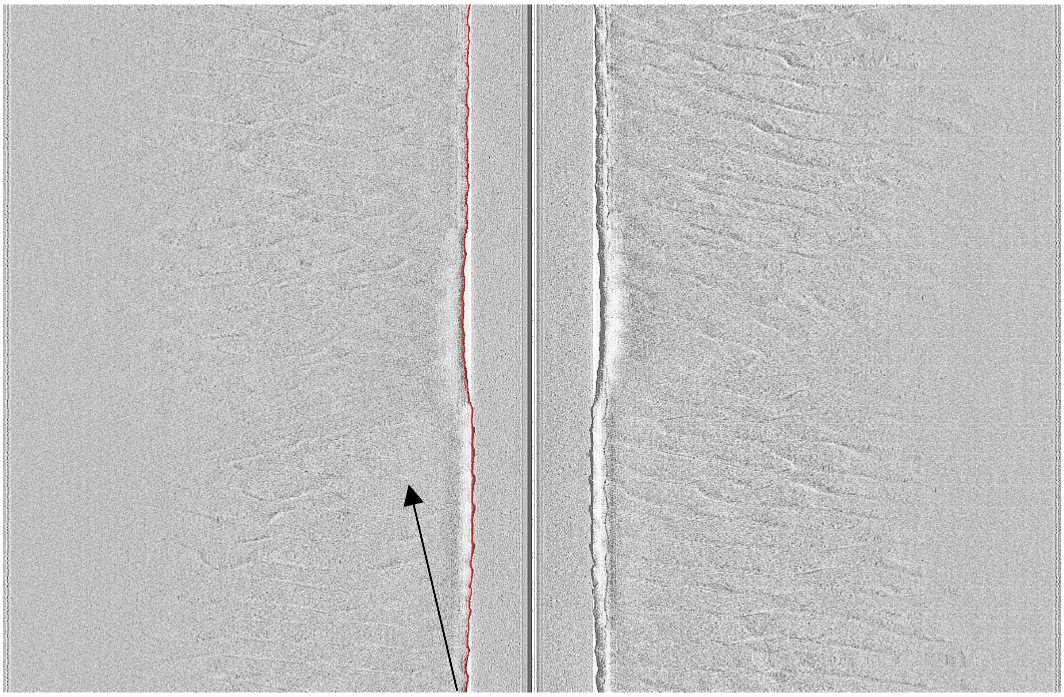


Figure 8 Linear megaripples migrating across sand waves in area C. Arrow denotes North. Width of image represents 100 m.

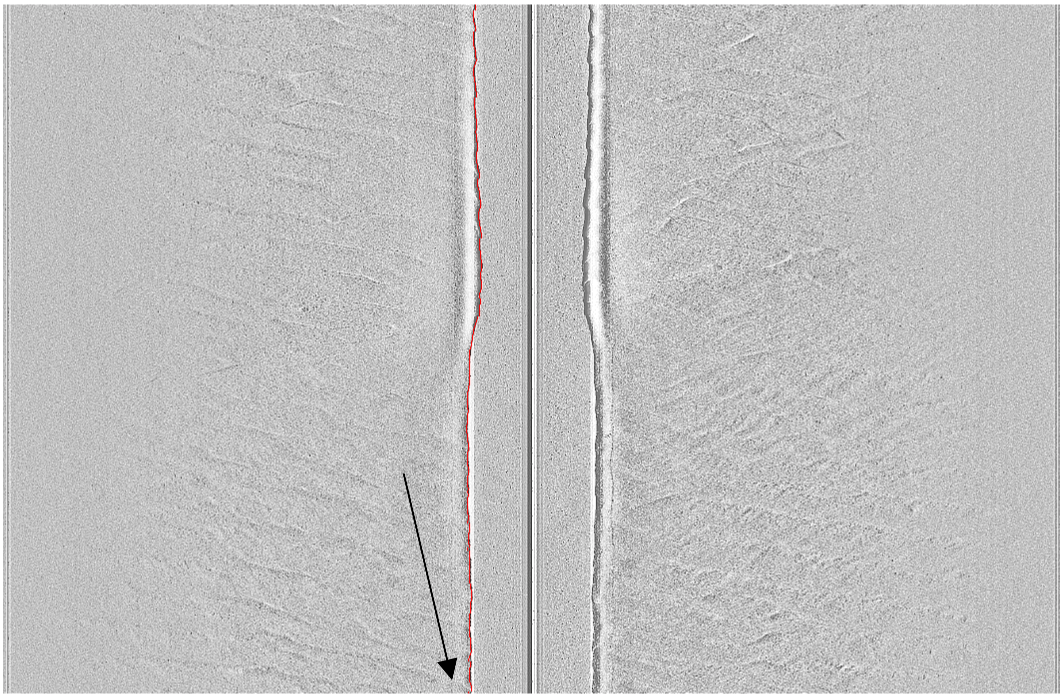


Figure 9 Clear subdivision between areas dominated by linear megaripples and areas with abundant 3-D bedforms. Arrow denotes North. Width of image represents 100 m.

4.1.3 Box corer

4.1.3.1 Introduction

Thus far, 18 of the 99 box cores collected have been analyzed for their sedimentological characteristics. For each cluster location in areas A and B, grain-size data have been recorded. Only a few samples have been examined for their macrozoobenthos content. Such quantitative ecological analyses require a lot of time. To maximize the scientific output, it is imperative to examine the samples in order of importance. For prioritization purposes, multibeam images showing the locations of the box cores relative to morphological features on the seafloor, which have become available only recently, are needed. The studied samples show a predominance of dead, commonly fragmented material.

The sedimentological characteristics are presented in a geological context as determined from grab samples, cores, and seismic records in the surrounding areas. A seabed-sediment map of the Dutch continental shelf (Figure 10) shows that areas A and B are dominated by medium sand, whereas area C is dominated by fine sand.

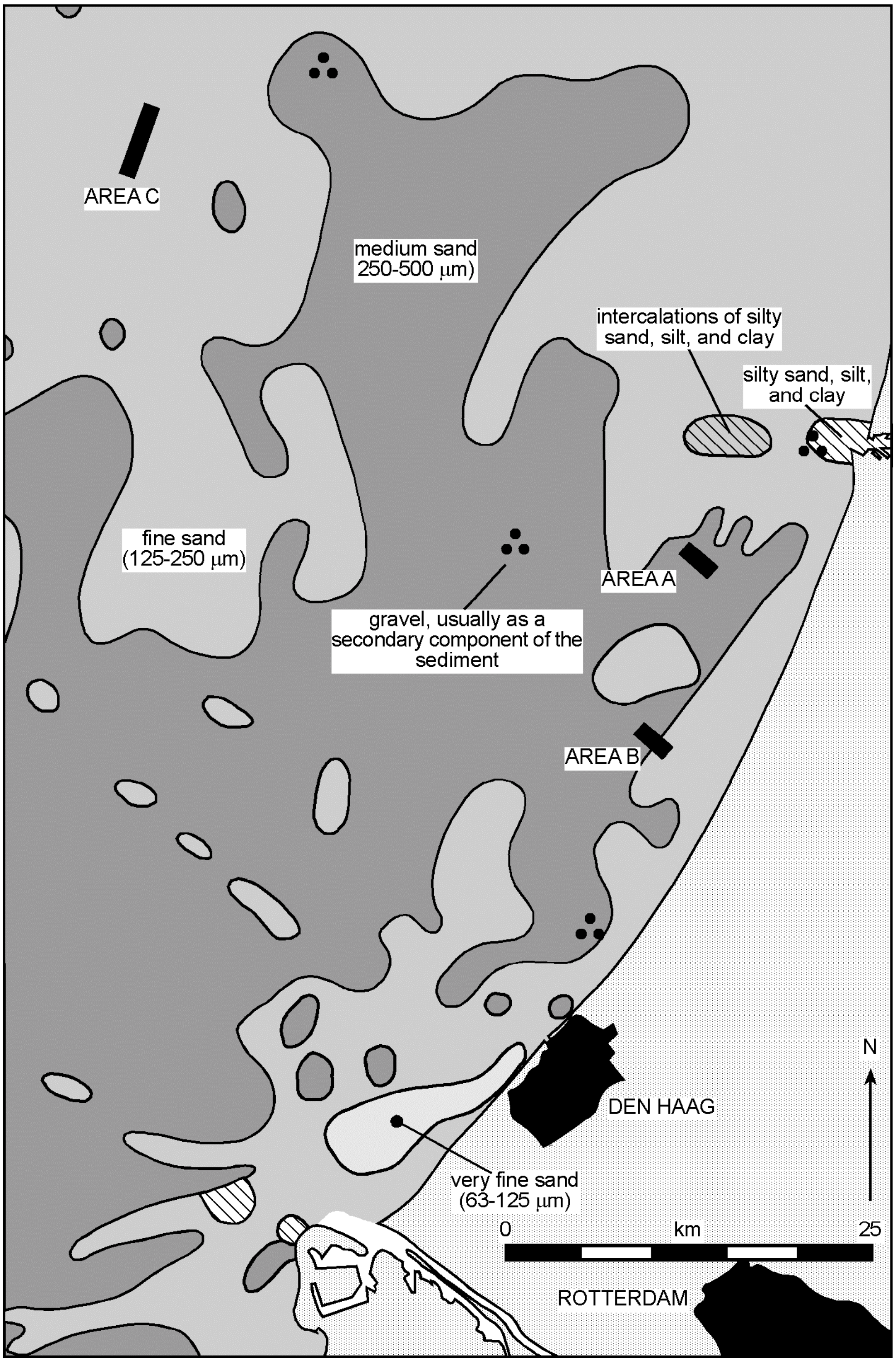


Figure 10 Surficial sediment on the North Sea floor (from Rijks Geologische Dienst, 1986).

4.1.3.2 Area A: Margin of sand-wave area on shoreface-connected ridge

The measured grain-size range in the box cores, 296-362 µm, corresponds to the grain-size ranges found in nearby grab samples and cores, 255-364 µm (Figure 11). When superimposed on the local ridge-and-trough relief, a trend in mean grain size appears to be present. The trough and ridge crest are dominated by the 330-340 µm fraction; finer sand is concentrated on the seaward slope of the ridge, and coarser sand on its landward slope.

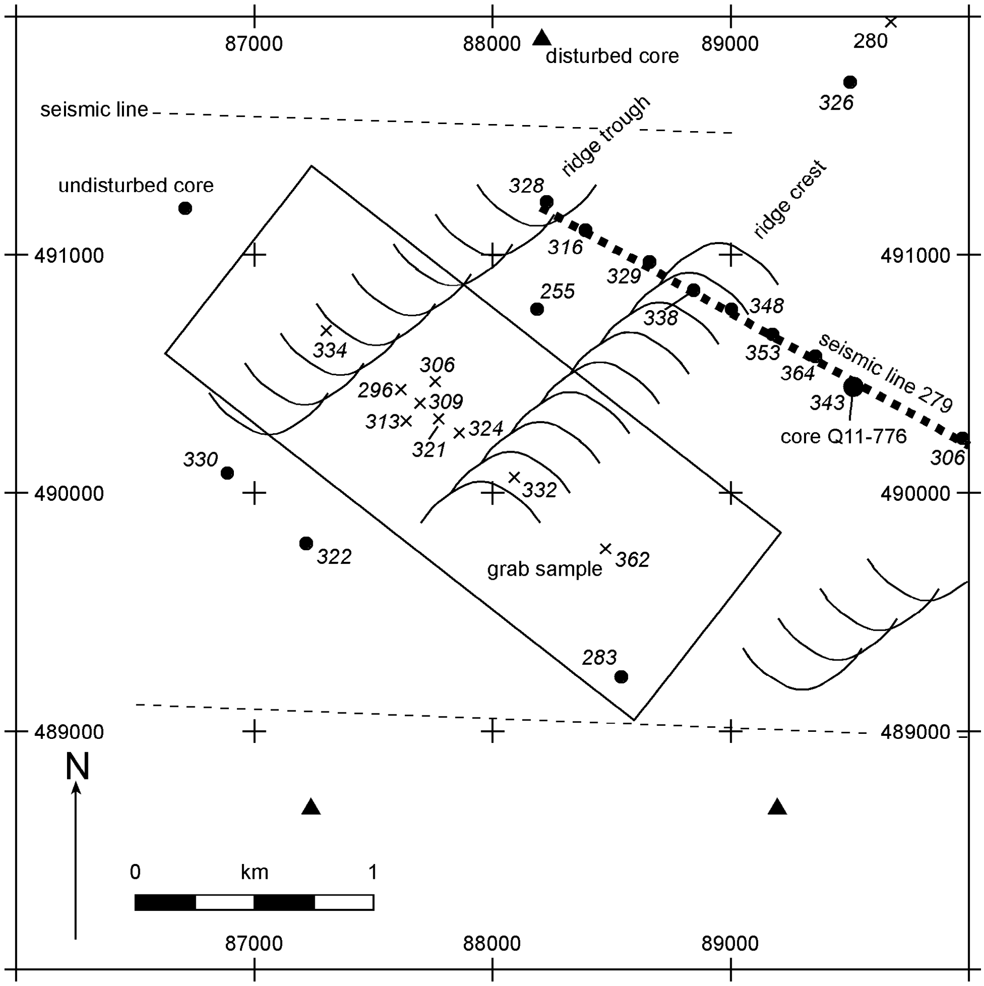


Figure 11 Geological data for area A. Core and cross-section shown in Figures 11 and 12 are highlighted.

Undisturbed cores provide detailed information not only on grain size and shell content, but also on sedimentary structures present in the seabed sand. Commonly, the upper layer of sand contains sets of cross bedding and moderate to large amounts of shells and shell fragments (Figure 12). The cross-bedded unit, which is rarely more than 1 m thick, is formed by migrating megaripples, as observed on the side-scan-sonar images. The cross beds comprise the top of a recent sea-sand unit that includes the shoreface-connected ridges. It has been formed during the past 500 years and covers much older sediment, formed several millennia ago (Figure

13), also in open-marine conditions. Underlying this subrecent sea sand is Pleistocene fluvial and eolian sand and silt. Locally, fine-grained channel fills, probably of back-barrier origin, incise the Pleistocene paleosurface (Figure 13). These fills date from the Atlantic, 8,000 to 5,000 ^{14}C years ago (Figure 12).

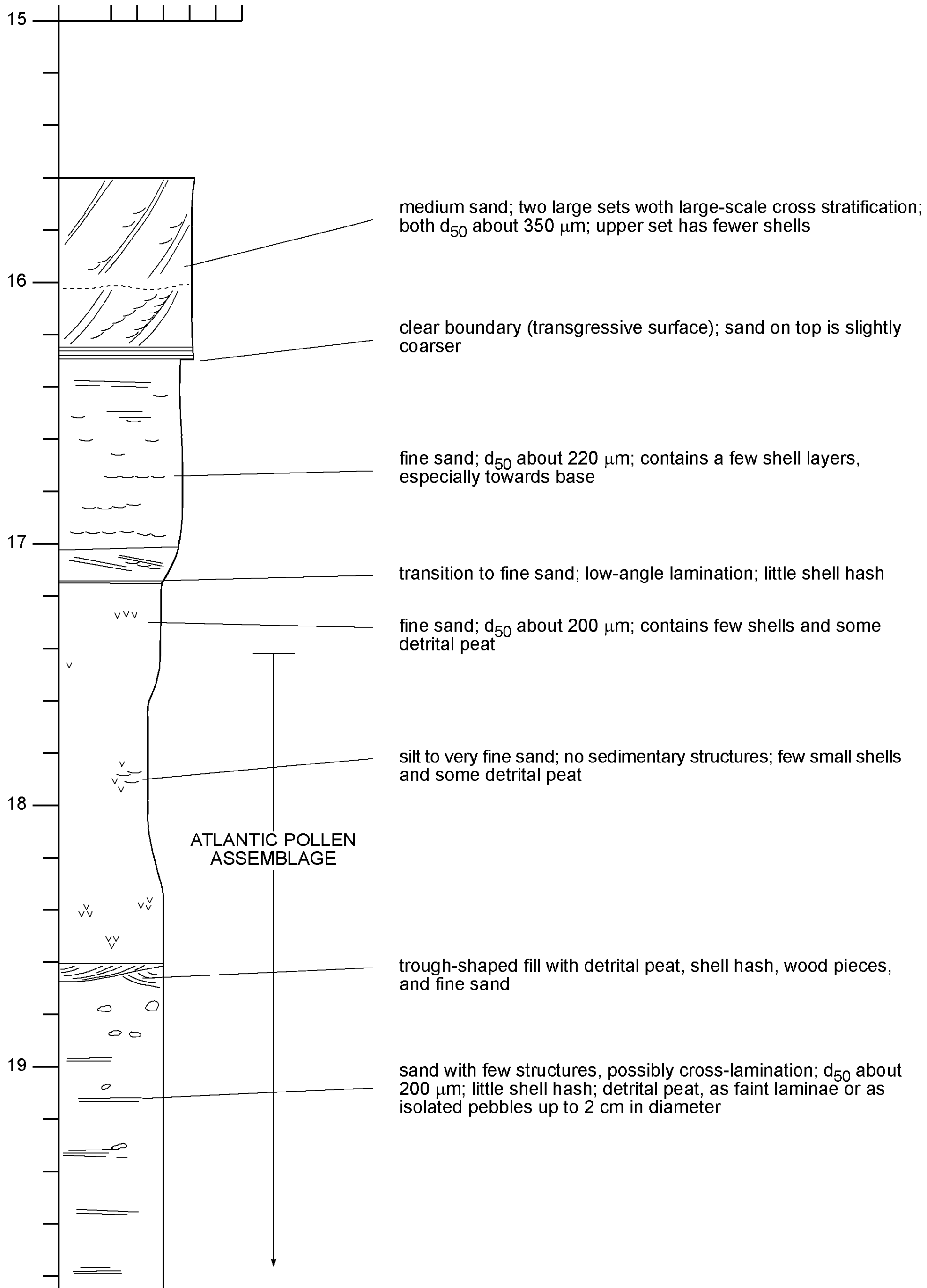


Figure 12 Sedimentological log of core Q11-776.

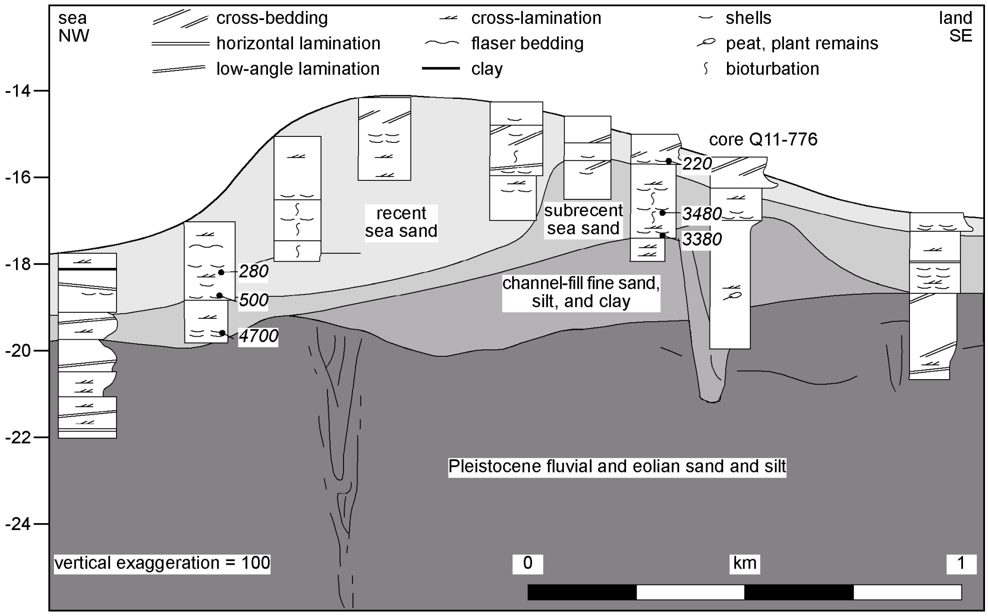


Figure 13 Geological cross section through area A (van de Meene, 1994). Core Q11-776 is labeled.

4.1.3.3 Area B: Transition from lower shoreface to inner continental shelf

The measured grain-size range in the box cores, 368-396 µm, is somewhat coarser than the grain-size ranges found in nearby grab samples and cores, 262-327 µm (Figure 14). The reason for this size discrepancy is unknown at present. Possible explanations are the use of a different technique for grain-size analyses and temporal effects. The currently used Malvern laser particle sizer provides grain-size parameters slightly coarser than those obtained from traditional sieving methods. Temporal changes in mud content, for example seasonally linked, may result in significant variability in mean grain size. Both hypotheses can be tested following additional research. Potental seasonal variability is one of the focal points of the present research. As in area A, a trend in mean grain-size appears to be present. In a seaward direction, grain size increases gradually.

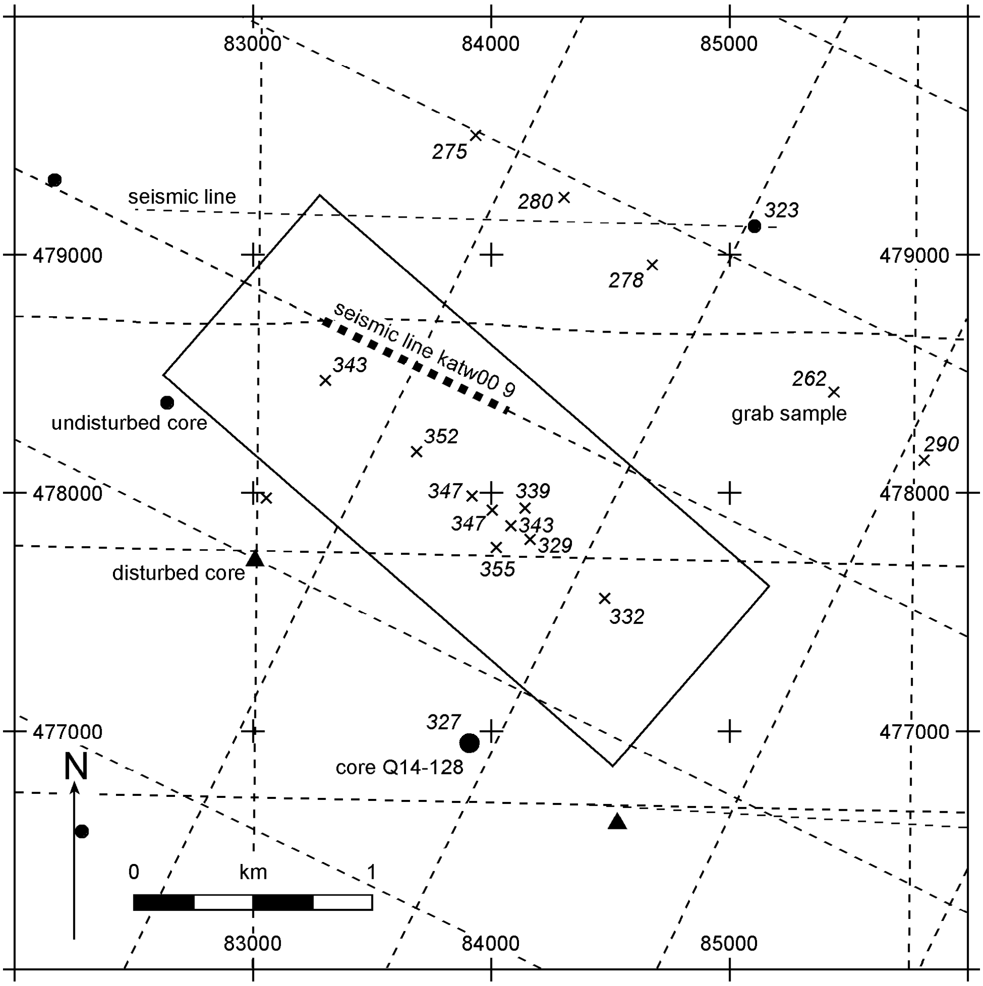
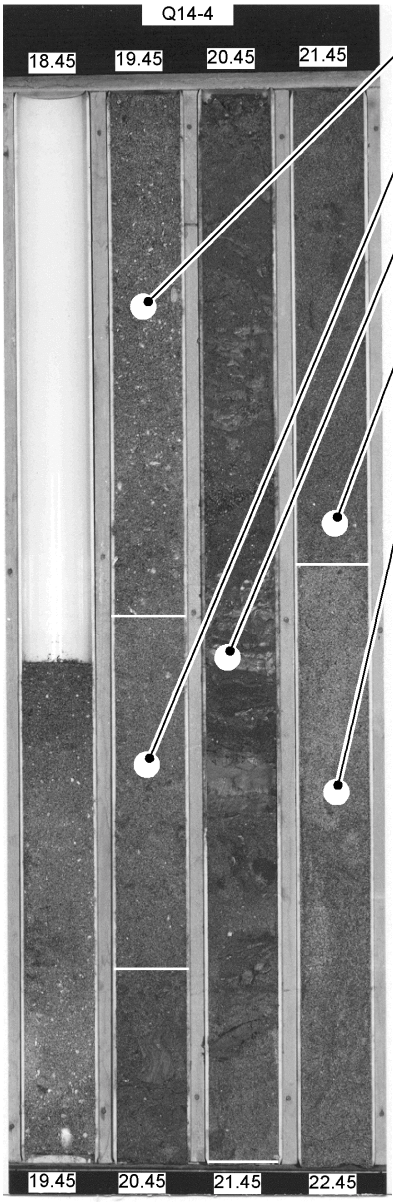


Figure 14 Geological data for area B. Core and seismic-section shown in Figures 16 and 17 are highlighted.

Two undisturbed cores illustrate the typical seabed and shallow-subsurface sedimentology of area B. Core Q14-4 (Figure 15), about 1 km north of the area depicted in Figure 14, shows fine-medium sand with abundant shells and shell fragments at the top. The shell content decreases downward, where the unit overlies very fine-fine, slightly silty sand, laminated with clay lenses and some peat detritus. Core Q14-128 (Figure 16) shows a thin shell-rich unit of fine-medium sand on top of fine, slightly silty sand with with little shell material and few clay clasts. Both cores and seismic records (Figure 17) indicate the presence of a discontinuous, fine-grained unit at 1-2 m below the seafloor, marking the top of the Pleistocene.

A macrozoobenthos sample from the most seaward box core within the area shows a predominance of reworked shells, with only minor live organisms (Figures 18 and 19).



19.00 - fine-medium sand; abundant shells and shell fragments

19.96 - fine-medium sand; few shell fragments; clay clast at the base

20.30 - very fine-fine, slightly silty sand; few shell fragments; laminated with clay lenses (up to 8 cm thick); some peat detritus

21.45 - fine-medium, slightly silty sand; thin shell layer at the base

21.90 - fine-medium sand; variable concentration of shells

22.45 - end of core

Figure 15 Core Q14-4.

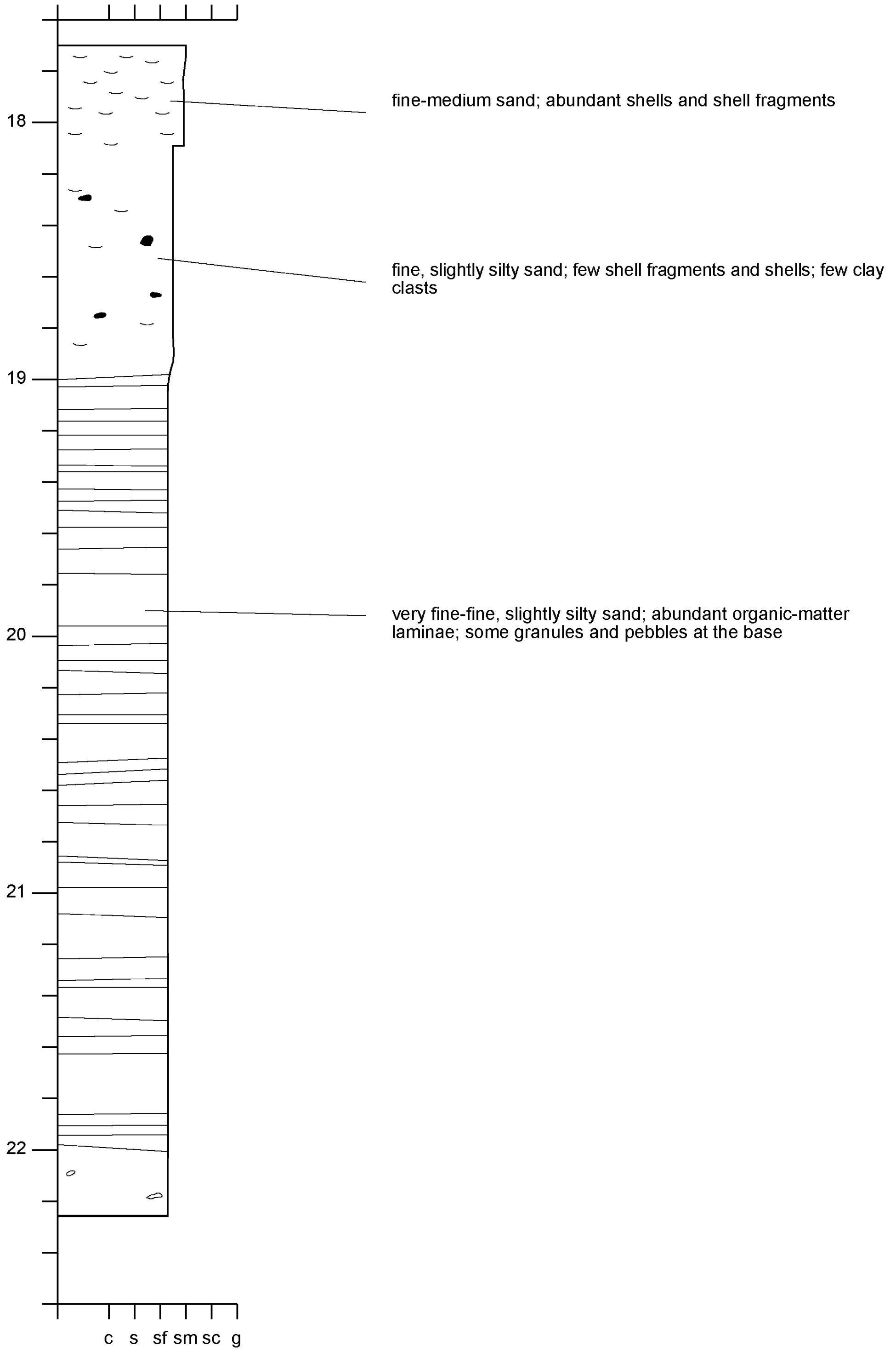


Figure 16 Sedimentological log of core Q14-128.

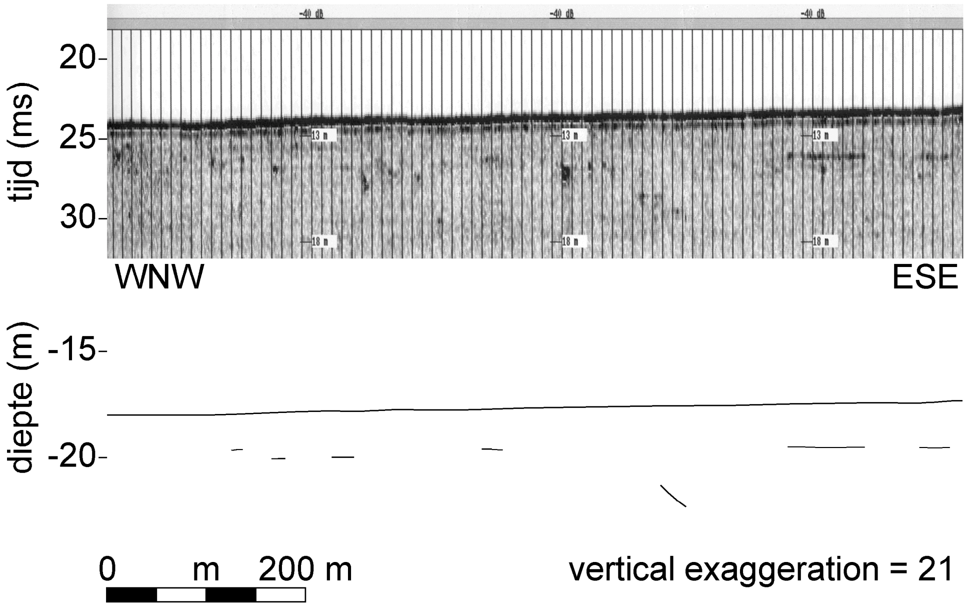


Figure 17 Seismic profile through area B.

Figure 18 Macrozoobenthos sample from area B.

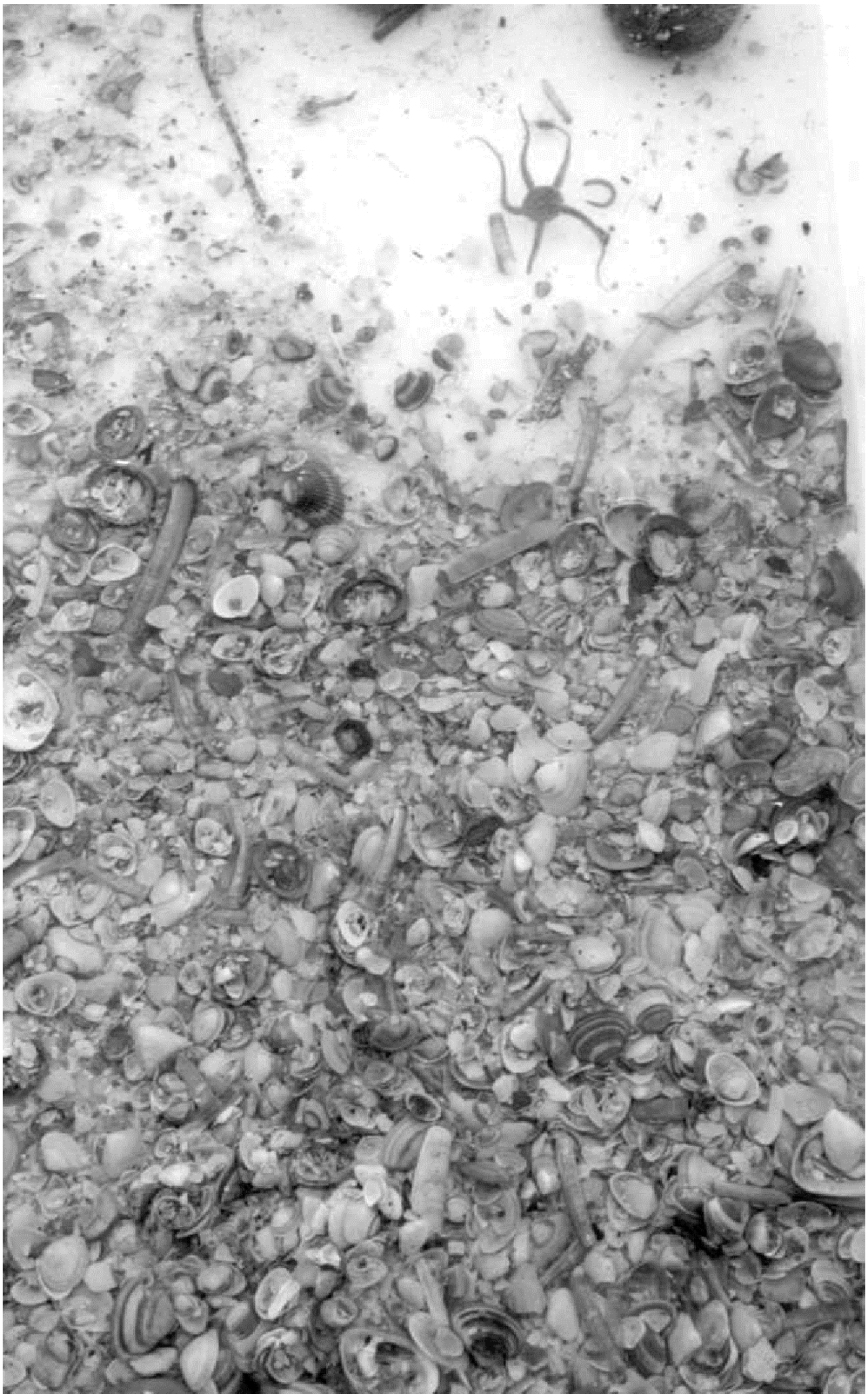


Figure 19 Predominance of dead, reworked shells in sample of Figure 18.

4.1.3.4 Area C: Sand-wave area on the inner continental shelf

The measured grain-size range in this area, 225-245 µm, is notably smaller than those of areas A and B (Figure 20). Undisturbed cores (Figure 21) show cross-bedded sets of fine, slightly muddy sand directly underneath the seabed, reflecting megaripple migration. At depths of less than 2.5 m, very fine-fine sand with variable amounts of peat is pesent. Locally, a peat layer of up to 0.5-m thickness occurs at the base of the sand-wave unit. The fine, peat-rich unit forms a discontinuous, moderate- to high-amplitude reflection on seismic records of the area (Figure 22). Its age is unknown.

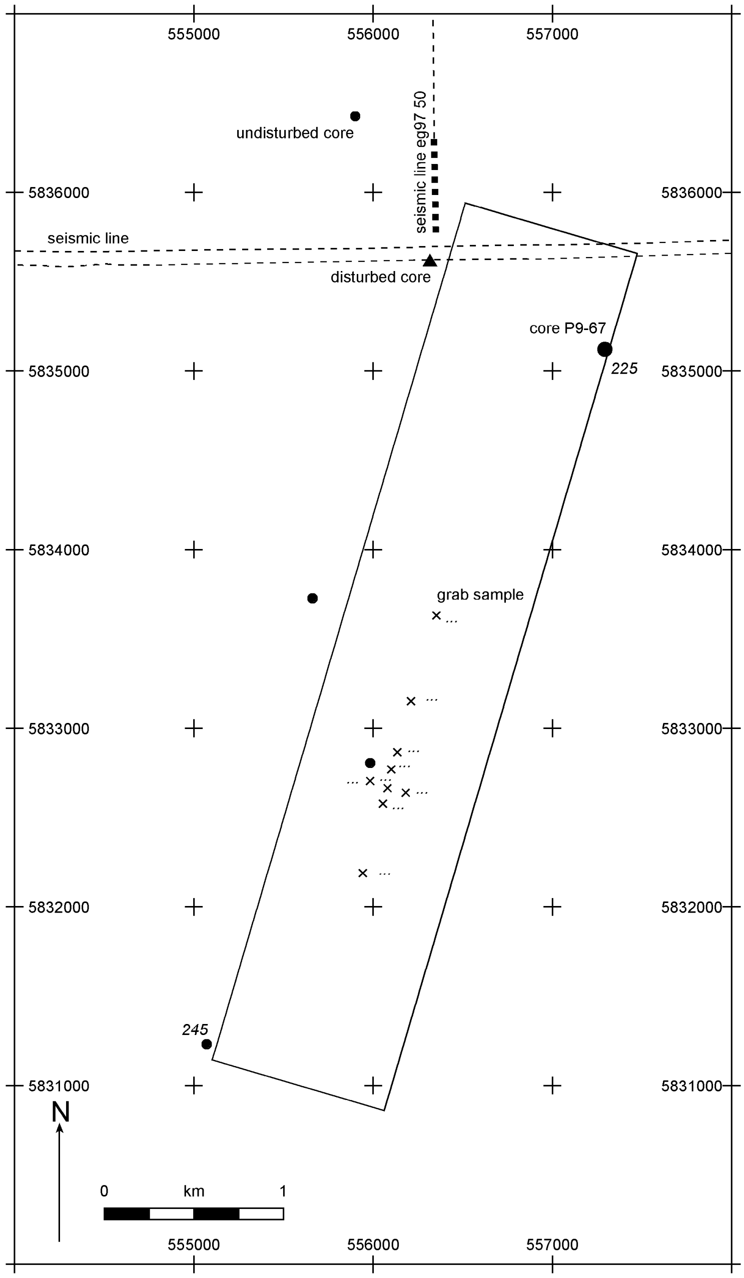


Figure 20 Geological data for area C. Core and seismic section shown in Figures 21 and 22 are highlighted.

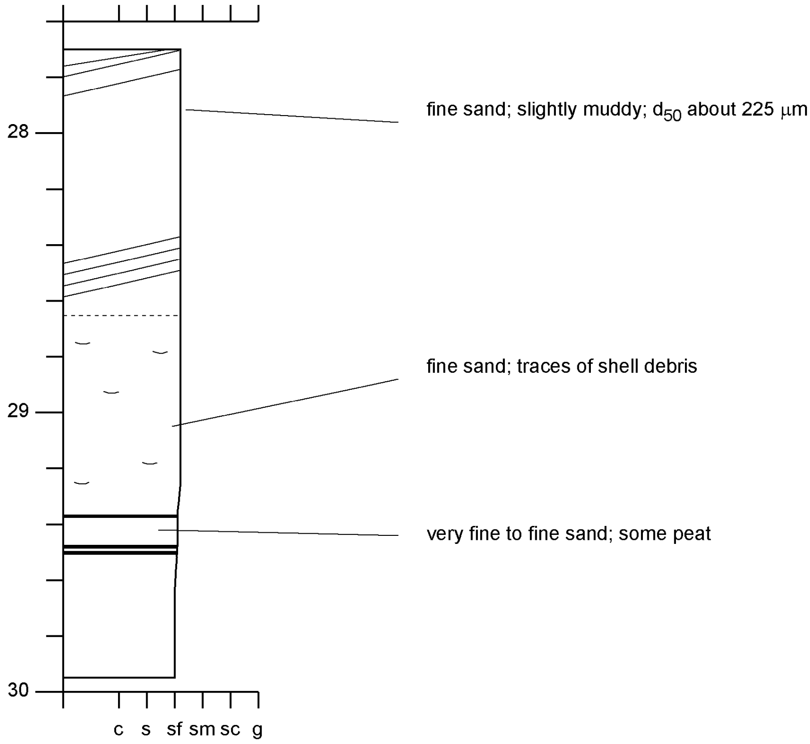


Figure 21 Sedimentological log of core P9-67.

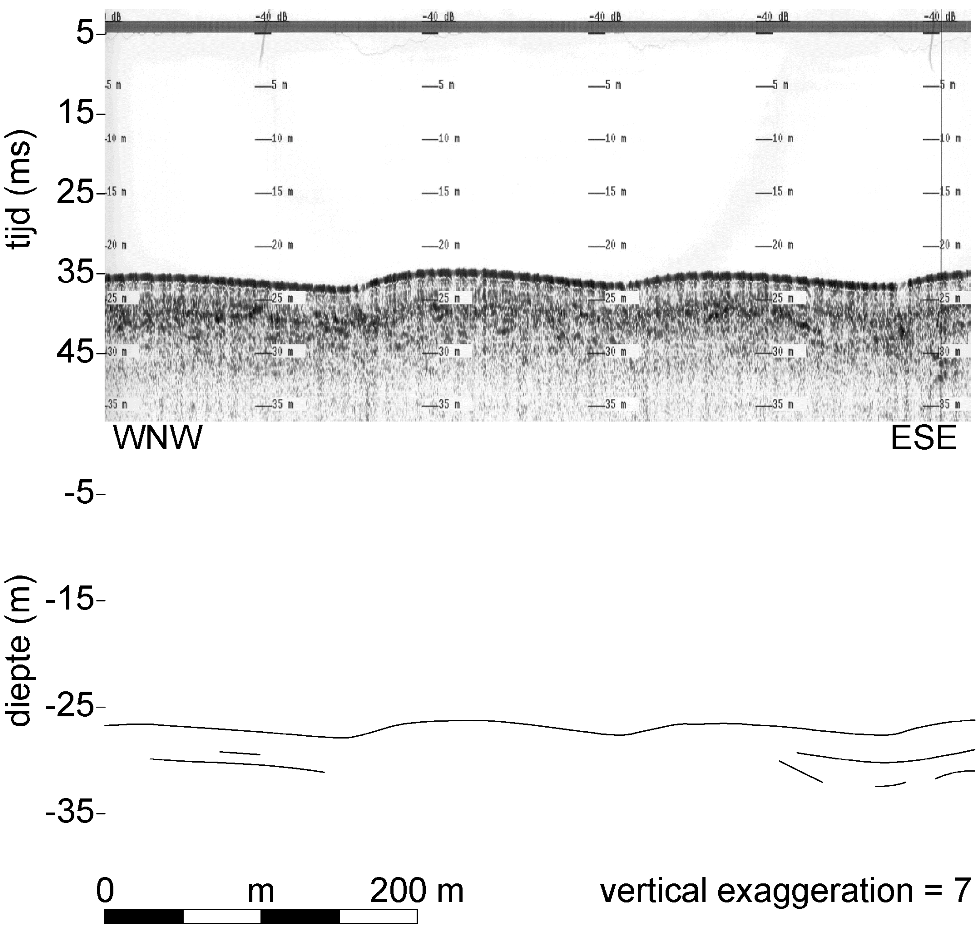


Figure 22 Seismic profile proximal to area C.

4.1.4 Frame with sensors (C.N. van Bergen Henegouw)

The observed current velocities in areas B and C (Figure 23), combined with textural analyses of seafloor sediment, indicate that small current ripples may be present at these locations. The mean current velocity was highest in area C, about 0.4 ms^{-1}. Migration of current ripples across the seafloor should in theory be observable by a sensor that measures temporal changes in the distance to the seabed. When a current ripple migrates underneath the transducer, the distance to the seabed will decrease at first, along the stoss side of the ripple, and then increase more slowly along its lee side (Figure 24).

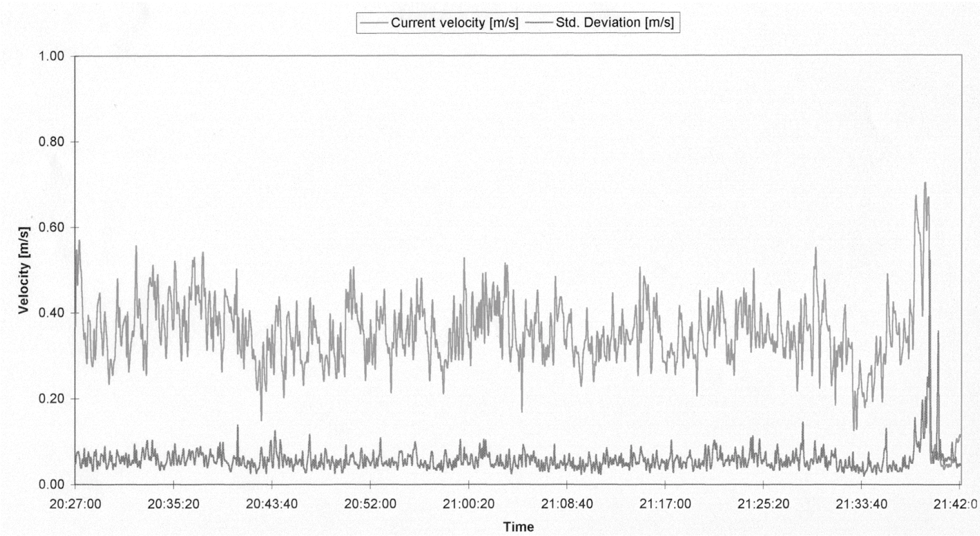


Figure 23 Measured current velocity above seabed in area C.

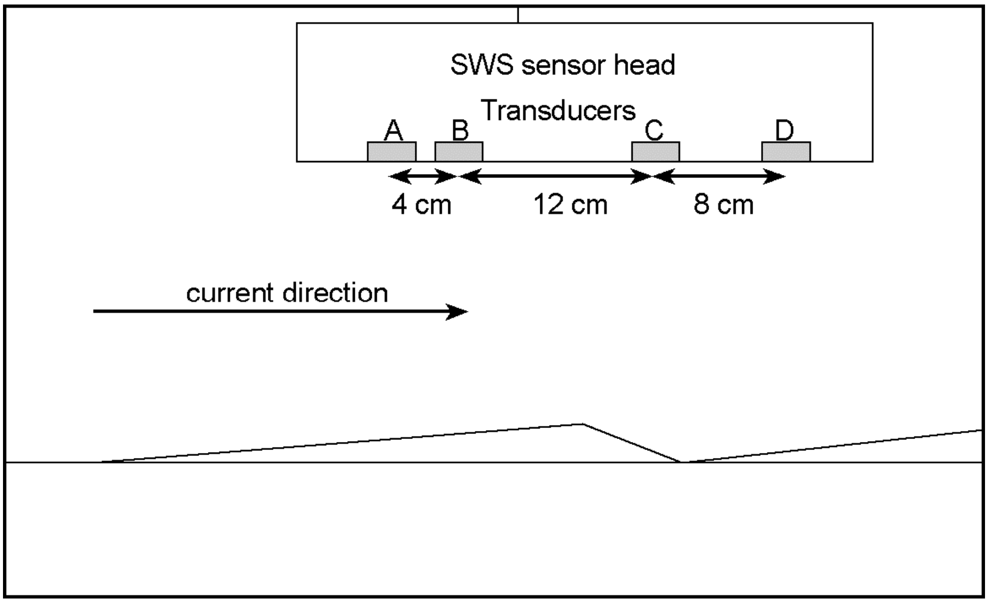


Figure 24 Imaging of migrating current ripples.

Sonar work-station measurements in area C show some cm-scale dynamics in the course of one hour (Figure 25). However, no current-ripple migration is evident. Instead, the seafloor moves towards the transducer during the entire measuring period, by a maximum of 0.04 m. A measurement over several hours indicated that the cm-scale dynamics, as observed by the sensors, was apparent rather than real. Small overall decreases in distance of the transducers to the seabed are explained by slow settling of the measuring frame in the seabed sediment during measurements.

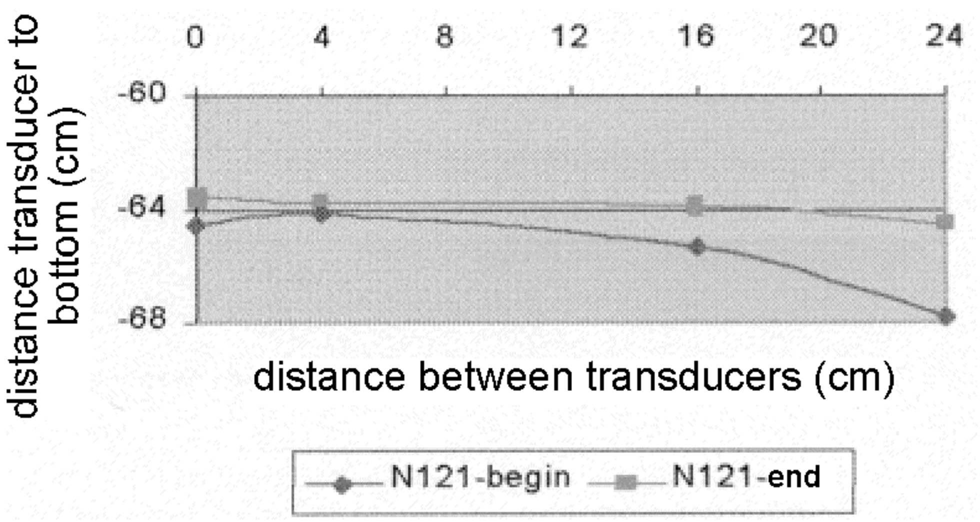


Figure 25 Decreasing distance between transducers and seafloor over time, caused by settlement of the frame into the bottom sediment.

As the reliability of the measurements is governed in part by the stability of the measuring frame, this slow settlement prevents accurate data from being collected. Possible correction for the settlement using data from the pressure sensor proved to be unfeasible. Air-pressure variability and other factors contribute to a large inherent uncertainty of the pressure-sensor measurements. The error introduced by the pressure-sensor-based depth measurements of the frame, corrected for tidal and atmospheric influences, is considerably larger than the morphodynamics as measured by the sonar work station.

4.1.5 Beam trawls

During week 34, areas A and B have been sampled by m.s. Tridens (project leader I. de Boois), using a 2-m beam trawl (BTS2-M20, maze width 4 cm). Samples were collected along 6 transects:

Table 2 First series of beam-trawl measurements

Transect nr.	Starting position	Distance (m)	Duration (min)
A1	52N24,004E23	153	5
A2	52N24,004E24	168	5
A3	52N23,004E24	140	5
B1	52N14,004E20	160	5
B2	52N14,004E21	160	5
B3	52N15.004E22	170	5

During week 36, areas A and B have been sampled by m.s. Isis (project leader G.J. Piet), using two 8-m beam trawls (BT8, maze width 4 cm). Samples were collected along 6 transects:

Table 3 Second series of beam-trawl measurements

Transect nr.	Starting position	Distance (m)	Duration (min)
B4	52N14,4E22	1019	8
B5	52N14,4E20	1018	8
B6	52N14,4E22	994	8
A4	52N17,4E23	1006	8
A5	52N17,4E24	986	8
A6	52N18,4E22	1017	8

4.1.6 Description (using idealized models) of dominant proceses in seabed evolution

4.1.6.1 Progress in modeling

The evolution of the sand-wave-dominated sea bed is being modeled at the present time. The tidal flow and sediment-transport processes are simplified to identify the dominant elements. With this approach, it can be shown that sand waves are free instabilities that are coupled with a secundary flow circulation on the mean tidal flow (Komarova and Hulscher, 2000). With this model, it is possible to identify which areas are dominated by sand waves and/or tidal ridges (Komarova and Hulscher, 2000). If tidal asymmetry is introduced into the model, the migration of sand waves can be explained. This asymmetry can, for example, be caused by a wind-driven current. (Nemeth et al., 2000a; 2000b).

With the idealized models, it is also possible to analyse the effect of human activity on the natural processes and the natural seabed evolution. Extraction of gas, for instance, causes subsidence. The models show that this subsidence may interfere with the natural processes related to formation of tidal ridges. Consequently, the subsidence may result in a horizontal spreading of large wave patterns (Hulscher and Fluit, 2000; Roos and Hulscher, 2000).

The sand-wave model can be used to evaluate the effeciency of dredging in sand-wave fields. After the dredging, the sandwaves grow back to their natural dimensions. A model, tuned to data, can be used to evaluate different dredging strategies (Knaapen et al., 2000).

4.1.6.2 Data Analysis

On the access route to Rotterdam harbor, ships cross a field of sand waves. The crests of these sandwaves determine the effective navigation depth. To warrant navigability, the North Sea Directorate of the Netherlands Ministry of Transport, Public Works and Water Management continually monitors the bathymetry in the sand-wave area, using echo sounding. In addition to the sand waves, our analysis of these data has revealed small-amplitude sandbanks and a new rhythmic pattern. The wavelength of this new pattern, labeled here as long bed waves, is three times the one of sand waves, and the crest orientation is different. Interference of the three modes leads to the rather complex bathymetry, as revealed by echo soundings.

5 Literature studies

5.1 Relationship of the benthic community on the North Sea floor with hydro- and morphodynamical parameters

5.1.1 Introduction

The purpose of this literature study is threefold:

- Generating an overview of existing knowledge regarding the distribution of benthic organisms in the North Sea;
- Providing an overview of possibilities for numerical modeling of hydro- and morphodynamics in the North Sea;
- Indicating specifics regarding the interaction between the distribution of benthic organisms and morphodynamical models, and the possible contribution of (ongoing) benthos research.

5.1.2 The North Sea as habitat for benthic organisms

5.1.2.1 Distribution

The distribution of benthic organisms and of benthic communities/assemblages in the North Sea is not homogeneous. Distribution patterns of species, life stages, or complete benthic communities are determined by physical and biological parameters that are strongly interlinked. Spatial and temporal scales are factors as well. The occurrence of individuals of certain species at a particular location is governed by a large number of factors, both before and after their establishment on the seafloor. Before colonization, reproduction and supply will be of influence (recruitment limitation), whereas after colonization, habitat suitability will be essential (Newell et al., 1998; Ólafsson et al., 1994; Trush et al., 1992). Substrate type, competition for space and food, predation, and disturbance are the most important suitability parameters.

Table 4 Factors relevant to distribution of benthos

Before colonization	After colonization
Reproduction	Substrate type
Supply	Competition
	Predation
	Disturbance
	Temperature?

Owing to its hydrodynamical, geological, and climatological variability, the North Sea offers a wide variety of habitats. The Dutch part of the North Sea floor is characterized by an abundance of sandy areas, but muddy areas and gravel fields occur as well. The presence of shallow coastal areas and deeper marine areas and of different morphological structures such as sand waves and shoreface-connected ridges creates significant habitat variability, both on a micro- and on a macroscale. Even artificial substrates such as wrecks are colonized quickly, including by species that were previously rare or absent in the area. On the one hand, this fact shows that substrate is an important factor in the occurrence of species; on the other, it demonstrates the excellent distribution possibilities for many species. Organisms living on the seafloor surface may serve as substrate for species that would not otherwise be able to colonize an area. Shellfish living on the surface enable the establishment of epifaunal species such as barnacles and Anthozoa, and the tubes of some worms provide shelter to other organisms as well.

5.1.2.1.1 Colonization

In most instances, colonization of "open" space will progress according to a more or less established pattern. Open space is colonized quickly by opportunistic species with large dispersion capabilities and few demands regarding habitat (r-strategists: MacArthur and Wilson, 1967). These species are characterized by high reproduction rates, strong growth, and, commonly, high mobility. Subsequently, species with smaller dispersion capabilities, many demands regarding habitat (k-strategists), and excellent competition capabilities will begin to occupy the space. These species are commonly characterized by slow growth, long life spans, and slow reproduction rates. At first, habitat variables will play a prominent role in the composition of the assemblage, but in the course of the succession process, the structure of the assemblage will be affected increasingly by biological interactions. In most instances, the bottom fauna in an area will be at a succession stage in which both opportunistic and equilibrium species occur. The structure of such an assemblage is governed by all environmental variables and by biological interactions. A physical or biological disturbance will result in recession of the succession process to an earlier phase.

Reproduction and supply determine first and foremost whether or not an organism can reach a certain area. The first life stage of many species is planktonic, lasting days to weeks. As a result, the distribution of eggs and larvae is dependent primarily on hydrodynamical processes, including speed and direction of water currents. In addition, the mortality in this life stage will affect the distribution. In view of the residence time of water in the North Sea and the range of current velocities, species can colonize large areas of the North Sea floor by transport of eggs and larvae. Other species do not spread via a planktonic stage, but by active migration that relates distribution to the distribution of the parental population. The smaller distribution radius associated with this type of colonization increases the time needed for colonization of an area. Several studies have shown that adult individuals of a species in particular contribute to the colonization of disturbed areas, both by active and by passive migration. Sometimes, recruitment determines patterns in density of marine organisms, making it a main governing factor in the composition of benthic communities (Ólafsson, 1994).

5.1.2.1.2 Survival

Upon arrival of an individual in a particular area, its chance of survival is determined by the presence of a suitable habitat. The individual will compete with other organisms for the available space and food.

Once established, the chance of survival of organisms is governed primarily by biological interactions. Important factors are competition for food, predation, and habitat disturbance. The quantity and quality of the food are related to the primary and secondary production in the water column, or on or in the bottom sediment, and are also dependent on supply from elsewhere. In different parts of the North Sea, these factors are vastly different.

The mortality of larvae as a result of predation and disturbance (for example, by bioturbation), is determined primarily by the density and life stage of the organisms that are already present (Ólafsson, 1994). The activity of the fauna present in an area can result in a habitat modification to such a degree that the habitat is no longer suitable for other species. The density of organisms present on the seafloor is of primary importance in this process, and may determine whether a species plays an inhibiting or facilitating role. Rhoads and Young (1970) showed that the burial and foraging activities of deposit-feeders has a negative effect on the colonization and survival of other species.

5.1.2.1.3 Summary

Summarizing, a wide range of habitats is available in the North Sea, coupled to an equally wide variety of bottom-faunal communities. As a result of their reproductive strategy and of the existing hydrodynamical regime in the North Sea, most species are capable of colonizing many areas. However, differences in abiotic parameters and biological interactions create differing chances of successful colonization, resulting in diverse specific bottom-faunal communities. To better explain the distribution of species and assemblages in the North Sea, the relationship between abiotic and biotic parameters needs to be researched in detail. The degree to which organisms affect the creation and maintenance of their environment is very important. A better insight is necessary into the factors that are important in the development of different bottom-faunal communities and in their role in further development. Attention needs to be paid to developing a method aimed at characterizing parameters responsible for the different North Sea ecotopes.

5.1.2.2 Interaction between sediment and bottom fauna

5.1.2.2.1 Introduction
Marine sediments consist of more or less mobile particles, varying in size and composition, stability, density, organic content, and chemical characteristics. In combination with other abiotic parameters, including water depth and hydrodynamics, highly variable particle characteristics result in a wide variety of potential habitats for organisms. Many studies have shown the existence of a relationship between physical parameters, including sediment composition, and biological parameters, including the organisms living on or in the sediment (Gray, 1974; Rhoads, 1974; Thayer, 1983, 1984; Weston, 1988; Hall, 1994; Snelgrove and Butman, 1994). The relationships are determined by multiple parameters and are usually complex. The relationships differ for individuals of a species, populations of one species, or species assemblages. Almost all organisms affect their environment to some degree. The characteristics of the bottom sediment can sometimes be strongly influenced by the activity of organisms, because the majority of sediment on the seafloor consists of particles small enough to be ingested or manipulated. Transport of sediment particles by (macrofaunal) organisms is usually coined as bioturbation.

5.1.2.2.2 Bioturbation
Bioturbation results in changes in sediment composition, grain size, and grain-size distribution, and also influences the biogeochemistry and microbial activity (Cadée, 1976). On the one hand, intensive bioturbation may result in homogenization of the sediment by complete mixing of substrate particles. On the other hand, it may result in the development of aggregates and differences in distribution of various sediment fractions, because “manageable” fractions are separated from larger fractions. In addition, bioturbation can bring particles into suspension directly. Bioturbation also affects the water content and porosity of the sediment, changing critical values with regard to erosion and transportation (Rhoads and Young, 1970). Damage to algal mats (microphytobenthos) on the seafloor and to mucus bonds between sediment particles can adversely affect their stabilizing function.

Macrobenthos forms the most important group of bioturbating organisms. Deposit feeders in particular are quantitatively important in changing bottom characteristics. Deposit feeders feed on material on or slightly below the surface, ingesting selectively or aselectively particles of variable size and composition. Most deposit feeders alter the sediment in order to assimilate only the most useful part of the material (Lopez and Levington, 1987). After this selection and possible passage through the digestive system, excretion takes place, which can result in aggregate-type fecal pellets. Mobile deposit feeders move both laterally and vertically, thus transporting and mixing bottom particles as well as interstitial water and gases. Sedentary or immobile deposit feeders, particularly polychaetes, may form dense populations with vertically oriented living burrows. When these species search for food at the base of their burrows, they relocate sub-bottom sediment to the surface (conveyor-belt type: Hylleberg). Sediment particles too big to move (e.g. shell fragments) may be concentrated within the sediment in this way. The depths of such concentrations depend on the depths at which the deposit feeders live and eat. It is possible that burrowing species may no longer be able to bypass such layers when they reach critical thicknesses, in effect reducing the actual layer in which the organisms live.

Aside from deposit feeders, other organisms, including fish, birds, and even whales foraging on the seafloor, may alter the sediment.

In the field, bioturbation is determined mostly on the basis of profiles of tracers such as chlorofyl-a, artificial particles such as glass beads, isotope-labeled algae, or particles recognizable on x-ray images. Much research has been conducted on bioturbation by means of laboratory experiments (Thayer, 1983; Stamhuis, 1997). Predicting the effects of bioturbation usually relies on models that take into account the results of bottom profiles and experiments.

5.1.2.2.3 Other effects

Aside from active disturbances like bioturbation, bottom-faunal organisms can also affect sediment composition in different ways. Suspension feeders catch actively or passively suspended matter from the water column using flagellum-lined appendages, mucus nets, or flagellum- and mucus-lined respiratory organs. High-density populations of these species are very effective in removing seston from the water column, and in adding this seston to the sediment in the form of fecal pellets.

5.1.2.2.4 Morphological effects

As a result of the presence and activity of organisms, the morphology of the seafloor can change. Dwelling or excretion heaps, formed by transport of subsurface sediment to the area around burrows, create positive relief on the seafloor. Foraging pits, burrowing and crawling traces from organisms foraging or moving along the surface, such as fish crabs, and sea-urchins, create negative relief. Such morphological features affect water turbulence and flow, and thus sedimentation and erosion. The dimensions of these structures vary from millimeters to meters. The presence of densely spaced burrows may have either a stabilizing or a destabilizing effect on the substrate, and may influence areas many thousands of square meters in size (Fager, 1964; Rhoads and Young, 1970). Burrows formed of cemented sediment particles may result in increased stability of sediment, especially when the species concerned occur in high densities, as colonies. Eckman et al. (1981), however, relate the correlation between stable sediment and high burrow concentrations to cementing of sediment particles by mucus. Structures protruding from the substrate, such as cemented tubes, affect the current velocity of the water, allowing organisms to catch suspended matter.

5.1.2.2.5 Summary

The relationships between benthic organisms and sediment are very important forcing factors of the marine-life community. Bioturbation of the substrate by organisms can affect these communities very strongly (Reise, 1985; Ólafsson, 1994). Colonization patterns and interactions between existing fauna and newly arrived colonists can be affected on large temporal and spatial scales by bioturbation processes that can be both inhibiting and facilitating (Trush et al., 1992).

Relationships between organisms and sediment have been the subject of much research, particularly with regard to estuarine and shallow-water areas. In recent years, faunal communities in deeper and more distal parts of the North Sea have attracted increasing attention from the research community. The distribution of these communities and their relationships with bottom-sediment characteristics deserves our interest. The activity of bioturbators and the mutual interactions among sediment characteristics, seafloor morphology, and composition of the zoobenthic community will have to be researched in detail.

5.1.3 Models describing North Sea hydro- and morphodynamics

5.1.3.1 Water movement in the North Sea

The North Sea morphodynamics is governed primarily by water movement, which manifests itself on different time scales. In this section, we discuss various types of water movement in the North Sea, and possible changes that may result from human interference, such as infrastructural works and sand extraction.

5.1.3.1.1 Water movement on a tidal scale

On the scale of a tidal cycle, one can distinguish between astronomically forced and meteorologically forced (primarily storm surges) variability in water movement. The presence of obstructions along the Dutch coast, such as dams, groins, jetties, windmill parks, or islands, may exert a significant local influence on this variability. Research into the effects of a 24-km^2 island offshore Noordwijk (WL|Delft Hydraulics, 1997) has shown that this influence stretches out across an area of 15 to 40 km near the island. In case of even larger islands, the areas in which the hydrodynamics are affected increase approximately in a linear fashion with increasing island width and length. If an island is connected to land via a solid or partly open structure, this connection will determine the width of the disturbance, meaning that the disturbance may not merely have a local effect, but also influences the large-scale pattern of tidal and storm-surge propagation in the southern North Sea. Amphidromic points may shift, and significant amplitude and phase changes may occur along the North Sea coast.

5.1.3.1.2 Residual water movement on a time scale of seasons to years

Time-averaged over a tidal cycle, residual water movement on a seasonal to annual scale can be identified, governed by tides, fluvial discharge, and meteorological factors. This water movement is important to the large-scale pattern of horizontal and vertical temperature and density stratification. It is also highly influential with respect to transportation of bedload, suspended load, and dissolved materials. Along the Dutch coast, a zone of relatively fresh water from the Rhine/Meuse river mouth occurs, the so-called ‘coastal river’. Human interference in this area will likely result in a changing large-scale residual current pattern. An island location closer than 20 km from the shore falls just within the frontal surface boundary between salty North Sea water and more brackish Rhine/Meuse estuarine water. It is likely that such a construction would affect this boundary, and even more so in case of a island with a dam connecting it to the mainland. A local effect that will certainly occur concerns decrease of the landward-directed residual bottom current that compensates for the offshore-directed freshwater discharge. The presence of a construction may reduce this residual current.

5.1.3.1.3 Water movement on a time scale of waves

The wind-induced wave and swell climate in the North Sea may be strongly affected by infrastructural works. The spatial effect will be stronger when the structure is located closer to the mainland. The area affected will be smaller, but the spatial gradients are stronger. Also, convergence effects may take place. Special attention should be paid especially to possible effects on the swell climate, as studies conducted in the framework of the project Coastal Genesis indicate that swell climate probably plays an important role in the morphology and steepening of the shoreface.

5.1.3.2 Morphology of the North Sea floor

The morphology of the North Sea floor is governed primarily by water movement. Human interference may also affect the morphology. One can distinguish:

- So-called near-field or local effects;
- Far-field or distal effect; and
- Shoreface and shoreline effects.

Around obstructions, such as an island, near-field changes of the seafloor occur, especially on the northern side. These changes are caused primarily by current changes (particularly contractions and divergences) and also by wave changes and reflections. Simulations with morphological models predict that these local changes take place during a period of 50 years. Quantitatively, these changes have dimensions of maximally half the water depth. The uncertainty of these predictions, however, is large.

An important morphology-related question is whether or not these near-field seafloor changes result in direct interaction with the shoreface. The distance of the obstruction to the mainland and the size of the obstruction are important governing parameters.

Far-field effects are assumed to be the result of changes in the large-scale tidal and residual tidal current patterns. These patterns are affected across large areas. Subtle mechanisms give rise to self-organizing, intrinsic phenomena such as tidal ridges, sand waves, and shoreface-connected ridges. An approximate projection of a 100-km^2 island 10 km off the coast of the province Zuid-Holland on the geomorphological map shows that such an island would occupy for the most part an area with 2-4-m-high sand waves, and will also interfere with shoreface-connected ridges. The process-based simulation models currently in use are unable to describe the dynamics of these large-scale structures. Hence, calculations do not provide a reliable image of possible effects. Since the ridges are attached to the shoreface, changes in shoreface dynamics in the area between Noordwijk and Egmond would be likely.

5.1.3.3 Biogeomorphology of coast, beach, and dunes

Morphological changes of the seafloor, changes in residual and tidal currents, and a decrease in wave energy will undoubtedly result in changes in the phyto- and zoobenthos composition of the North Sea. The dynamics of the beach environment may decrease. The dynamics of the dune environment will not suffer from a changed wind regime, but a decrease in salt spray will affect vegetation, and hence dune dynamics.

5.1.3.4 Models regarding water movement

This section provides an overview of existing models describing and predicting water movement.

5.1.3.4.1 DCSM (Dutch Continental Shelf Model)

DCSM was created as a 2D model for the NW European Continental Shelf (Greater North Sea) with boundary conditions for deep water (>200 m). By means of a water-level correction at the model boundaries, the latter allowed inclusion of the ocean contribution to storm surges. The model is intended to predict operational storm surges (KNMI) and to provide boundary conditions to be used in detailed models of the North Sea. The primary evaluation of the model, which consists of 20,000 wet grid cells of 1/12 x 1/8 degree, has been in terms of water levels. A cutout of the model (NSM) has been used for 3D applications as part of NOMADS (model intercomparison of advection-diffusion models).

5.1.3.4.2 “Kuststrook” (coast-proximal area)

This model was set up by RWS to describe in detail water movements within about 70 km of the Dutch coast. It is compatible with detailed models for the Delta area of the provinces Zeeland and Zuid-Holland, the Rhine/Meuse mouth, and the Wadden Sea. The model has been used for 2D and 3D applications with regard to both water levels and transport studies. The model boundary is located 50-75 km from the coast and Wadden Islands, rather close when studying the effect of human interference 40 km from the coast. The effects of human interference may extend beyond the open end, meaning that the boundary conditions represent more than the natural situation. For the same reason, the model boundary is a limiting factor when modeling long-term particle transport; the particles will travel beyond the boundary.

5.1.3.4.3 PROMISE

This model was established at WL as a basis for flexible 3D simulations and sensitivity research of transport and suspended sediment, on a North Sea scale and on temporal scales of seasons. The model is characterized by small grid dimensions adjacent and perpendicular to the coast, increasingly large grid dimensions farther from the coast, and the free exchange of matter throughout the southern North Sea in the local absence of a model boundary.

The model has open boundaries at 57°N and 2°W (in the Channel) and is nested within DCSM. The model has been used extensively to carry out sensitivity research in regard to horizontal water movement and to the distribution of suspended sediment. However, without local refinements, this model is too coarse for detailed analyses of exchanges between the North Sea and the Wadden Sea.

5.1.3.4.4 PROMISE – island in the North Sea version

This model is based on the PROMISE grid, and has been refined near the coast. It has been applied to schematize in detail changes in transport and morphology resulting from a man-made island in the North Sea (internal project at WL). The model is sufficiently flexible to perform series of long-term 3D simulations efficiently, with minimal computational and manpower.

5.1.3.4.5 Curvilinear ZNZ model

This RIKZ model was established as basic North Sea model of a curvilinear "model train" for the coastal zone and estuaries. It was constructed as part of the Nautilus project to study water movement. An adapted "coastal waters" (kuststrook) model is now a 3x3 refined cutout of ZNZ, just like models for the Oosteschelde and Westerschelde in the province Zeeland. The model has about 34,000 grid cells in the horizontal, and has been calibrated using water levels for 2DH. The desired density of grid points along the coast of the southwestern Netherlands results intrinsically in a much coarser representation along the concave coast of Holland.

5.1.3.5 Potential applications of models

On the basis of existing models, an inventory can be made of the possibilities offered by modeling water movement and morphodynamics in the North Sea to show the effects of human interference. One can distinguish large- and small-scale models.

5.1.3.5.1 Large-scale model

In order to model large-scale water movement, water quality, and mud transport in the North Sea, a 3D model can be developed using a RWS model of the southern North Sea. A first scheme (Figs. 5.1 and 5.2) suggests that a curvilinear model with about 20,000 grid cells and about 10 layers is sufficiently effective and feasible. Correlation to “Kuststrook” remains possible, but not necessarily in a seamless fashion.

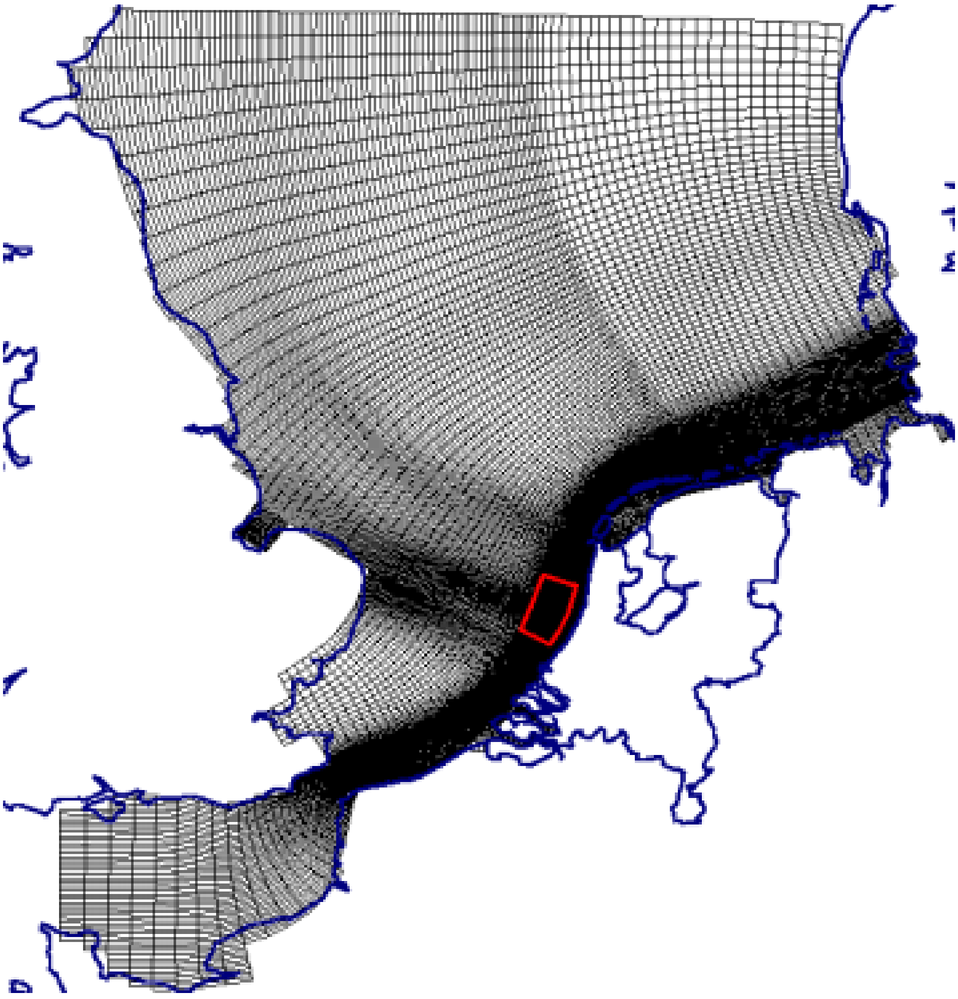


Figure 26 Possible computational grid.

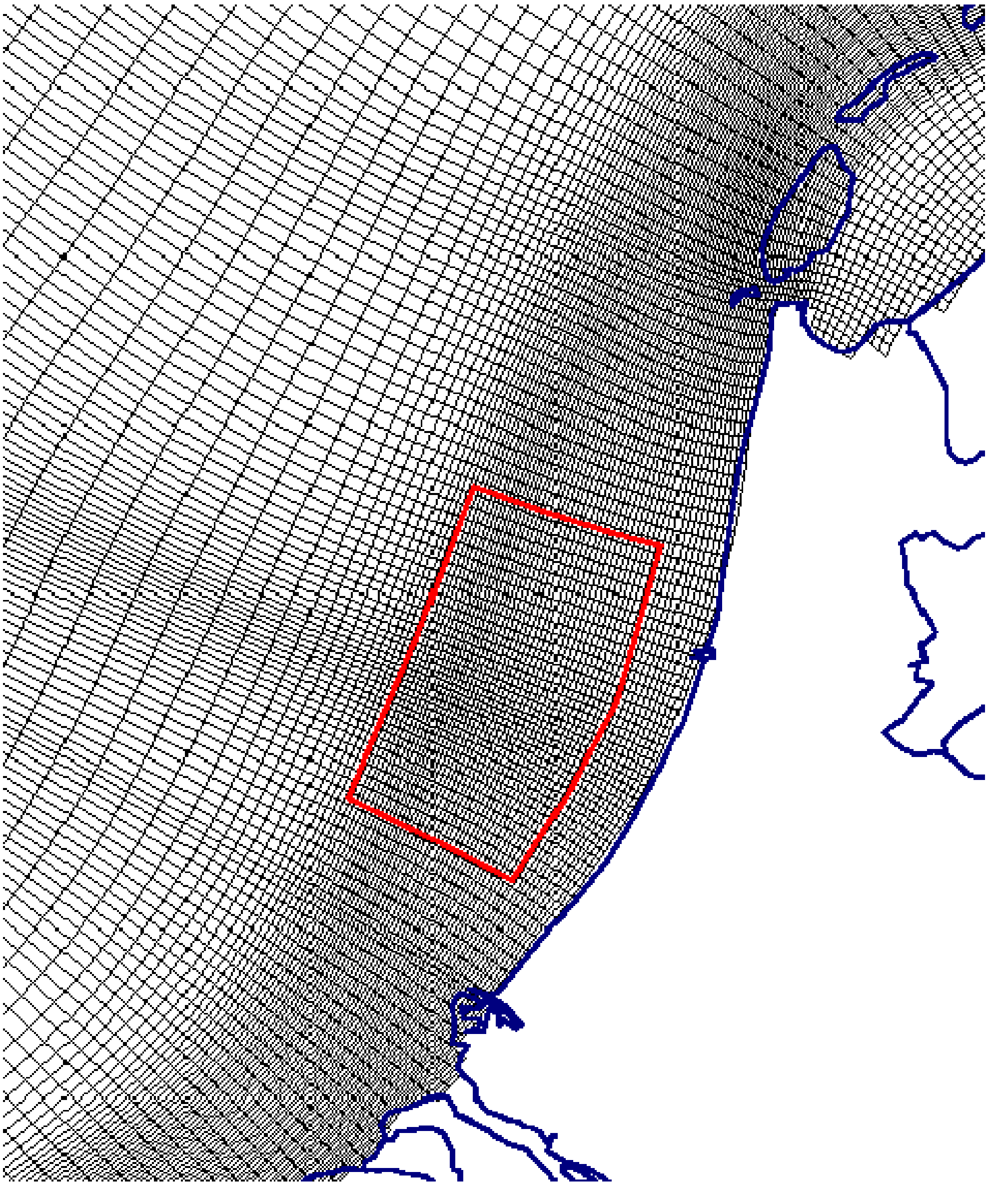


Figure 27 Part of the computational grid.

With about 20,000 computational grid cells, a 3-month period can be analyzed in about 10 days, in a 10-layer schematization with temporally variable Rhine discharge and wind. To accomplish this task, the grid-cell distances are increased near the Rhine mouth and the Delta distributaries, and at the northern and eastern edges of the grid. They are decreased to about 1 km off shore the coast of Holland, which is similar to the “Kuststrook” model. The model calibration will rely on information from the calibration of the RWS model; accurate reproduction of the water movement and especially of the residual current offshore the coast of Holland and in the western Wadden Sea is required.

A correct reproduction of the variability of discharge and wind requires a 2DH simulation over a year with a realistic time series of these variables. On the basis of results of this analysis, a representative, shortened time series will be generated, which will be shown to create approximately the same mean current and the same current variability. This time series of discharge and wind conditions will be a good measure of 3D simulations. These simulations, which will last several months, will include spring-neap variability, discharge variability, and wind-climate variability.

In order to estimate the morphological changes in the coast-proximal zone, time series of velocities and water levels can be generated from this model, benefiting the coastal profile and coastline models UNIBEST and PONTOS. The model can also be used to create boundary conditions for detailed, small-scale models.

5.1.3.5.2 Small-scale models

To study small-scale influences on water movement and the seafloor, detailed models are created with grid spacing on the order of 100 m. The grid spacing is such that the model can represent large-scale horizontal turbulent structures. To accomplish this feat, the sub-grid turbulence model developed by Uittenbogaard, which has already been applied to an area near IJmuiden, is applied. The model allows accurate assessment of turbulence-related viscosity, which varies with water movement. The model will be applied to accomplish the objectives listed below:

Generating representative sand-transport fields that allow estimation of local bottom changes across large areas on a time scale of decades;
Analyzing large-scale turbulent structures and their associated influence of the “coastal river”;
Analyzing the effects on sedimentation in access channels (particularly the IJ Geul);
Analyzing the effect on the size and variability of cross currents in the access channels, in light of nautical aspects;
Translating these structures to appropriate values of horizontal viscosity in large-scale models.

The vertical structure of the water movement does not play a major role in these processes; thus, a 2DH schematization is sufficient. The model simulations will require substantial computation time, owing to the fine resolution and small time steps.

5.1.3.6 Summary characteristics of numerical models

The table below summarizes different model aspects point by point.

Table 5 Characteristics of numerical models

Characteristic	Large-scale model Water movement	Small-scale model Water movement and morphology
Spatial resolution	500 m – 1000 m	< 100 m
Vertical resolution	5 to 20 layers	Depth-averaged to 10 layers
Time interval	~ 2 minutes	< 30 seconds
Smallest resolved time scale	Tide	Large-scale turbulent structures
Largest resolved time scale	About 1 year (2DH); several months (3D); long-term after aggregation in time and space	Several decades to about 50 years
Processes explicitly represented	Variable freshwater-saltwater and temperature-governed density-driven currents; variable wind forcing; tidal variation	Tide, large-scale turbulence
Important parameterizations	Horizontal turbulence viscosity via algebraic model, vertical mixing via k-ε model	Logarithmic velocity profile or k-ε model, horizontal mixing by solving large-scale turbulent structures plus sub-grid model
Schematizations	Seasonal fluctuations – spring-neap cycle and short-term variations discharge and wind are depicted on a scale of several months, wave climate is depicted in about 20 conditions	Morphologically representative tide is combined with five representative wave conditions
Formulations	Shallow-water equations (3D hydrostatic), waves via SWAN	Shallow-water equations (2DH, 3D hydrostatic), Q3D advection-diffusion equation sand transport, Bijker or Soulsby-Van Rijn formulation for equilibrium concentration
Most important assumptions	Horizontal scales >> vertical scales	Fixed shape concentration profiles
Method of and expertise in prediction	Reproduction average solutions and error ranges, expert interpretation at aggregated level	Reproduction average solutions and error ranges, expert interpretation at aggregated level

5.1.4 Interaction between benthos distribution and morphodynamics-related models

5.1.4.1 Introduction

The distribution of benthos is determined partially by the hydrodynamical and morphodynamical conditions, but in turn affects these two variables. In short, a mutual interaction exists:

Benthos ⇄ Hydro- and morphodynamics

5.1.4.2 Predicting hydro- and morphodynamics-governed benthos distribution

In order to predict benthos distribution in the North Sea with models, a habitat-evaluation procedure must be carried out.

A habitat-evaluation procedure (HEP) consists of a collection of analytical methods and habitat-suitability models for species or communities. These models are used to predict changes in habitat suitability resulting from changes in environmental factors such as current velocity, water depth, substrate composition, concentration of suspended matter, available nutrients, etc. Habitat-suitability relationships are deduced from field observations, through data analyses, or from literature studies.

Usually, an index value between 0 (not suitable) and 1 (optimal conditions) is calculated and assigned to habitat suitability. The environmental factor with the lowest score with regard to a species or community is the limiting factor in the overall score. Curves showing the habitat suitability of different environmental factors are combined with model results for these factors, calculated, for example, per computational grid cell. Using the scores per grid cell, or for larger aggregates of grid cells, the size of the suitable habitat can be calculated, as well as the potential biomass of a species or community.

Input necessary for these analyses is:

Habitat-suitability functions for important environmental factors;
A predicted value of these environmental factors by means of a numerical model.

5.1.4.2.1 Habitat-suitability functions

From paragraph 5.1.2, it can be concluded that abiotic conditions are of fundamental importance to the colonization and subsequent survival of bottom fauna in the North Sea. When a community matures, biological interactions such as competition and predation will play an increasingly important role. Important environmental factors are substrate composition, depth, temperature, food supply, and, primarily as a result of human intervention, sedimentation rates. For each of these parameters, suitability functions can be formulated for different species.

5.1.4.2.2 Prediction of environmental factors

From paragraph 5.1.3, it can be concluded that models are possible with a spatial resolution of maximally 500 m to 1000m for large-scale water-movement analyses and < 100 m for small-scale morphodynamics-related analyses, given enough computation time and adequate efficiency. With these models, predictions can be made for a year to several decades. A number of issues are important. Can the model output contain the desired environmental factors on the appropriate temporal and spatial scales? For example, is the average current speed or the maximum current speed important to habitat suitability? The models can supply these parameters. Also, the spatial resolution has to correspond to habitat heterogeneity. Grid-cell sizes of 100 x100 m in the small-scale models appear suitable to describe habitats. Even units of 1 km^2 can be very suitable to analyze large-scale patterns in the North Sea. One problem in habitat prediction is the fact that biological interactions are not part of the output of hydro- and morphodynamics-related models.

5.1.4.2.3 Conclusion

Using several assumptions and simplifications, the present models allow prediction of habitat suitability for types of communities as a result of human-induced changes in water movement or morphology.

5.1.4.3 Prediction of hydro- and morphodynamics affected by benthos distribution

Bottom fauna can alter sediment characteristics in such a way that morphological effects take place (see paragraph 5.1.2). These changes commonly manifest themselves on a small scale, from millimeters to meters. However, there are also indications that the presence of dwelling tubes, for example, can affect areas thousands of m^2 in size through sediment stabilization.

At the model scales considered, effects of bottom fauna can theoretically be incorporated into the mathematical description. Continuous bioturbation of bottom sediment may influence the critical value of bottom shear stress. Also, relatively small-scale structures, accumulations, or depressions can affect bottom roughness. Expansive colonies of dwelling burrows, mentioned previously, can stabilize the seafloor sediment.

Thus far, the influence of bottom fauna on hydro- and morphodynamics has not been incorporated into the models. In part, this fact can be attributed to a lack of knowledge, in part to the much larger uncertainty associated with other model components.

5.1.5 Usefulness of (current) benthos research

Different institutes conduct benthos research on the North Sea. The type of research depends on the underlying questions, meaning that data are not always comparable and compatible. To examine to which extent the results of such research projects can be used in determining the relationship between benthos and hydro- and morphodynamics, an inventory was made of available information on macrozoobenthos distribution in the North Sea. As a start, (Dutch) research on the Dutch Continental Shelf (NCP) was considered. An overview of available literature (TNO library), with annotations, is included in the appendix.

5.1.5.1 Ecology

A number of basal inventories concerning macrozoobenthos distribution in the North Sea have been conducted, especially by NIOZ. For the most part, these inventories were made with a large-scale purpose, such as within the ICES framework or to characterize large units (environmental zones) for policy-related purposes. Detailed information concerning sediment characteristics are not always reported. An overview of these inventories has been made by Holtmann et al. (1996). On the basis of such large-scale inventories, smaller-scale aspects have received some attention, linking the presence of one or more species to abiotic parameters (e.g. Duineveld et al., 1987; Künitzer et al., 1992). Furthermore, research has been conducted to characterize certain biotopes or species (e.g. Cadée, 1984, Creutzberg, 1986, and De Gee et al., 1991).

5.1.5.2 Monitoring the effects of offshore oil and gas extraction

To research the effects of offshore oil and gas extraction on macrozoobenthos, detailed inventories have been carried out near wells, relating presence and densities to environmental changes caused by offshore activities (e.g. drilling mud) (e.g. Mulder et al., 1988; Groenewoud et al., 1999). Such inventories provide detailed information on the presence of macrozoobenthos species in limited areas, especially when baseline studies before the start of the activities exist as well. This detailed information allows a better coupling with abiotic (and biotic) variables.

5.1.5.3 Sand and gravel extraction

The extraction of sand and gravel results in disturbance of the bottom sediment and, thus, of the bottom fauna. Research into this issue has also been restricted to relatively small areas – locations of planned or past activities – and is usually characterized by relatively high sample densities (e.g. Sips and Waardenburg, 1989; Van Dalfsen, 2000).

5.1.5.4 Sand nourishment and dredge spoils

Sand nourishment (along the coast) en dredge spoils result in disturbance of the benthic community as well, in this case because the species present in the affected areas are covered by a layer of sediment. The effects of these activities are limited to small areas and are thus monitored with a dense monitoring network. From the monitoring data, detailed information can be obtained on benthos composition and bottom characteristics (e.g. Brils et al., 1993; Van Dalfsen and Essink, 1997).

5.1.5.5 Research into the effects of beam-trawl fishing

Beam trawls disturb the upper sediment layer, seriously affecting the bottom fauna present on the seafloor. Many organisms present in the sediment die. In the long-term, an indirect effect is a change in the structure of the benthos community. This issue has been researched extensively, in order to quantify these effects (e.g. de Groot and Lindeboom, 1995). Research into the consequences of beam-trawl fishing activities typically uses multiple sampling techniques. Aside from a Van

Veen grab sampler and a box corer, small trawls and other techniques that allow sampling of large areas (and other organisms) are employed. In this way, this type of research may provide additional information regarding benthos distribution.

5.1.5.6 Research in areas surrounding the NCP

Comparable research has been conducted in the countries surrounding The Netherlands, on occasion within the framework of multinational cooperation. In Germany, the compositions of zoobenthos communities in the German Bight and on the Doggersbank have been studied (e.g. Salzwedel et al., 1985; Kröncke, 1992), along with other subjects. Off the Belgian coast, researchers at the University of Ghent (DeGraer et al.) have conducted extensive research into the relationship between benthos and the physical environment.

In the context of ICES, an attempt is made to coordinate research programs during the next years, in order to make information complementary and compatible, allowing its application as a benthos-mapping tool on the scale of the entire North Sea.

5.1.5.7 Conclusion

Data of the different research projects outlined above are not necessarily useful in determining the relationship between benthos and hydro- and morphodynamics, as much of this research was conducted to address different research questions. Commonly, detailed information is not available. It is clear, however, that more (useful) information is available in a number of cases.

5.2 Applicability of models

Sand-wave migration has been studied in situ by many researchers, including Lanckneus et al. (1991) and Terwindt (1971). The current method for quantifying migration has serious limitations, as data tend to be inaccurate (especially older data). Furthermore, often only the crests are considered, which ignores the major part of the available information. Building long-term data sets and developing objective and accurate methods to process these data will take a considerable amount of time and effort.
Sand waves have been modelled in the past as a direct extension of bedform dynamics in rivers (Fredsøe and Deigaard, 1992). However, the residual current in a tidal environment is much smaller than the steady currents found in rivers. Therefore, the migration velocities of tidal sand waves are one to two orders of magnitude smaller than the velocities attained by dunes in rivers (Allen, 1980). Fredsøe and Deigaard (1992) describe the behavior of finite-amplitude dunes under a steady current. They assume the time-dependence of the flow to be negligible when modeling sand waves in a tidal environment.

Huthnance (1982) was the first to look at a system consisting of depth-averaged tidal flow and an erodible seabed. Within this framework, one can investigate whether certain regular patterns develop as free instabilities of the system. Unstable modes comparable to tidal sand banks were found, whereas smaller modes corresponding to sand waves were not initiated. Hulscher (1996) extended this work by using a model allowing for vertical circulations, and found formation of sand waves was governed by a basic tidal motion that was horizontally uniform and symmetrical in time. Hulscher (1996) showed that net convergence of sand can occur at the top of the sand waves over an entire tidal cycle (see also Gerkema (2000) and Komarova and Hulscher (2000)). In these models, sand waves do not migrate. Hulscher and Van den Brink (1999) showed the predictive ability of their model for sand-wave occurrence. Blondeaux et al. (1999) introduced forcing due to surface waves on top of the tidal motion. These wind waves accomplish a net transport of energy and the authors found migration of sand waves. However, the numerical treatment left many questions about the specific mechanisms behind migration unanswered. Komarova and Newell (2000) extended a linear analysis (Komarova and Hulscher, 2000) into the weakly non-linear regime to investigate the behavior of finite-amplitude sand waves. This later model does not include migration, either.

6 Related studies carried out by the National Institute for Coastal and Marine Management

6.1 Sand extraction on coastal ridges (M. Boers and. J.J. Jacobse)

The framework for this study is the Coast 2005 research program of the Directorate-General of Public Workss and Water Management, which aims at the development of knowledge and region-specific expertise in coastal morphology. Future modifications of the Regional Extraction Plan (RON) may allow sand extraction from tidal ridges located within the –20 m NAP contour. However, high waves may penetrate the coastal areas more easily when the heights of such tidal ridges are decreased by sand extraction. Therefore, a study has been carried out to predict the influence of sand extraction from tidal ridges on the wave conditions along the coast of Zeeland and Zuid- Holland. The effects were studied using numerical wave models.

The coastal ridges are situated seaward of the Delta west of the Zeeland and Zuid-Holland islands. The two northern ridges are connected to the shore at water depths of –15 and –18 m NAP and form the “Bollen van Goeree” (Figure 1). The three southernmost ridges (Schouwenbank, Middelbank and Steenbanken) lie parallel to the coastline. Minimum water depths above these ridges are –10 m to –15 m NAP.

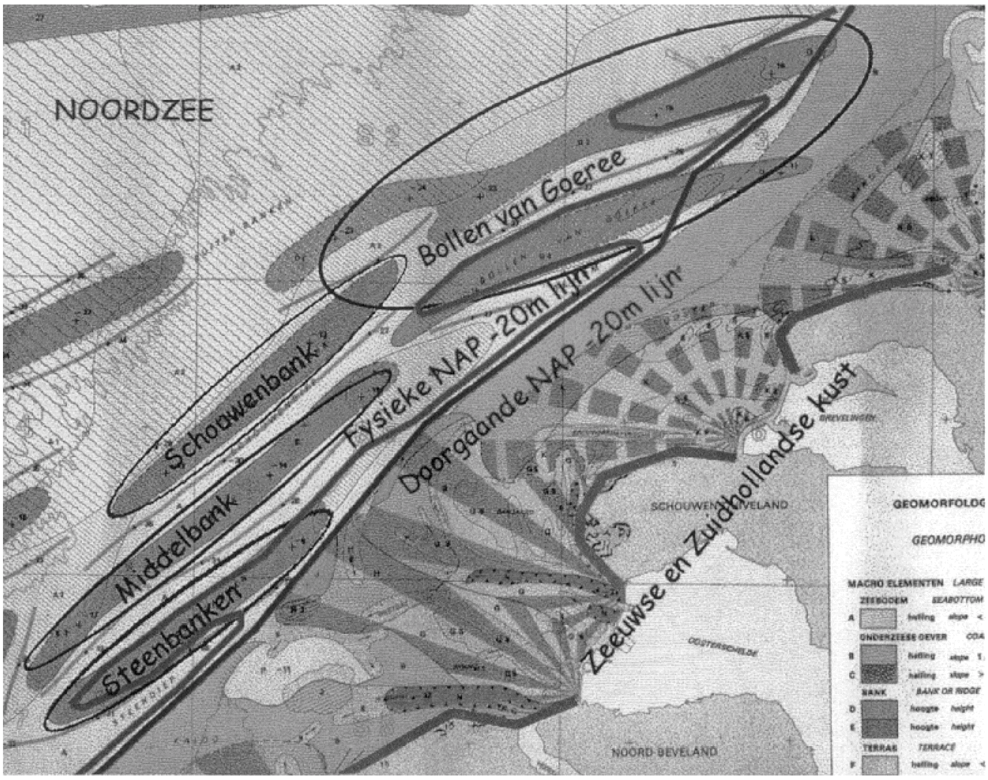


Figure 28 Tidal ridges offshore the provinces of Zeeland and Zuid-Holland.

Identical calculations were carried out with two numerical wave models (SWAN and ENDEC) for a situation *with* coastal ridges and a situation *without* coastal ridges. The situation *without* coastal ridges is achieved by removing all material in the ridges above the –20 m NAP contour. The numerical wave models used in this study consider only short waves, because little is known about the occurrence of long waves (with periods of more than 20 seconds) and their influence on coastal ridges. The SWAN model was run only with boundary conditions occurring once every 4000 years, because the model is rather intensive and time-consuming. With the ENDEC model, calculations with boundary conditions of a higher recurrence frequency could be carried out. The modeling results suggest that the wave conditions along the "Bollen van Goeree" will not be influenced significantly by sand extraction (Figure 29; Table 6), because the ridges are in relatively deep water and the Delta is also important in the dissipation of wave energy. However, the excavations of the southern ridges (Schouwenbank, Middelbank and Steenbanken) do result in a small increase in wave height and a rotation of the wave direction near the coast of Walcheren, especially when the waves approach from the west (Figure 30; Table 7).

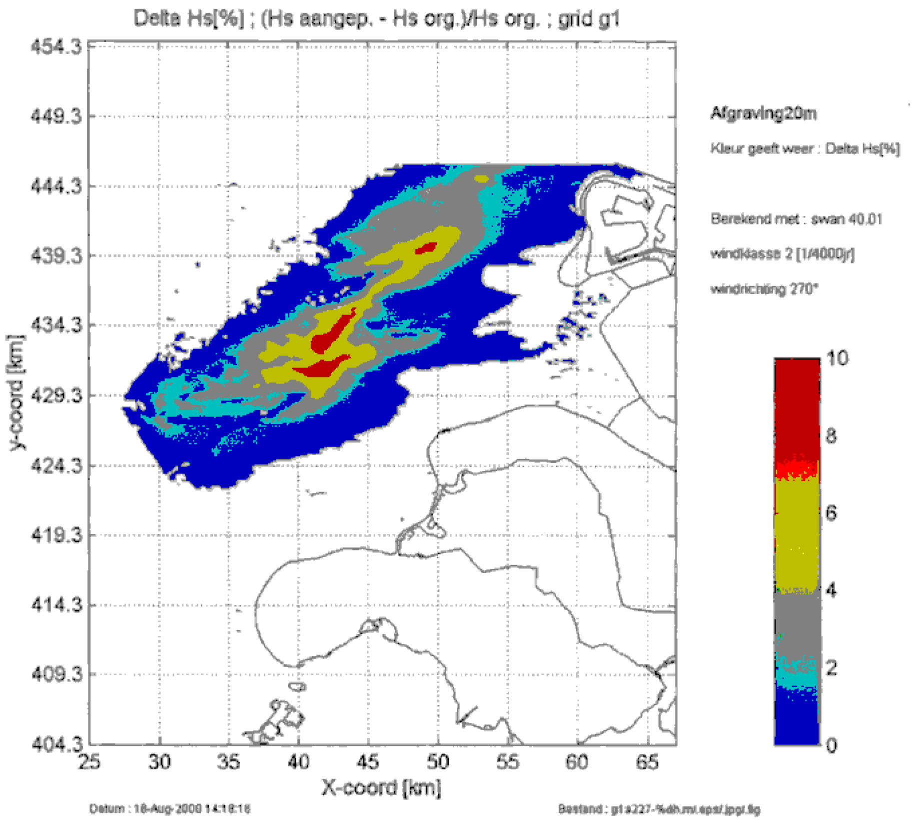


Figure 29 Change in significant wave height upon sand extraction at the "Bollen of Goeree".

Table 6. Change in wave height (Hs) and direction (Th_0) as a result of sand extraction from the sand ridges. Calculation: Goeree W

Position	Water depth (m)	Hs before extraction (m)	Hs after extraction (m)	Th_0 (°)	Th_0 (°)
1	9.16	3.18	3.18	277	277
2	8.77	2.58	2.58	265	265
3	7.19	2.96	2.96	300	300
4	8.24	2.51	2.50	300	300

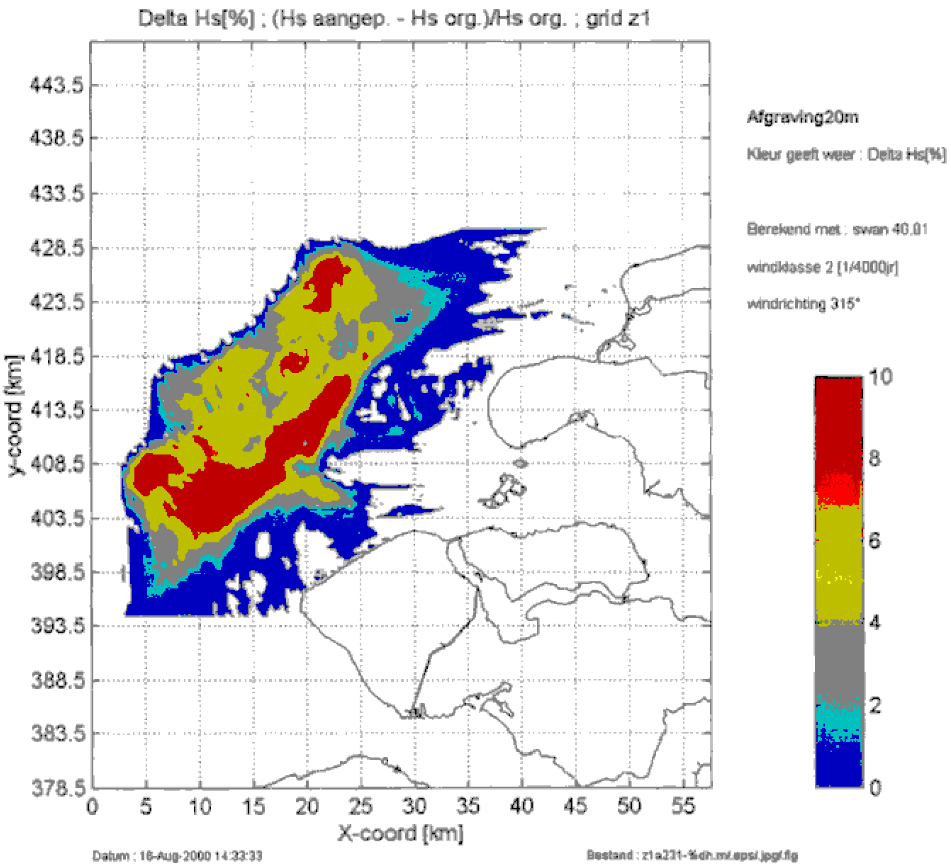


Figure 30 Change in wave height upon sand extraction at the southern ridges.

Table 7 Change in wave height (Hs) and direction (Th_0) as a result of sand extraction from the sand ridges. Calculation: Walcheren W

Position	Water depth (m)	Hs before extraction (m)	Hs after extraction (m)	Th_0 (°)	Th_0 (°)
5	10.62	3.17	3.19	261	261
6	12.10	3.32	3.30	251	252
7	15.70	3.75	3.72	297	297

8	12.73	4.13	4.15	290	290
9	12.42	4.65	4.68	288	288
10	12.82	4.59	4.63	287	288

The higher waves near the coast of Walcheren are caused by the shallower setting of the southern ridges resulting in removal of a larger volume of sand down to the –20 m NAP contour. The effects are most pronounced with boundary conditions occurring every 4000 years, but even then they seem not significant enough to decrease the stability of the coastline. However, the latter assumption should be tested with coastal erosion models. The wave conditions along the Zealand and South Holland islands are strongly influenced by the presence of the Delta. Therefore, the results of this study are not applicable to other areas along the Dutch coast.

6.2 PUTMOR-field measurements (S. Hoogewoning)

6.2.1 Introduction and background

The framework for the PUTMOR-field measurements is the Coast*2000 research program, which aims at predicting the effects of large-scale sand extraction on local and regional morphology and ecology of the seabed. Numerical modeling of two-dimensional water movement and morphology for extraction of 500 million cubic meters below a water depth of -20 m NAP suggests that the dimensions of this large-scale sand extraction have a significant influence on the tidal flow. Deepening of the center of the extraction area can be expected as well as morphological changes in the surrounding area. Especially in the case of increased local depth of the extraction area, information about the (vertical and horizontal) mixing rates is relevant. Increased vertical stratification may result in reduced oxygen levels near the bottom, which may have ecological effects.

6.2.2 Field measurements (PUTMOR project)

The measurements are carried out in the Lowered Dumping Area (LDA), which consists of six future dumping pits with dimensions 1300 m x 500 m x 10 m each. The LDA is located 10 km west of Hoek van Holland, north of the Euromaas channel at a water depth of -22 m NAP (Figures 31 and 32). Lowered Dumping Pit LDP 1 was finished in September 1999 and was studied through field measurements from October 1 1999 till March 31 2000, before dumping started.

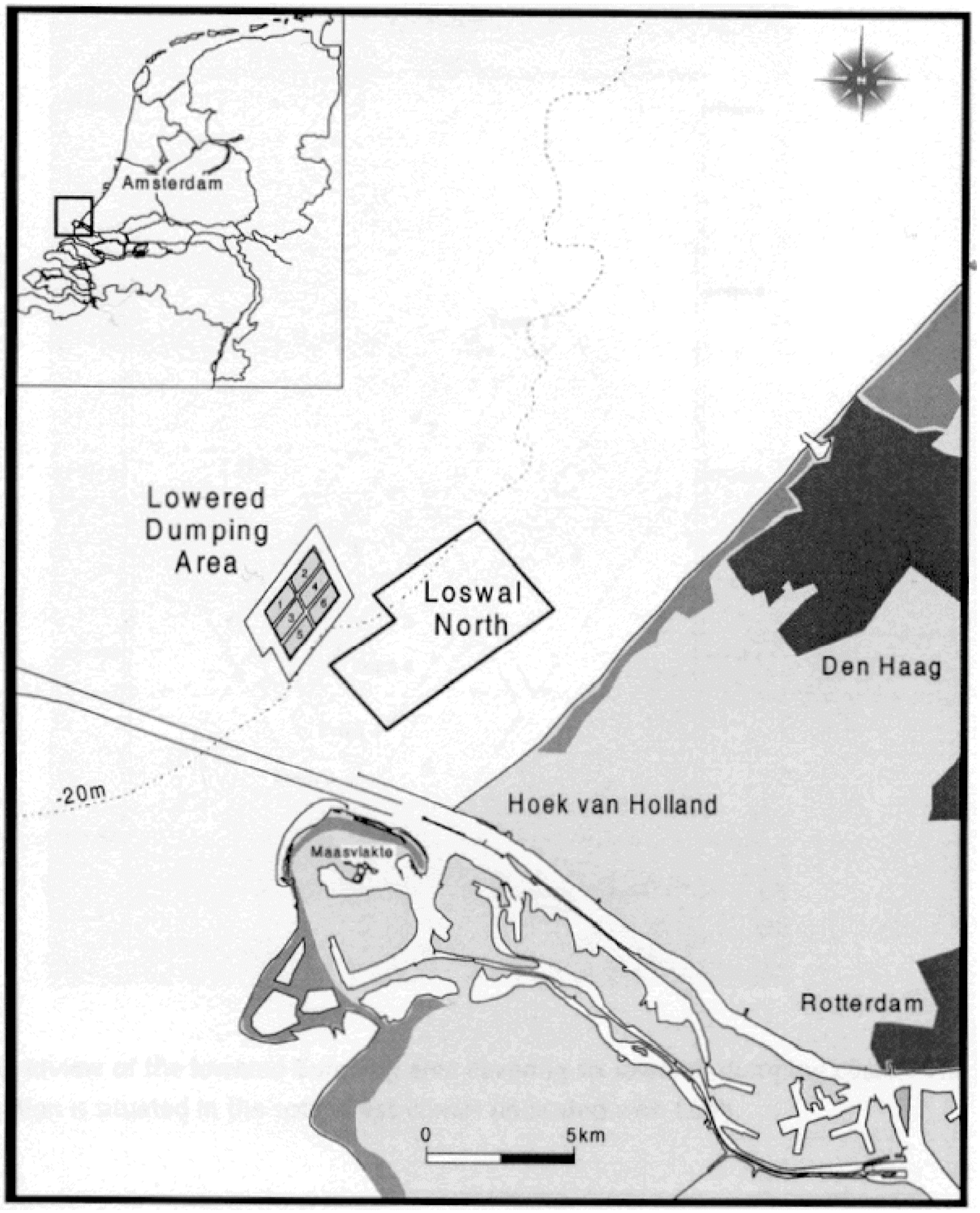


Figure 31 Location of the LDA.

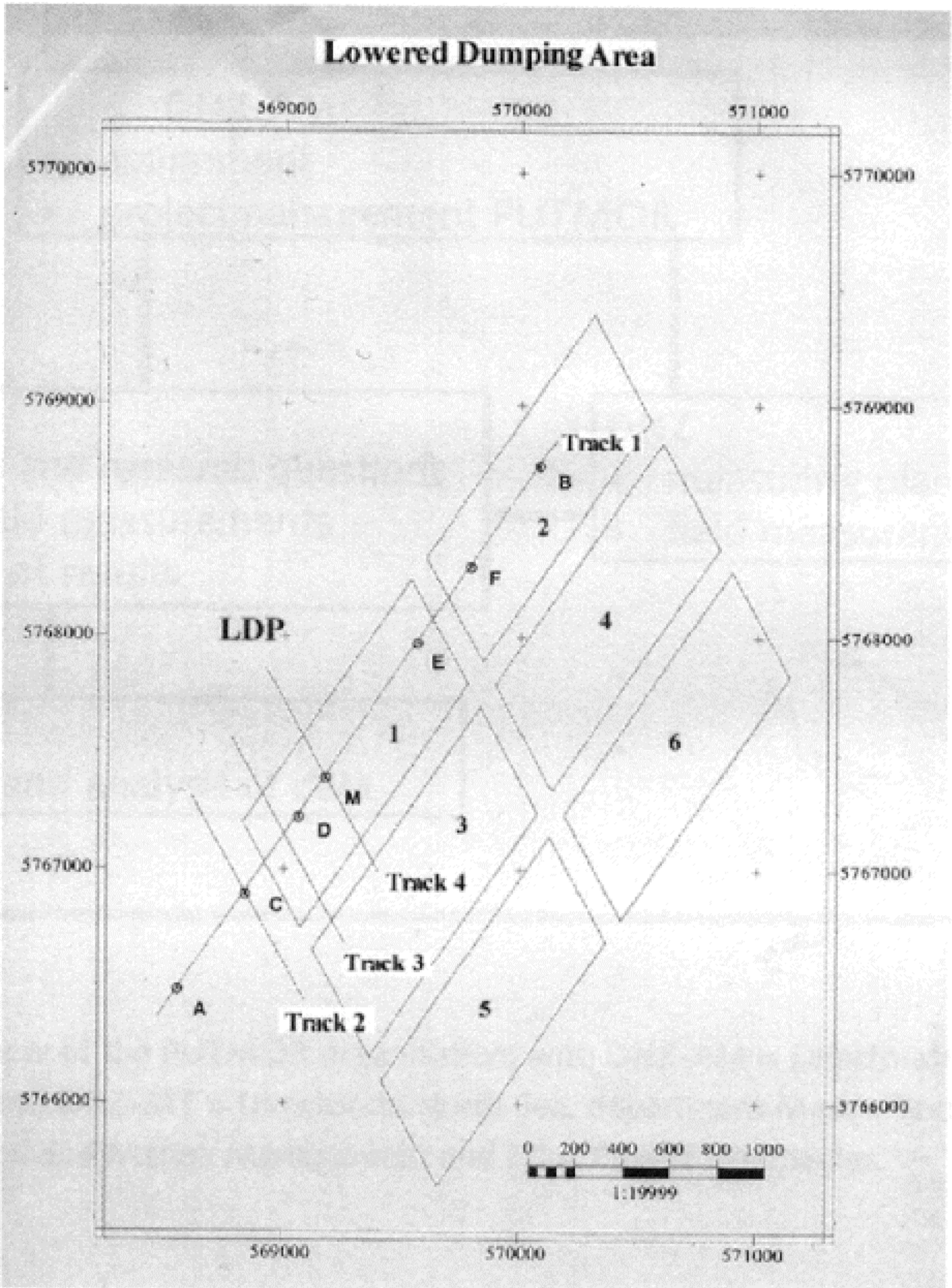


Figure 32 Overview of the LDA.

The PUTMOR measuring plan comprises measurements at *fixed locations* and *shipmounted* measurements. Background data were gathered by RIKZ on: wind speed, wave height and direction, air pressure, freshwater influx from the river Rhine, temperature of the freshwater from the river Rhine.

6.2.3 Preliminary results

6.2.3.1 Measurements at fixed locations:

a) The ADCP is used to measure vertical velocity profiles inside and outside the pit. At this time, no vertical velocity profiles are available yet.
b) Hydrolab data: near-bottom values of temperature, conductivity, water depth, and turbidity inside and outside the pit.
c) Aanderra-string data: temperature and conductivity in vertical profile (5 heights above the seabed) within the pit (Figures 33 and 34).

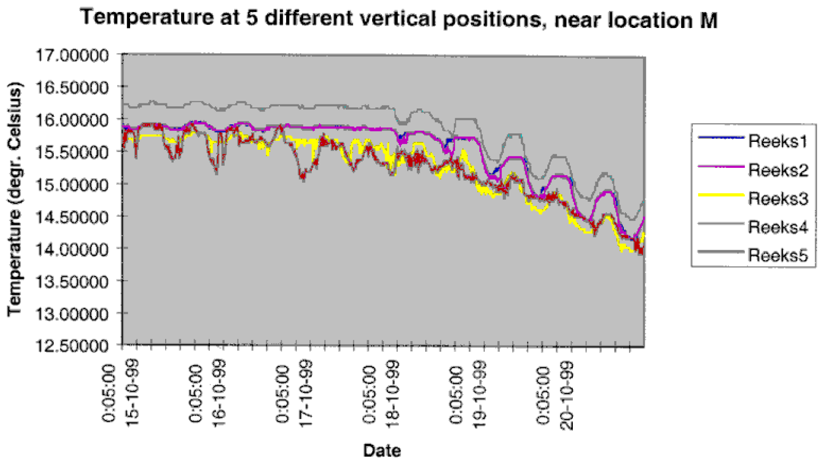


Figure 33 Example of temperature measurements.

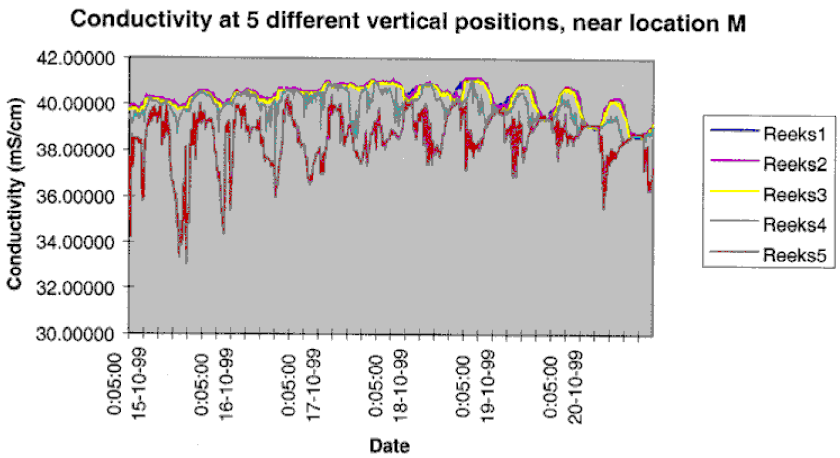


Figure 34 Example of conductivity measurements.

The temperature data from the Aanderra-string need to be adjusted for systematic errors and then compared to those from the Hydrolab, air temperature, and the Rhine discharge to explain the observed vertical distribution.

d) The MORS data consist of near-bottom (+1 m) measurements of temperature and pressure at location B outside the pit (Figure 32). The temperature measurements should be regarded as a backup for more reliable temperature measurements by the Hydrolab and Aanderra-string. The main purpose of the MORS is its relatively precise and reliable measurement of local pressure (Figure 36), which is used to monitor the tidal variation. When local air-pressure data are available, mean sea level (MSL) is calculated in order to check the values for local bottom depths from the bathymetric surveys (see below).

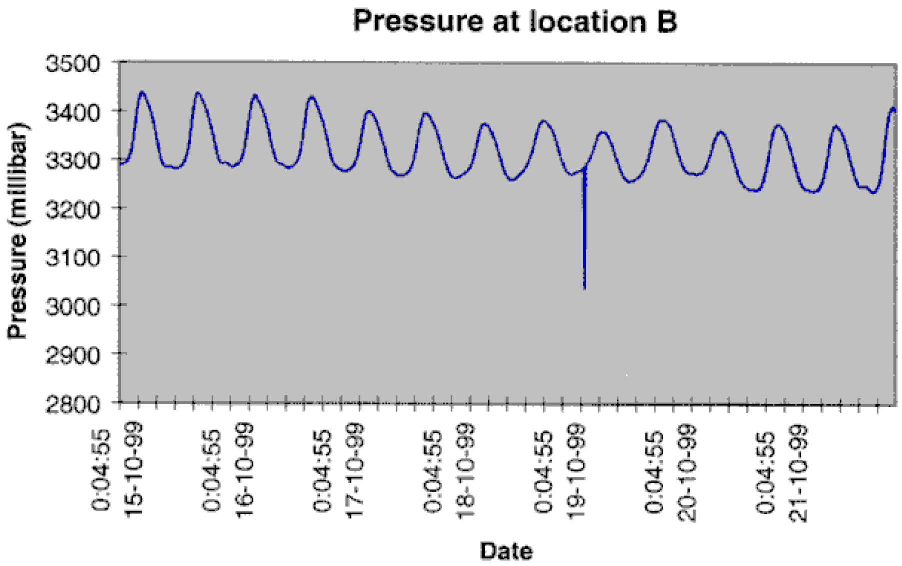


Figure 35 Local air-pressure data.

6.2.3.2 Shipmounted measurements

a) Aboard the m.s. Mitra, two ship-mounted velocity surveys using an ADCP took place, one in November 1999 and one in March 2000. Measurements were carried out around spring tide, when differences in water movement between the areas outside and inside the pit are expected to be the largest. The ADCP was fixed to a measuring fish and positioned just beneath the water surface. Four pre-defined tracks were measured (at maximum flood and at maximum ebb) to establish differences in the tidal flux outside and inside the LDP. Results of the ship-mounted ADCP are comparable to those of the fixed locations, however, the former results need to be corrected for the movement of the ship and for deviations of the ship track.

b) At most twice a week vertical profiles of temperature, conductivity, turbidity and oxygen were measured within and outside the pit (locations A and M, Figure 37).

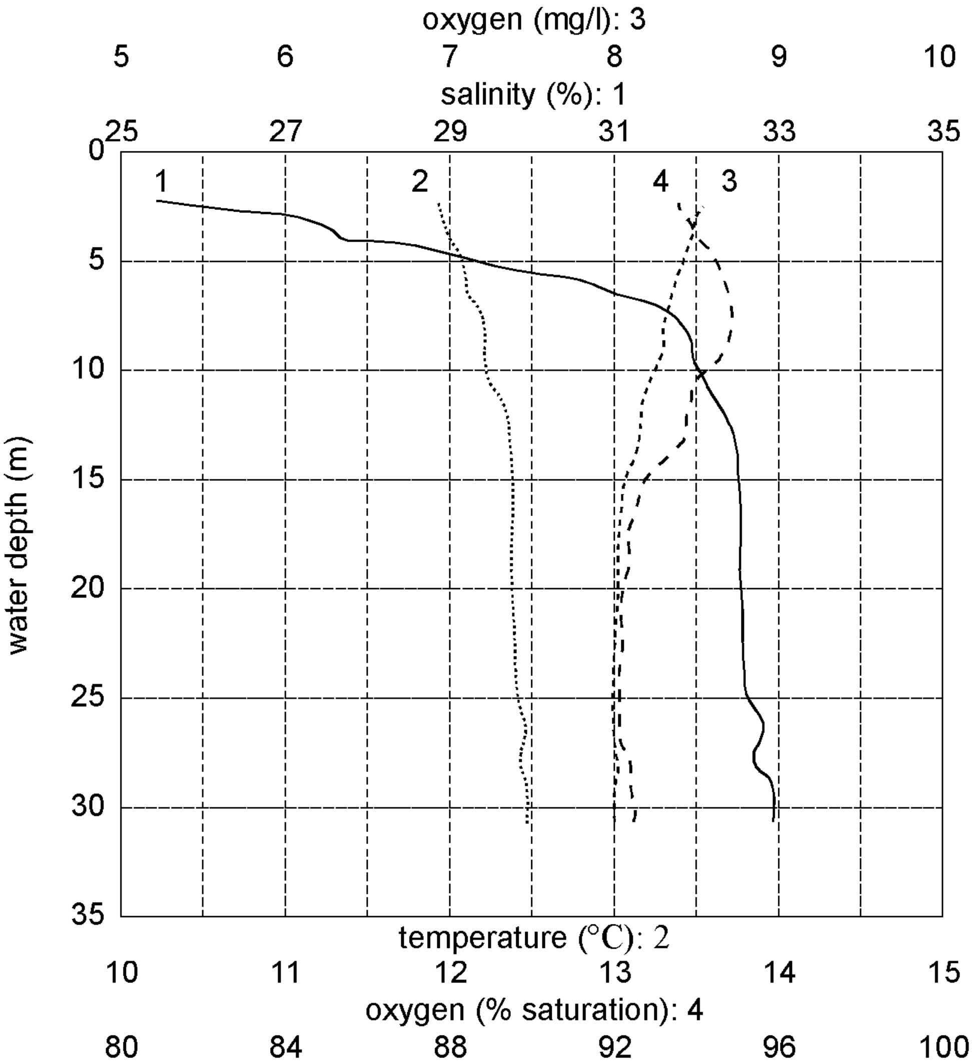


Figure 36 ADCP profiles of temperature, conductivity, turbidity and oxygen

c) Monthly bathymetric surveys using multibeam equipment were scheduled, but as a result of bad weather only 4 surveys were carried out in the 6-month PUTMOR measuring period. The resulting bathymetric data will be presented with respect to MSL after correction for tidal water-level variation using fixed MORS measurements and will be interpolated to a rectangular grid of 5 x 5 m.

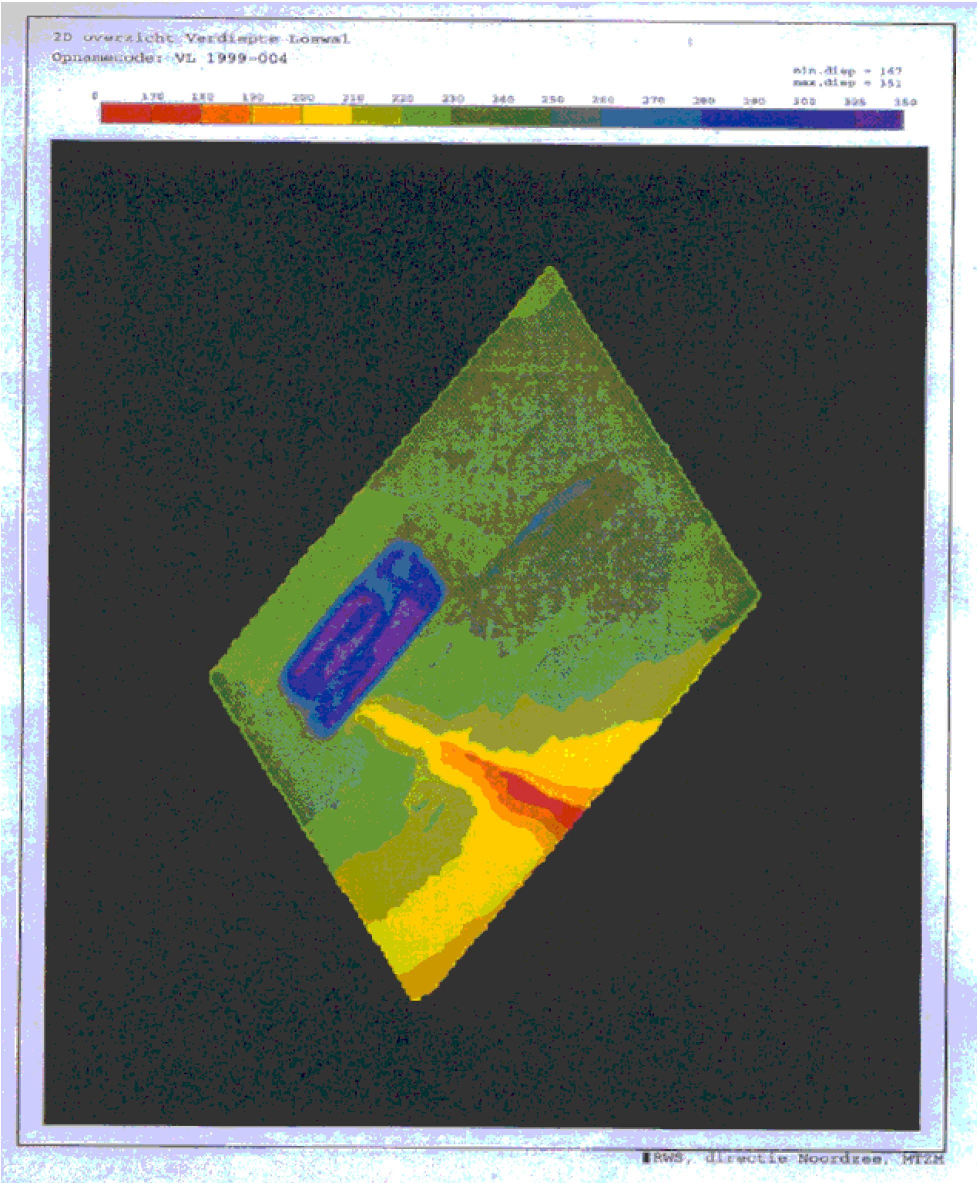


Figure 37 Multibeam image of the LDP.

d) Sampling of undisturbed sediments at nine locations inside and outside the LDP took place in January and March 2000 (0.25 cm Van Veen sampler and 0.5 m boxcores). Grain-size distributions were determined by the Lab of RIKZ in Middelburg and the results will be used to determine differences in sediment between the areas inside and outside of the LDP and to monitor erosional or accretionary processes.

6.2.3.3 Processing and analysis of the field data

Processing and analysis of the field data is carried out by third parties under contract with RIKZ. The analyses will probably be completed in September 2001.

Processing of the raw field data will be presented in a “data report”. Validated field data will be stored in the DONAR database (Rijkswaterstaat). Analysis of the data will be presented in an “analysis report” and a final report will be produced, summarizing the data processing and analysis.

6.3 Feasibility study large-scale sand extraction and dumping

6.3.1 Introduction

Within the framework of ICES-1, Ballast Nedam and RWS-RIKZ carried out the research program “Sand management” between 1995 and 1999. This research resulted in a joint initiative to study the possibility of a large-scale field experiment. This feasibility study was conducted in 2000 by the two initiating parties, along with RWS-North Sea Directorate, RWS-Civil Engineering Division, and Delft Cluster (GeoDelft and TNO-NITG). The results have been presented to potential clients, and a project proposal has been written.

The proposed project aims primarily at reduction of uncertainties associated with possible land reclamation associated with Project Mainport Development Rotterdam. At the same time, it will result in improved insight into problems concerning:
Exploration of sand for concrete and masonry,
Long-term maintenance of the coast, and
Construction of an airport in the North Sea (Flyland).

6.3.2 Purpose of a large-scale experiment

The specific purpose of the experiment is reduction of uncertainties associated with construction of a large-scale underwater sand pit and of a large-scale artificial sand body. These uncertainties concern design- and construction-related aspects with respect to construction and exploitation, as well as various effects at different spatial and temporal scales. Owing to a lack of field data, most physical models used for design and for prediction of effects cannot be validated. Yet, morphological model runs are very sensitive to formulation of sand transport and to local depth-determined boundary conditions. For water depths greater than 10 m, only 7 sets of field data are available from the literature, none of which are representative of North Sea conditions.

At present, the accuracy and reliability of model runs are unknown. A proper decision-making process, including comparison of different scenarios, is hampered by this uncertainty. Reducing this uncertainty requires improvement of the predictive models. Many of these models can be improved significantly by conducting a large-scale field experiment that includes measurements (and analyses of these measurements) of a sand pit and an artificial sand body. Central issues are:

A. Uncertainties regarding effects following construction
A.1 Hydraulic and morphological effects relevant to nautical accessibility
A.2 Morphological effects relevant to maintenance of reclaimed land, coast, offshore channels, and sediment cover on cables and pipelines
A.3 Disturbance and recovery of bottom fauna at the locations of the sand extraction and deposition (caused, for example by changes in oxygen contents, in a shallow and a deep pit)
A.4 Changes in the transportation of mud, nutrients, and fish larvae

B. Uncertainties regarding effects during construction
B.1 Increased water turbidity during various sand-extraction and dumping processes
B.2 Efficient dumping process (where does the sand end up?)
B.3 Slope instability in deep sand-extraction pits with steep slopes, caused by compaction-related liquefaction

C. Uncertainties regarding construction-technical aspects
C.1 Feasibility of the application of geocontainers and/or geotubes in large-scale offshore constructions
C.2 Feasibility of methods of dumping sand in such a way that steep slopes and dense packing are possible
C.3 Feasibility of new dredging techniques (e.g., fractionation)

6.3.3 Components of a test

6.3.3.1 Construction of a sand pit and an artificial sand body in the North Sea

The experiment concerns construction of a sand pit and an artificial sand body in the North Sea. The dimensions of the pit and dump must be sufficient to allow observation of both small- and large-scale effects. Accordingly, the quantity of sand that must be moved has to be at least 2 million m^3 and does not have to exceed 5 million m^3.

Subsequent to construction, natural marine processes will be allowed to reshape the pit and dumping area. Many variables will be measured over the course of many years. It is expected that any effects following the completion of these measurements will not require compensating measures. The dump will be planned at a location that would be a good candidate for sand nourishment.

6.3.3.2 Measurements before, during, and after construction

Measurements will be made during a 10-year period. They will provide:
Hydrodynamical data (water levels, currents, and waves),
Morphodynamical data (bathymetry, seafloor characteristics, seabed morphology, sediment concentrations, etc.),
Ecological data (water and seabed-sediment quality, turbidity, fauna and flora, etc.),

Geological and geotechnical data (stratification, grain-size distributions, mineralogical composition, packing, etc.),
Data regarding dredging process and dumping/spraying process (frequent bathymetric surveys; location and movements of pipes for sand extraction and deposition, coupled to external conditions; speeds, concentrations, and grain-size distributions of sediment-water mixtures within the pipes; cone-penetration tests in dumping area, etc.),
Data regarding construction and positioning of geocontainers and geotubes (behavior of material, behavior of geocontainers and geotubes, etc.).

6.3.3.3 Analysis of results and improvements of predictive models

The measuring program and the number of analyses ensure reduction of various uncertainties, as mentioned above.

6.3.4 Location of the pit and dumping area

Table 8 provides several conditions that must be satisfied by the locations:

Table 8 Prefered location characteristics

Sand-extraction pit	Depth and location	arguments
	Just seaward of the NAP – 20m line	No permit for area landward of the NAP – 20m line; shallower areas are characterized by a more dynamic environment (can be measured more easily)
	North of the Euro Channel, south of Noordwijk	Close to the dumping area, within the area covered by the MER “Verdiepte Loswal” and the MER “Beton- en Metselzand
	Availability of coarse sand and/or gravel	Study on realization of steep slopes; study of extraction techniques for sand and gravel
	Outside shipping lanes	Interference of measurements with shipping
	Far from cables and pipelines	
Dumping area	Large-scale nourishment with seaward boundary between depth contours NAP -10m and NAP – 15m	As close to the coast as possible; even more landward would result in a top too close to the water surface and/or too gentle a slope; also, it would provide accessibility difficulties
	Location Delfland; integration with shoreface nourishment between km 107.5 and 112.5 or	Delfland is one of the weakest links along the Dutch coast; pilot study on possibilities of large-scale coastal maintenance
	Location between Scheveningen and	Offers possibilities for experiment at location

Noordwijk Outside shipping lanes and far from cables and pipelines	with smaller direct risks

7 Discussion of 2000 results and plan for 2001-2002

7.1 Introduction

The first data-acquisition activities, in August-September 2000, have resulted in a data set that can be used to characterize the eco-morphology of the research areas in a genaral way. Some overall patterns and relationships can be identified. More detailed analyses, however, are not possible using the data collected thus far. Several of the instruments used proved inadequate for seabed characterization, limiting progress in ecological work and hampering efforts to identify specific links among ecological and morphological variables. For 2001, we anticipate much improved results, as up-to-date instruments are now available for acquisition of morphological data. The experience of 2000 forms the basis of a protocol for data acquisition aimed at maximizing the efficiency and success rate of the research.

7.2 Multibeam echo sounder

The Kongsberg Simrad EM 100, installed aboard the m.s. Zirfaea, has a relatively narrow path width. In shallow water, the required 20-25 m track-line spacing, combined with the fact that all data had to be collected in tracks along the width of the areas, resulted in very inefficient data collection. Each 1 km x 2.5 km area required about 36 hours of non-stop acquisition. The first series of multibeam measurements also confirmed earlier observations that the EM 100 does not allow accurate imaging of the seafloor in water depths below 15 m. On the basis of this previous experience, the shallowest research area, selected to study the lower shoreface, had to be shifted to somewhat deeper water than was intended originally. Despite this adjustment, the image quality achieved was low for all three areas. So-called asparagus fields, apparent ridge-and-swale topography along the length of the images, dominate the records. These features are caused by far-beam errors. In the meantime, the EM 100 has been removed from the m.s. Zirfaea.

Future measurements will be made with the more advanced Kongsberg Simrad EM 3000, which was designed specifically for imaging shallow-water areas. This hull-mounted system is installed on the m.s. Arca. Experiences with the EM 3000 system have been very positive. Research area B will be shifted back to the upper shoreface, in accordance with the original plan.

7.3 Side-scan sonar

Although acquisition of data using the Dowty side-scan sonar went smoothly, the quality of the resulting images is low. The system aboard the m.s. Zirfaea suffers from interference when the fish is towed at a depth less than 9 m below the sea surface. In shallow water, this fact has severe implications. Curiously, a similar system, available on the m.s. Arca, does not suffer from this problem. Therefore, we anticipate much better results in 2001.

It will not be possible to create large mosaics combining all side-scan-sonar images of each area. Traditionally, such mosaics were made by hand, but this procedure is no longer feasibly, owing to financial reasons. Software designed to perform this task in an automated way is unable to create smooth transitions between adjacent images. We will attempt to link small mosaics of relevant features with the associated multibeam images.

7.4 Box corer

Sample collection with the box corer proved to be a success. The sandy nature of the seafloor sediment made sieving of the samples on board easy. Some slight protocol adjustments will be implemented to ensure maximum-quality macrozoobenthos samples.

At this time, processing of the samples is still in a preliminary stage. Analysis of all samples on a seasonal basis is not feasible; therefore, choices have to be made. Strategically, it is important to test whether or not variability in sedimentological and ecological parameters within one sample cluster is significant. Knowledge on this point will answer one specific research question posed in the project proposal. Also, if such variability is negligible, it will limit the number of samples to be analyzed significantly, reducing the workload and increasing the feasibility of the proposed research.

7.5 Frame with sensors

The experiment with frame-mounted sensors showed that observation of real-time sediment transport is not possible in the study areas at the present time. The error associated with the sensors resulted in an accuracy insufficient to resolve the transport operating on the seafloor.

In 2001, we intend to approach the sediment-transport question by means of a different, indirect methodology. Series of multibeam images, recorded during a tidal cycle, will be compared using temporary location markers placed on the seabed. We hope to resolve bedform migration and, indirectly, to derive rates of sediment transport for several seasons. When achieved, this revised objective will serve as an appropriate starting point for more accurate sediment-transport measurements in the future.

7.6 Beam trawl

The beam-trawl measurements were successful. This method I very useful in determining demersal fish stock on the North Sea floor, but should not be relied on for shellfish and other macrobenthos counts. In planning the beam-trawl surveys, their impact on the seafloor deserves consideration. The box cores should be planned in areas unaffected by the beam-trawl surveys; also, the surveys should preferably be completed before multibeam and side-scan-sonar data are recorded, so that the tracks can be identified.

7.7 Protocol for data acquisition

The experience of 2000 forms the basis of a protocol for data acquisition aimed at maximizing the efficiency and success rate of the research. The North Sea Directorate has included much of this protocol in a measuring plan encompassing the multibeam and side-scan-sonar surveys, the box-coring activities, and several related issues (calibration with tide data, meteorological observations).

7.7.1 Multibeam survey

To achieve 100% coverage, the multibeam images will first be recorded with trackline spacings of 20 m (area A), 25 m (area B), and 40 m (area C). As the EM 3000 will be used, this spacing will probably be doubled in subsequent measuring sessions. The trackline orientations are 036/216° (area A), 040/220° (area B), and 016/196° (area C). The data will be stored on a Sun Work Station.

To monitor seafloor roughness during the recording, a Deso-25 singlebeam echo sounder will be used. Data recorded by this instrument will be stored in PDS-1000. The paper speed will be 1:2000; the other parameters will be set as the usual default values for singlebeam recordings, but with MB offsets.

The sound velocity in the vertical will be determined using a sound-velocity probe several times: before the multibeam survey, after the multibeam survey, and at least once every 24 hours.

7.7.2 Side-scan-sonar suvey

The sonar recordings will be made using a Dowty system. To ensure optimal results, the fish should be positioned between 10 and 15 m above the seafloor. This aspect requires constant attention on board during the recording. The orientation of the tracklines is the same as for the multibeam lines, but the spacing is 50 m for all areas.

The recordings are made using a seafloor path width of 100 m and are stored on ISIS optical disks. The operator will mark possibly interesting events on the paper records and on the plot lists.

7.7.3 Box coring

The current strategy for box-core collection will be discontinued. The latest insights from TNO-MEP show that it is more economical to sample according to a less rigid scheme. Multibeam images should be used to plan sample locations, as these images allow identification of morphological units and gradients. The multibeam data are also useful in assigning degrees of importance to the samples, so that the most relevant samples can be analyzed first.

The same box core should be used to collect the sample for sedimentological analysis and to provide the macrobenthos sample. In separating the macrobethos from the material smaller than 1 mm, a protocol provided by TNO-MEP should be followed.

7.7.4 Beam-trawl survey

Preferably, this survey should take place shortly before the other surveys, in particular the side-scan activities. The side-scan images can be used to identify and to assess the freshness of the beam-trawl tracks.

7.8 Plan for 2001

7.8.1 Nature and scope of the problem

Ecologically and socially justified management and use of the North Sea requires proper integration of field measurements and knowledge regarding the ecomorphodynamics of the North Sea. Such integration has not yet been accomplished, owing to a lack of reliable, high-quality data. Currently, there is no consensus on dominant mechanisms. Also, few suitable measurements have been made on the actual morphodynamics of the seafloor, neither under natural circumstances, nor after human intervention. In addition, the relationship of this morphodynamic behavior to sediment transport and the interaction of morphodynamic processes with macrozoobenthos on the seafloor have been subject to very little research.

This lack of accurate measurements and a lack of clarity about the relative importance of different natural processes hamper evaluation of existing models that suggest a strong interaction between human interventions and natural processes on the same scale. The project “Ecomorphodynamics of the North Sea floor” aims at a process-based approach of the dynamics of small- and large-scale phenomena on the sea floor, both in the short term and in the long term.

Within the framework of the project, a number of objectives can be identified:
(1) measuring and analyzing morphodynamics at a number of North Sea sites under natural circumstances (changes of the lower shoreface, shoreface-connected ridges, and sand-wave areas);
(2) initiating quantification of morphodynamic processes, on the basis of both measurements and idealized models;
(3) initiating determination of the role of zoobenthos in eco-morphodynamic processes and sediment characteristics;
(4) creating a database enabling modeling of sediment transport and eco-morphodynamics in the North Sea under natural circumstances.

7.8.2 Anticipated results

7.8.2.1 Long-term (2001-2010)

One of the primary objectives of the Delft Cluster program is expansion of the existing capability to predict the eco-morphodynamics of the North Sea to such an extent that long-term consequences of large-scale man-made structures are properly understood. This primary objective can be met by achieving three secondary objectives:

(1) creating a database of seafloor eco-morphodynamics;
(2) developing a coherent network of models developed to predict the eco-morphodynamics of the North Sea floor on different temporal and spatial scales, and supplying quantitative quality indicators for predictions made using these models;
(3) predicting long-term ecosystem response to natural morphologic changes and to large-scale and repeated small-scale activities by man.

From the perspective of this final secondary objective, we participate in the RIKZ-led initiative “Field Research Large-Scale Sand Extraction and Dumping”. The feasibility of this research is the subject of a study that is currently being completed. A positive outcome of this study will increase the probability of sector-subsidized research into the eco-morphodynamic response of the North Sea floor to large-scale human activities.

7.8.2.2 Duration of the project (2001-2002)

Within the duration of the project, we will pursue:

(1) acquisition and analysis of a data set concerning the morphology and morphodynamics of the seafloor, trying to achieve a high temporal and spatial resolution (this data set may serve as a t_0 measurement for possible field research regarding large-scale sand extraction and dumping);
(2) evaluation of existing morphodynamic models on their suitability to make long-term predictions, identification of the most important gaps in current knowledge and of any limits in predictability;
(3) evaluation of existing knowledge regarding the zoobenthos of the North Sea floor;
(4) initiation of ecological system descriptions and prediction methods (approach as dynamic systems, rather than orientation on species), on the basis of observation-derived causal relationships;
(5) initiation of a dynamic model in which the eco-morphodynamics of the North Sea floor is coupled to natural processes;
(6) development – from the analysis of field observations and other information – of a rapid method for the classification of seafloor sediments.

7.8.2.3 Short-term (2001)

In the short-term, central issues are:

(1) continuing evaluation of existing knowledge (data and models) and predictive methods regarding the eco-morphodynamics of the North Sea floor, and identification of the most important gaps in current knowledge;

(2) acquisition of field data (multibeam and side-scan-sonar records and box cores) that provide insight into the changing seafloor morphology and will allow coupling of physical and ecological factors;
(3) continuing analysis of existing field data that provide insight into the changing seafloor morphology;
(4) initiation of dynamic ecological system descriptions and predictive methods;
(5) initiation of a dynamic model coupling eco-morphodynamics to natural processes.

7.8.2.4 Products

(1) reports;
(2) scientific publications, both at scientific meetings and in peer-reviewed journals;
(3) technical publications in specialist literature;
(4) popular-scientific publications;
(5) web site (with access to reports and publications), functioning as a resource to potential end users of collected knowledge.

7.8.3 Activities and planning for 2001

1	Selection of weeks during which data will be acquired Products: none	January
2	Completion of progress report 2000, including project plan 2001 and accompanying spreadsheet Products: report, plan, and spreadsheet	January-March
3	Continuing evaluation of relevant available data and of gaps in current knowledge Products: report sections with literature and data overviews for ecologic, morphologic and model components; seabed sediment map; coupling to RIKZ Kust2005 reports	January-May
4	Development of hypothesis (on the basis of the first measurements, existing data, and theory) that can be confirmed or rejected via measurements Products: see activity 3	January-May
5	Construction of web site Product: TNO-NITG web site, hyperlinked to partner web sites and to Delft Cluster web site	January-May
6	Data acquisition (four times until the end of 2001 to identify seasonal variability) in three North Sea areas, using multibeam and side-scan sonar, and processing of field data to enable further analysis Products: digital multibeam data in 1 x 1 m grid (mean depth), color maps at scale 1:2500 with suitable depth intervals, for each area three profiles, profiles of changes; side-scan-sonar data on optical disk, and selected areas as hard copy; basic geologic maps	March-December
7	Collection of box cores and other data required to analyze sediment characteristics and bottom fauna for selected areas Products: sedimentologic core descriptions, macrozoobenthos analyses	March-December
8	Data acquisition using beam trawls to determine distributions of demersal fish and shellfish; collection of data on fisheries activities Products: species list per area, micro-distribution data	March-December
9	Interpretation of new data Product: integrated (ecology and morphology) progress report with t_0	March-December

	information for sector	
10	Incorporation of the zoobenthos factor into sedimentation and morphodynamic models as soon as sufficient indications of interactions between ecology and seafloor morphology are available Product: first version of model	March-December
11	Development of a plan for 2002, focusing on: analysis of temporal and spatial zoobenthos variability related to morphodynamics (sedimentation and erosion rates); initiation of a model-based extension of a series of measurements in time and space Product: project plan 2002	December
12	External audit Products: none	December

This schedule is feasible when the first measurements are made in March 2001.

7.8.4 Project organization

TNO-NITG (C. Laban, A.J.F. van der Spek, S. Passchier, S. van Heteren, P.C.M. van der Klugt, P.C. Zonneveld, L.R. Pijl)

- Project management. Products: project plans 2001 and 2002, progress reports 2001 and 2002.
- Formulation of a number of specific research objectives that are both relevant and feasible. Product: section of report.
- Field research, data processing (multibeam and side-scan sonar through RWS-DNZ, sediment sampling) and staffing of the ship. Products: series of measurements and other field data.
- Construction of a seabed-sediment map with sediment characteristics. Product: map.
- Integration and presentation of existing and newly collected data regarding the morphodynamics and sedimentology of the North Sea floor. Product: section of report.

WL (M. Baptist, M.B. de Vries, J.A. Roelvink, A. Crosato)

- Evaluation and analysis of ecological data, and in particular of process-response knowledge and gaps in the current knowledge of ecomorphology. Study of three topics: benthos distribution on the basis of maps, charts, and other sources (NIOZ en RIVO data); effects of fisheries and sand extraction on benthos; and interaction between morphology and ecology on the North Sea floor. Product: section of report.
- Initiation of modeling of seafloor dynamics. Products: model, section of report.
- Development of plan for full-scale physical experiment, to be conducted after 2002.

UT (S.J.M.H. Hulscher, M.A.F. Knaapen)

- Description (by means of idealized models) of dominant processes in seafloor evolution. Initiation of integrated modeling of natural behavior and human activities. Initiation of modeling of seafloor dynamics. Products: model, section of report.

- Analysis of existing field data for the Eurogeul access route. Product: section of report.

RIVO (F. Storbeck, assistants)

- Supply of information on repeated small-scale disturbances of the North Sea floor that are the result of fishery activities. Product: map.
- Collection of data on the distribution of demersal fish and shellfish. Product: species lists.

TNO-MEP (J. van Dalfsen, N.H.B.M. Kaag, H. Hoornsman)

- Evaluation and analysis of data regarding the bioturbation of the North Sea floor by organisms. Product: section of report.
- Identification and quantitative analysis of zoobenthos from collected box cores. Products: species lists, section of report.

Oceanographic Company of the Netherlands (C.N. van Bergen Henegouw, R. Morelissen)

- Analysis of multibeam image series with a high temporal resolution. Product: protocol for processing with software, section of report.

RIKZ (S.E. Hoogewoning, J.P.M. Mulder, J. de Vlas)

- Analysis of field measurements on the physical effects of a deep extraction pit on the North Sea floor. Data regarding bathymetry, current speeds, water level, temperature, conductivity, seabed sediment, and turbidity are collected to determine the effect of the pit's presence on current-speed distribution, on possible formation of stratification within the water column, and on morphological changes inside and outside the pit. Product: KUST2005 report.
- Feasibility study of the possibility for multi-year field research on the effects (physical and ecological) of large-scale sand extraction and dumping off the Netherlands coast. Products. Final report feasibility study, plan for field research.
- Audit (J.P.M. Mulder en J. de Vlas).

7.8.5 Budget and financing

The budget for 2001 reflects commitments of the participating Delft Cluster partners, the participating sector (P) and the contributing sector (C). For 2002, the possibility exists that the contributing sector will make a financial contribution, dependent upon the outcome of the aforementioned feasibility study.

DC-partners	activities	ICES budget 2001	Own budget 2001	Sector budget 2001	ICES budget 2002
TNO-NITG	management and audit	5.476	4.694	0	92.063
	literature study and fieldwork preparation	4.889	4.191	0	
	data-acquisition	39.975	34.265	0	
	data processing and reporting	38.108	32.662	0	
TNO-MEP	literature study,	26.438	22.662	0	17.490

	fieldwork preparation, and reporting				
WL	management	4.536	0	0	53.284
	data acquisition	7.560	0	0	
	data analysis and reporting	11.076	0	0	
	model comparison and reporting	0	42.840	0	
P-sector	**activities**	**ICES budget 2001**	**Own budget 2001**	**Sector budget 2001**	**ICES budget 2002**
UT	model comparison and reporting	35.619	30.531	0	76.327
	data analysis and reporting	40.708	34.892	0	
RIVO	literature study and data supply	18.695	16.025	0	16.972
	data acquisition	14.388	12.332	0	
OCN	data processing and reporting	24.446	20.954	0	14.669
C-sector	**activities**	**ICES budget 2001**	**Own budget 2001**	**Sector budget 2001**	**ICES budget 2002**
RIKZ	study and report offshore sand pit	0	0	191.500	0
	feasibility study	0	0		0

Summary of the information listed above:

DC-partners	**ICES budget 2001**	**Own budget 2001**	**Sector budget 2001**	**ICES budget 2002**
	138.058	141.314	0	162.837
P-sector	**ICES budget 2001**	**Own budget 2001**	**Sector budget 2001**	**ICES budget 2002**
	133.856	114.734	0	107.968
C-sector	**ICES budget 2001**	**Own budget 2001**	**Sector budget 2001**	**ICES budget 2002**
	0	0	191.500	0
Total	271.914	256.048	191.500	270.805

8 References

Allen, J.R.L., 1980, Sand wave immobility and the internal master bedding of sand wave deposits, Geol. Mag. 117 [5], 347-446

Blondeaux, P., Brocchini, M., Drago, M., Iovenitti, L., Vittori, G., 1999, Sand waves formation: Preliminary comparison between theoretical predictions and field data, IAHR symposium on River Coastal and Estuarine Morphodynamics, Genova, Italy, Proceedings, Volume 1, 197-206

Cadée, G.C., 1976. Sediment reworking by Arenicola marina on tidal flats in the Dutch Wadden Sea. Neth. J. Sea Res. 10 (4), 440-460.

Eckman, J.E., A.R.M. Nowell & P.A. Jumars, 1981. Sediment destabilisation by animal tubes. J. Mar. Res. 39, 361-374.

Fager, 1964. Marine sediments: effects of a tube-building polychaete. Science 143, 356-359.

Fredsøe, J. and Deigaard, R., 1992, Mechanics of coastal sediment transport, Institute of Hydrodynamics and Hydraulic Engineering, Technical University of Denmark, 260-289

Gerkema, T., 2000, A linear stability analysis of tidally generated sand waves, Journal of Fluid Mechanics, vol. 417, 303-322

Gray, J.S., 1974. Animal sediment relationships. Oceanogr. Mar. Biol. Ann. Rev. 12, 223-261.

Hall, S.J., 1994. Physical disturbance and marine benthic communities: life in unconsolidated sediments. Oceanogr. Mar. Biol. Ann. Rev. 32, 179-239.

Hulscher, S.J.M.H., 1996, Tidal induced large-scale regular bed form patterns in a three dimensional shallow water model, Journal of Geophysical Research 101 (C9), 20, 727-20, 744

Hulscher, S.J.M.H. and Fluit, C.C.J.M., 2000, Modelling gasmined bed depressions and tidal sand banks, [Book of extended abstracts of the 10th biennial conference on physics of estuaries and coastal seas. 7-10 October 2000. Carl T. friedrichs and Arnoldo Valle-levinson eds. Samroe report 366].(pp. 221-224). Norfolk, USA.

Hulscher, S.J.M.H. and Van den Brink, G.M., 1999, Comparison between predicted and observed sand waves in the North Sea, University of Twente, The Netherlands, submitted to Journal of Geophysical Research

Huthnance, J.M., 1982, On one mechanism forming linear sand banks, Estuarine and shelf science 14, 79-99

Knaapen, M.A.F., Hulscher, S.J.M.H., and Scholl, O., Predicting the regeneration of sand waves after dredging: an amplitude evolution model tuned by a genetic algorithm, In Coastal Engineering 2000, edited by B.L. Edge, ASCE, Sydney, to appear.

Knaapen, M.A.F., Hulscher, S.J.M.H., De Vriend, H.J. and Stolk, A., A new type of seabed waves, accepted in Geophysical Research Letters.

Komarova, L. and Hulscher, S.J.M.H., 2000, Linear instability mechanisms for sand wave formation, Journal of Fluid Mechanics, vol. 413, 219-246

Komarova, N.L. and Newell, A.C., 2000, Non-linear dynamics of sand banks and sand waves, J. Fluid Mech., vol. 415, 285-321

Lanckneus, J. and De Moor, G., 1991, Present-day evolution of sand waves on a sandy shelf bank, Oceanologica Acta, Proceedings of the international Colloquium on the environment of epicontinental seas, Lille, vol, sp. No. 11, 123-127

Lopez, G.R. & J.S. Levington, 1987. Ecology of depesit-feeding animals in marine sediments. Quat. Rev. Biol. 62 (3), 235-260.

MacArthur, R.H. & E.O. Wilson, 1967. Theory of Island Biography. Princeton NY: Princeton University Press.

Nemeth, A.A., Hulscher, S.J.M.H., and De Vriend, H.J. (2000a). Modelling sand wave dynamics in shallow shelf seas., [Book of extended abstracts of the 10th biennial conference on physics of estuaries and coastal seas. 7-10 October 2000. Carl T. friedrichs and Arnoldo Valle-levinson eds. Samroe report 366].(pp. 296-299). Norfolk, USA.

Nemeth, A.A., Hulscher, S.J.M.H., and De Vriend, H.J. (2000b). Modelling sand wave dynamics in shallow shelf seas, CT&M research paper 2000W-008/MICS-020, 15 pp, 2000.

Newell, R.C., L.J. Seiderer & D.R. Hitchcock, 1998. The impact of dredging works in coastal waters: A review of the sensitivity to disturbance and subsequent recovery of biological resources on the sea bed. Oceanogr. Mar. Biol. Ann. Rev. 36, 127-178.

Ólafsson, E.B, C.H. Peterson & W.G. Ambrose, 1994. Does recruitment limitation structure populations and communities of macro-invertebrates in marine soft sediment: the relative significance of pre-and post-settlement processes. Oceanogr. Mar. Biol. Ann. Rev. 32, 65-109.

Reise, K., 1985. Tidal flat ecology: an experimental approach to species interactions. Ecological studies. Berlin: Springer.

Rhoads, D.C., 1974. Organism-sediment relations on the muddy sea floor. Oceanogr. Mar. Biol. Ann. Rev. 12, 263-300.

Rhoads, D.C. & D.K. Young, 1970. The influence of deposit feeding organisms on sediment stability and community trophic structure. J. Mar. Res. 28, 150-178.

Rijks Geologische Dienst, 1996, Raw materials at or near the surface, map at scale 1:1,000,000.

Roos, P.C., and Hulscher, S.J.M.H., Morphodynamic interactions of an offshore gasmined bed depression and tidal sand banks, CT&M research paper 2000W-008/MICS-019, 17 pp, 2000.

Snelgrove, P.V.R. & C.A. Butman, 1994. Animal-sediment realtionships revisited: cause versus effect. Oceanogr. Mar. Biol. Ann. Rev. 32, 111-177.

Stamhuis, E.J., 1997. Mining, brushing and flushing. Feeding mechanism, turbative activity and behavioural enegetics of the endobenthoc thalassinid shrimp

Callianassa subterranea. Thesis, University of Groningen, Haren The Netherlands.

Terwindt, J.H.J., 1971, Sand waves in the southern Bight of the North Sea, Marine Geol. 10, 51-67

Thayer, C.W., 1979. Biological bulldozers and the evolution of marine benthic communities. Science 203, 458-461.

Thayer, C.W., 1983. Sediment-mediated biological disturbance and the evolution of marine benthos. In: Biotic interactions in recent and fossil benthic communities, M.J.S. Tevesz & P.L. Mc Call (eds). New York: Plenum Press, 479-625.

Trush, S.F., R.D. Pridmore, J.E. Hewitt & V.J. Cummings, 1992. Adult infauna as facillitators of colonization on intertidal sandflats. J.Exp. Mar. Ecol. 159, 253-265.

Van Alphen, L.S.L.J., and Damoiseaux, M.A., 1987, A morphological map of the Dutch shoreface and adjacent part of the continental shelf (1:250.000). Rijkswaterstaat Directie Noordzee report NZ-N-87.21/MDLK-R-87.18 (with 4 color maps).

Van de Meene, J.W.H., 1994, The shoreface-connected ridges along the central Dutch coast, Dissertation Utrecht University, Netherlands Geographical Studies, v. 174, 222 p.

Van Unen, R.F. et al., 1997, High-resolution near-seabed velocity and sediment transport profiling, Proc. Ocean ’97, MTS/IEEE Conf., v. 1.

Weston, D.P., 1988. Macrobenthos-sediment relationships on the continental shelf off Cape Hatteras, North Carolina. Continental Shelf. Res. 8, 267-286.

WL | Delft Hydraulics, 1997. Eiland in zee, deel van een veerkrachtige kust; Verkenningen rond een vliegveld voor de Hollandse kust. WL rapport R3163.