Ministry of Transport, Public Works and Water Management
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National Institute for Coastal and Marine Management / RIKZ

Risk analysis of coastal nourishment techniques in The Netherlands

Part A
The ecological effects of shoreface nourishment off the island of Terschelling

Part B
The ecological effects of subaqueous sand extraction North of the Island of Terschelling

Part C
Literature references

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General introduction

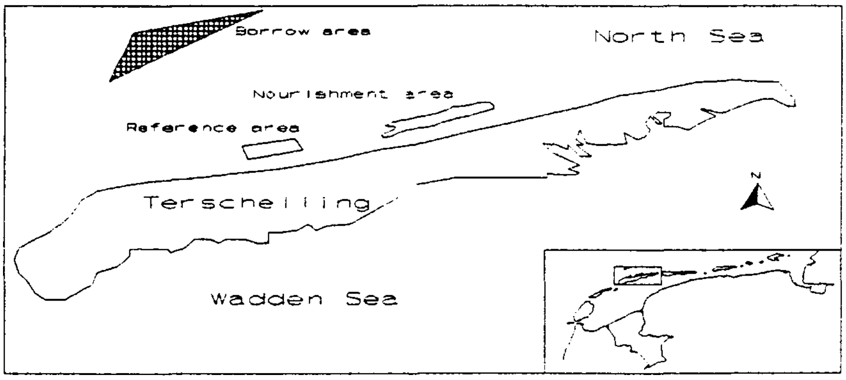
Beach nourishment to combat coastal erosion and loss of public amenity has been a common practice for long in many countries with a sandy seashore. In The Netherlands, an average annual amount of 7 million m^3 of sand were nourished in the years 1991-1994, equalling an expenditure of ca. 62 million Dutch Guilders per year (DE RUIG, 1995a). Beach nourishment generally requires relatively calm weather to be able to bring sand on the beach, sand mostly being borrowed from the nearby seabed and pumped ashore through pipelines. Due to these practical 'calm weather' constraints beach nourishments may interfere with recreational activities at beaches in spring and summer and, therefore, with economic interests.
A recent development in the field of coastal protection are shoreface nourishment and combination of beach- and shoreface nourishment. Shoreface nourishment implies deposition of a buffer of sand on the sea floor in front of a beach that is eroding or is threatened to be eroded (VAN HEUVEL & HILLEN, 1991). This buffer is intended to supply the beach with sand, in this way providing compensation for erosional loss of beach over several years. The effectiveness of shoreface nourishment is subject of a morphological and sedimentological study (NOURTEC) carried out in Denmark, Germany and The Netherlands (off Terschelling) and funded by the MAST 2 programma of the European Union (KAISER *et al.* 1994).
An important advantage of shoreface nourishment is that it can be done outside the recreational season. Also important is the fact that sand nourishments are cheaper than building and maintaining of dikes. They also reduce the cost of coastal defence (*e.g.* maintenance of groynes).
Shoreface nourishment is considered a realistic alternative for beach nourishment, except for stretches of sandy coast where deep tidal channels are close to the coast, such as at the western end of the islands in the Dutch Wadden Sea (ANONYMOUS, 1996).

The shoreface area along the Dutch coasts represents ecological as well as economic values. This shallow zone of the North Sea is relatively rich in benthic fauna (HOLTMANN *et al.*, 1996). Numerical densities reach values up to 34,000 individuals per m^2., and biomass up to 425 gram ash-free dry weight per m^2. This benthos provides food for juvenile demersal fish (*e.g.* plaice, sole, turbot) and for sea ducks (*e.g.* common scoter, eider). The coastal zone between 2 and 10 m depth below LW is of great importance as nursery for plaice and sole (VAN BEEK *et al.*, 1989) and has become an important area for fishery on brown shrimps (POSTUMA & RAUCK, 1978).
The Dutch coastal zone is an important wintering habitat for some diving ducks, especially for eider (*Somateria mollissima*) and common scoter (*Melanitta nigra*)(BAPTIST & WOLF, 1993; CAMPHUYSEN & LEOPOLD, 1994). In winter (December-March), 80,000 eider were counted to be present in the Dutch coastal zone in the years 1989-1992. The preferred

food of eider in the Dutch Wadden Sea consists of mussels (*Mytilus edulis*) and cockles (*Cerastoderma edule*) (SWENNEN, 1976). The coastal zone is important as overwintering area providing food in the form of *Spisula* sp., especially in years with food shortage in the Wadden Sea. Common scoters are most abundant in Dutch coastal waters in December-February with approx. 100,000 individuals (BAPTIST & WOLF, 1993; CAMPHUYSEN & LEOPOLD, 1994). Their food consists of bivalves that are obtained by diving down to depths of 30 m. Along the Dutch coast common scoters concentrate on beds of *Spisula* sp. (OFFRINGA, 1991; LEOPOLD, 1996). Recently, stocks of the bivalve mollusc *Spisula* sp. are being exploited providing an alternative for fishing of the edible cockle (*Cerastoderma edule*) in the Dutch Wadden Sea in lean years of the latter species (LEOPOLD & VAN DER LAND, 1996). This implies that shoreface nourishment may be a risk for some ecological and ecology dependent economic values of the shallow coastal habitat. In general terms, it was expected that the actual deposition of a body of sand would be detrimental to local benthos as not many species are able to survive burial by 1 - 2 m of sand (see BIJKERK, 1988; ESSINK, 1997). Because intensive hydrodynamic forcing in the shoreface area with its breaker banks and troughs, a relatively high mobility of macrobenthos was expected leading to colonisation of the new deposited body of sand from the surrounding area. Complete recovery requires successful reproduction and recruitment and would take one or more years, especially in long living species such as bivalves and sea urchins.

To investigate the risk of shoreface nourishment to the coastal benthic community and its consumers the RIACON (Risk Analysis of Coastal Nourishment Techniques) project was started in 1994 under the auspices of the MAST 2 programme of the Commission of the European Communities. In The Netherlands, effects of shoreface nourishment were studied North of the island of Terschelling (Fig. A-1). Two aspects were included: effects of sand deposition at the nourishment site and effects of subaqueous sand extraction at the borrow site. The study regarding the risk to the benthic fauna of the shoreface will presented in Part A of this report. The effects of subaqueous extraction of the sand needed for the nourishment are dealt with in Part B. Part C provides a listing of all references to the literature made both in Part A and B.

Figure 1
Map of the island of Terschelling and position of the areas studied: borrow area, nourishment area and reference area.



Acknowledgements

We are grateful to the Netherlands Institute for Sea Research (NIOZ) at Texel for letting us use their Reineck box corer till we got our own. The crews of the research vessels "Holland" (Rijkswaterstaat, North Sea Directorate) and "Aldebaran" and "Heffesant" (Rijkswaterstaat, Directorate North Netherlands) are thanked for their assistance rendered at the benthos sampling campaigns. We thank Ruud Backer Dirks (Rijkswaterstaat-North Netherlands), Piet Hoekstra (University of Utrecht) and Ruud Spanhoff (Rijkswaterstaat, RIKZ) for making available various data obtained in the NOURTEC project.
Willem van der Hoeven (Rijkswaterstaat, RIKZ) took care of producing the bathymetry-difference maps. Rob Jungcurt (Rijkswaterstaat, RIKZ) designed the cover.

PART A

THE ECOLOGICAL EFFECTS OF SHOREFACE NOURISHMENT OFF THE ISLAND OF TERSCHELLING

1 Introduction

The sandy coastline of The Netherlands is constantly moving due to accretional and erosional processes. To combat erosion of the coast sea dykes were built and reinforced in those places where recession of the coastline was not acceptable. For combating erosion of the dune coast, sand nourishments are being applied either to the seaward or the landward side of the dunes. Nourishment is primarily done to safeguard polders, and industrial and residential areas behind the dunes. Several nourishments, however, have been done for other reasons than safety, *viz.* to protect natural and recreational values and drinking water supply areas. General Dutch policy since 1990 is to stop coastal recession, but not at all locations and not at all costs. In other words: 'dynamic preservation of the coastline' (ANONYMOUS, 1990; DE RUIG, 1995b). A disadvantage of nourishments is that they have to be repeated on a regular basis. Generally, however, the costs for nourishments are lower than those associated with the construction and maintenance of hard coast defence works (ANONYMOUS, 1990).
For the decades to come it is expected that an annual volume of 6 - 7 million m^3 of sand nourishment will be sufficient to compensate the sand loss in erosive sections of the Dutch coast (DE RUIG, 1995b). In case of an anticipated sea level rise of 20 cm per century, an extra 5 million m^3 of sand may be necessary (ANONYMOUS, 1996).

Beach nourishments have the disadvantage that the best season for carrying out these works is spring and summer. So, beach nourishment may interfere with recreational, and therefore economical, interests of the beaches (ADRIAANSE & COOSEN, 1991; ROELSE, 1996). Shoreface nourishment may be an attractive alternative as during the works beaches will not be affected (VAN HEUVEL & HILLEN, 1991). Furthermore, it is expected that sand depots nourished to the shoreface may compensate beach erosion for approx. 5 years. An experimental shoreface nourishment was initiated in the framework of the NOURTEC (Innovative Nourishment Techniques) project supported by the MAST II programme of the European Union (KAISER *et al.*, 1994).

Ecological effects of nourishment of dunes and beaches have been the subject of several studies (see LÖFFLER & COOSEN, 1995). With respect to nourishment of the foreshore, knowledge regarding the nature and extent of effects on local benthic communities and depending other coastal ecosystem components was largely absent.

For the execution of the RIACON study in The Netherlands, the site of the experimental shoreface nourishment under study by the NOURTEC project was chosen. In this way, information on dynamics of sea-bed morphology and sediment characteristics obtained in NOURTEC became readily available to support the ecological study in RIACON.

2 Methods

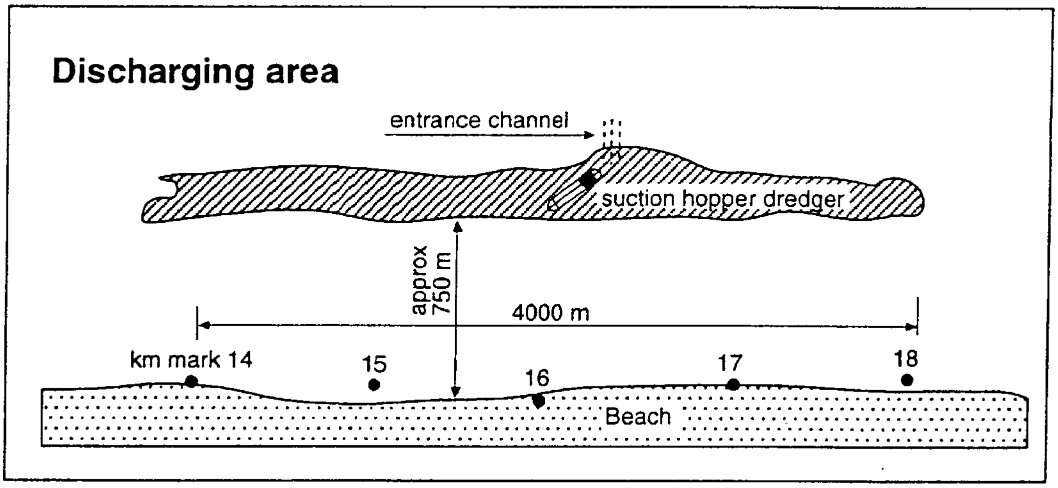
2.1 Study area

The beach of Terschelling is subject to erosion with a calculated loss of 110 x 10^3 m^3. The coastline recedes at a rate of 1-5 m/year). The area is very dynamic with a considerable transport of sediment (KAISER *et al.*, 1994). In the study area off Terschelling, the nearshore zone is characterized by 2 or 3 breaker bars parallel to the shore. Northwest of the area a large sand wave field is present (BIEGEL, 1994). Medium grain size in the nearshore area was ca. 185 μm (in 1993). The sediment in the trough between the second and third breaker bar had a median grain size of 165-178 μm. A strong correlation was found between particle size and seabed morphology. On the crests of the breaker bars sediments were coarser, whereas the sediments in the troughs were less coarse (BIEGEL *et al.*, 1995b). The mud content of the sediment (fraction < 63 μm) is highest seaward of the outer breaker bar.
Along the coast there is a residual current from (south)west to (north)east (GOEDECKE, 1968). At times of northeasterly wind stress residual currents reverse (BACKHAUS, 1984; RIEPMA, 1980; VAN DE KAMP, 1983).
The benthic communities of the foreshore off Terschelling have not been properly included in the MILZON benthos surveys by Rijkswaterstaat due to the rather wide random sampling grid (*cf.* HOLTMANN *et al.*, 1996). The foreshore area forms an important foraging area for diving ducks such as the common scoter (*Melanitta nigra*) and the eider (*Somateria mollissima*), especially because of the occurrence of large banks the bivalve mollusc *Spisula subtruncata* (LEOPOLD, 1996; OFFRINGA, 1991).

2.2 Nourishment operation

Nourishment off Terschelling was carried out in the period April - November 1993. Three suction hopper dredgers were used, having capacities between 1200 and 2100 m^3 each. On average, 3000 m^3 of sand was transported to the nourishment site every 4 hours. To provide access of the hopper dredgers to the nourishment site a passage ('entrance channel') was dredged through the breaker bar immediately North of trough to be nourished (Fig. A-1). Nourishment began simultaneously at the western and eastern end of the trough between the breaker bars, both ends being treated dependent on the phase of the tidal current. After completion of the nourishment, the dredged passage was closed again (KAISER *et al.*, 1994). A total of ca. 2.1 million cubic metres of sand were deposited on the seabed, covering a trough area of circa 1.7 km^2.

Figure A-1
Map of the nourishment area North off the island of Terschelling. Km-numbers of beach poles on Terschelling are marked.



2.3 Sampling strategy

The seabed morphology of the nourishment area showed an outer and a middle breaker bar and a through in between. As the nourishment consisted of filling up the trough, three strata were considered in a stratified sampling approach, *viz.* stratum Trough, stratum North (north of the trough) and stratum South (south of the trough) (Fig. A-2).
A reference area at ca. 3 km West of the nourishment area, having a similar seabed morphology and depth structure. Here, also a North and a Trough stratum were distinguished (Fig. A-3). As the southern breaker bar was relatively small, no South stratum was taken into account.
In each survey, 90 samples were distributed over the strata (stratified random sampling). In each of the North and Trough strata 20 samples were taken. In the smaller South stratum of the nourishment area 10 samples were taken. The positions of the sampling stations are listed in the separate survey reports (VAN DALFSEN & PINKHAM, 1994; VAN DALFSEN and DUYTS, 1995; VAN DALFSEN & OOSTERBAAN, 1996 a,c; VAN DALFSEN & BUNT, 1996).

Figure A-2

Schematic cross section of the nourishment area off Terschelling with indication of location of the strata sampled: North (N), Trough (T) and South (S).

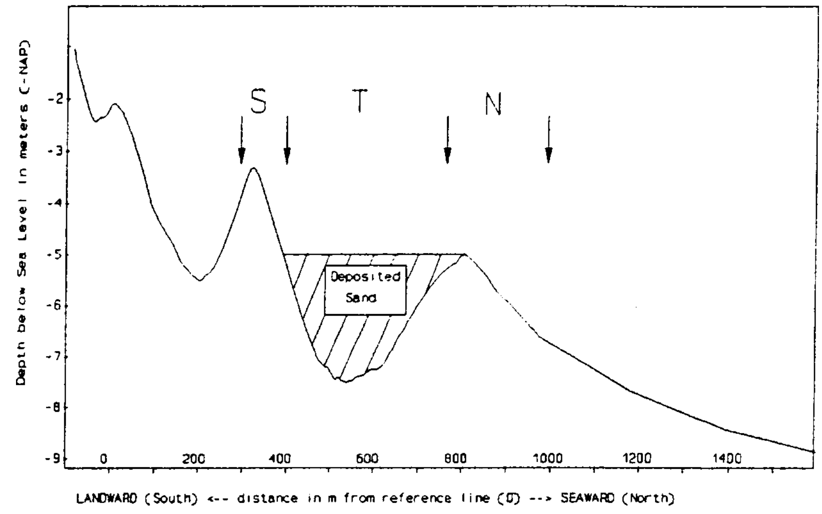
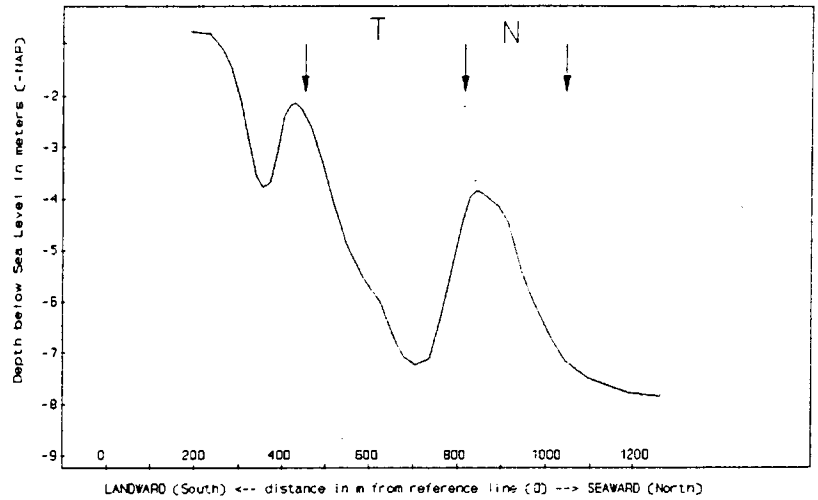


Figure A-3

Schematic cross section of the reference area off Terschelling with indication of location of the strata: North (N) and Trough (T).

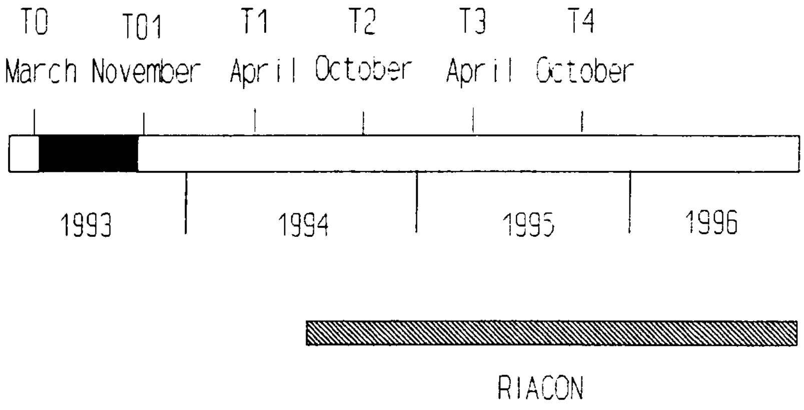


2.4 Bathymetric soundings and sampling of sediment

Bathymetric sounding charts were regularly made within the framework of the NOURTEC project, *viz.* February 1993, May 1993, November 1993, January/February 1994, April 1995, June 1994, September 1994, December 1994, March/April 1995 and April 1996 (BIEGEL *et al.*, 1995a). Sampling surveys for sediment and benthos were made in March 1993, April 1994, September/October 1994, April 1995 and October 1995 (Fig. A-4). A limited survey in the Trough stratum was made in November 1993, directly after completion of the nourishment, to investigate survival of the original fauna and possible import of species with the nourished sand.

The sediment samples were analyzed for mud content (fraction $< 53\ \mu m$), $CaCO_3$ and organic matter. Analyses were performed at the Middelburg laboratory of Rijkswaterstaat/RIKZ.

Figure A-4
Time schedule of bathymetric and macrobenthic surveys in the nourishment and reference area off Terschelling.



2.5 Sampling of macrozoobenthos

At each survey a total of 90 samples were taken: 20 in each North stratum, 20 in each Trough stratum, and 10 in the South stratum of the nourishment area. Samples were taken at randomly chosen positions within each stratum. The positions where the samples were taken are listed in the separate survey reports (VAN DALFSEN & PINKHAM, 1994; VAN DALFSEN and DUYTS, 1995; VAN DALFSEN & OOSTERBAAN, 1996 a,c; VAN DALFSEN & BUNT, 1996). In the limited survey in November 1993, 20 samples were taken (TYDEMAN, 1994).
Samples were taken with a Reineck box corer, made available by the Netherlands Institute for Sea Research (NIOZ) (sample area 0.06 m^2 in the T1 survey; 0.07 m^2 in the T0, T2, T3 and T4 surveys). After taking a small subsample for sediment analysis, each sample was washed over a 1 mm mesh sieve on board the ship. The residue was preserved in 4% formaldehyde in sea water. Within one to three days after sampling, the preserved samples were stored at -20°C to reduce loss of biomass (SALONEN & SARVALA, 1985).

2.6 Treatment of macrozoobenthos samples

Frozen samples were thawed and rinsed with tap water to remove formaldehyde using a 0.5 mm mesh sieve. The samples were then sorted with the aid of a low-power stereo microscope.
Density (ind/m^2) was recorded at species level for as much as possible, or otherwise at a higher taxonomic level. In *Nephtys* species and *Echinocardium cordatum*, juveniles and adults were counted separately. In none of the other species such a discrimination was made. Bivalves were

separated into length classes of 0.5 cm except for the small sized *Montacuta ferruginosa*.

Biomass was determined in grams ash-free dry weight (AFDW) per m^2. AFDW was determined by drying the organisms for 65 hours at 65°C. The animals were then weighed (dry weight) and incinerated at 570°C for a period of two hours and weighed again (ash weight).

For the major polychaetes *Nephtys hombergii* and *Magelona papillicornis* assessment of biomass was done for each species separately; for all remaining worms (polychaetes and nemertini) the combined biomass was determined. In bivalve molluscs biomass was determined per species. For echinoderms (mostly *Echinocardium cordatum*), only complete individuals were used for determination of an average individual AFDW, from which the biomass per m^2 was calculated. Discrimination was made between juvenile (<2 cm) and adult (>3.5 cm) *Echinocardium cordatum*. There was no determination of biomass of Crustacea.

2.7 Data analysis

Not all species found in the samples were considered. Mobile epibenthos (*e.g.* copepods, mysids, shrimps and crabs) were excluded, primarily because of inadequate sampling. Furthermore, it was agreed between RIACON-partners to exclude Bryozoa, Hydrozoa, Nematoda and *Brachiostoma lanceolatus* from the data analysis. In Appendix A an overview is given of all species found in the samples, of those species included in the data analysis as well as assignment of species to feedings types.

Density, biomass, species diversity and evenness were calculated for each of the seabed strata that were sampled. The diversity of the macrobenthic fauna is expressed by the Shannon-Wiener index H' and the distribution of the numbers of individuals among the species by Heips index E(H) of evenness (HEIP, 1974).

$$H' = -\sum_{i=1}^{S} p_i (\ln p_i) \qquad \text{with } p_i = n_i / N$$

where N = Total number of individuals
n_i = number of individuals of species i
S = total number of species

$$E(H) = \frac{N_1 - 1}{N_0 - 1}$$

where $N_1 = e^{H'}$
N_0 = total number of species

Heip's Index $E(H) = 1$ if all species present are equally abundant.

Differences in abiotic parameters, species composition, abundance and biomass between the successive surveys were tested, using the Mann-Whitney U-test. Within each survey, differences between the five strata were tested by an analysis of variance (ANOVA) using a 95 % Tukeys HSD test.
In each survey, the benthic community structure was analyzed using TWINSPAN cluster analysis (HILL, 1979) on the data of all samples. TWINSPAN analyses were performed on density data of species (cut levels: 0, 1, 10, 50 and 100/m^2). To be optimise comparison between the different surveys, the same cut levels were used in each analysis. Further data analysis included non-metric multi dimensional scaling ordination (MDS) (KRUSKAL & WISH, 1978) using a Bray-Curtis similarity matrix of double-root-transformed species abundance (BRAY & CURTIS, 1957) and Canonical Correspondence Analysis (CCA) also using species abundance. Finally, data on feeding type of species (predator, deposit feeder, suspension feeder) and age structure (based on shell length measurements) of some bivalve species were used to investigate the effects of sand extraction in more detail.
Differences between the 5 strata were tested for significance by a analysis of variance (ANOVA) using Tukey's HSD test. The results of the successive surveys were compared, using the Mann-Whitney U-test to test for statistical differences in abiotic parameters, species composition, abundance and biomass.
In this report results are presented as Box and Whisker plots (see Fig. A-5).

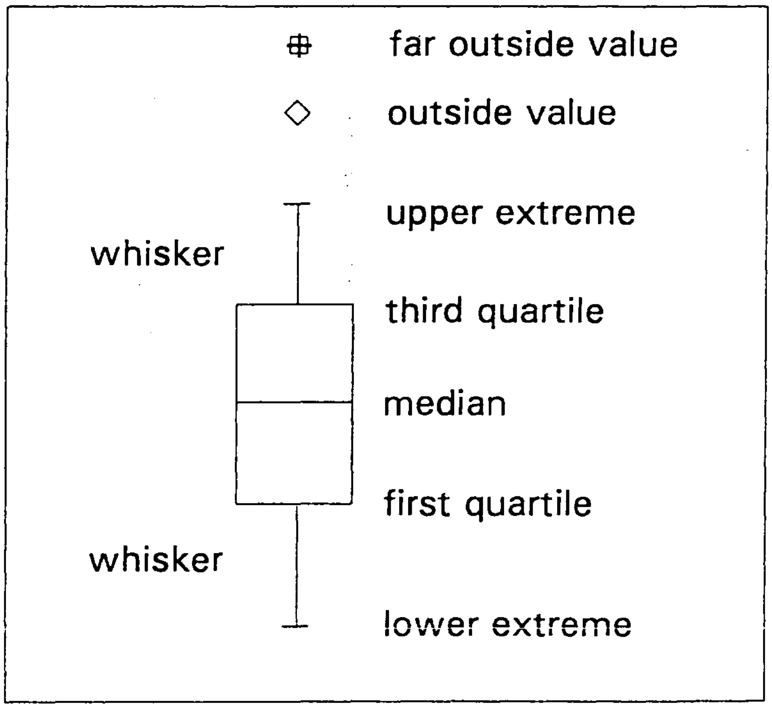


Figure A-5
Box and Whisker plot. The box encloses the middle 50 percent. The horizontal line inside the box represents the median value. Whiskers are drawn from the first and third quartile to the smallest, respectively the largest data point within 1.5 quartile range.

3 Results

In this report no attention will be given to the data obtained in the South stratum of the nourishment area. The reason for this is twofold. Firstly, no good reference area for this stratum was present. Furthermore, in the period of investigation only little changes in macrozoobenthos occurred in this stratum. Detailed information on this stratum is available in the separate survey reports (VAN DALFSEN & PINKHAM, 1994; VAN DALFSEN and DUYTS, 1995; VAN DALFSEN & OOSTERBAAN, 1996 a,c; VAN DALFSEN & BUNT, 1996).

3.1 Seabed morphology and sediment characteristics

Between April and November 1993, ca. 2.1 million m^3 of sand were placed at the foreshore of Terschelling. This resulted in filling up of the trough between the second and third breaker bank to a level about 1 m above the crest of the outer (= third) breaker bar, creating an almost flat sea bed surface (BIEGEL, 1994) (Fig. A-6). Immediately after completion of the nourishment, the formation of a new trough commenced. The sand that was eroded was transported partly towards the beach as well as alongshore towards the east. In this way a new bar-trough system was formed, the profile of which changed gradually over time towards the original profile present before the nourishment was started (BIEGEL, 1994). In the reference area, between the T0 survey (pre-nourishment; March 1993) and the T1 survey (April 1994) a reduction of depth was observed (Fig. A-7). This was caused by an incoming sand wave (BIEGEL, 1994).

Figure A-6
Cross profiles of the nourishment site at km 17.5 in February 1993, November 1993 and January 1994.

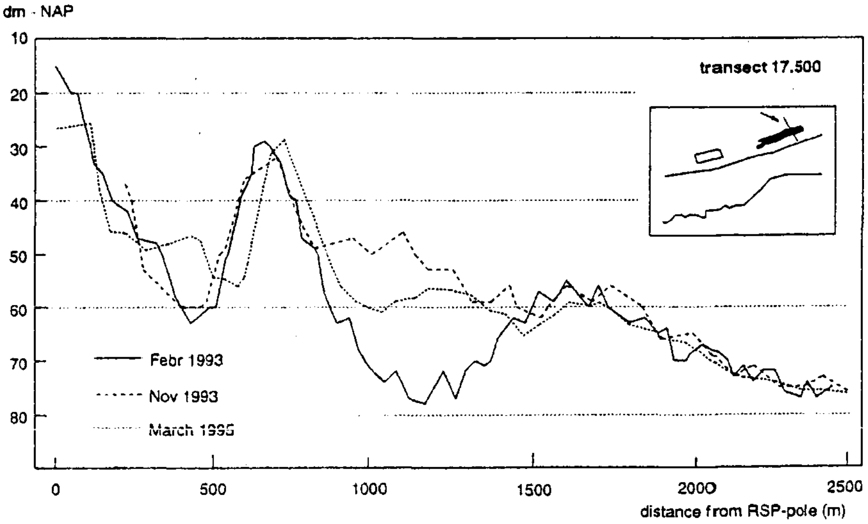
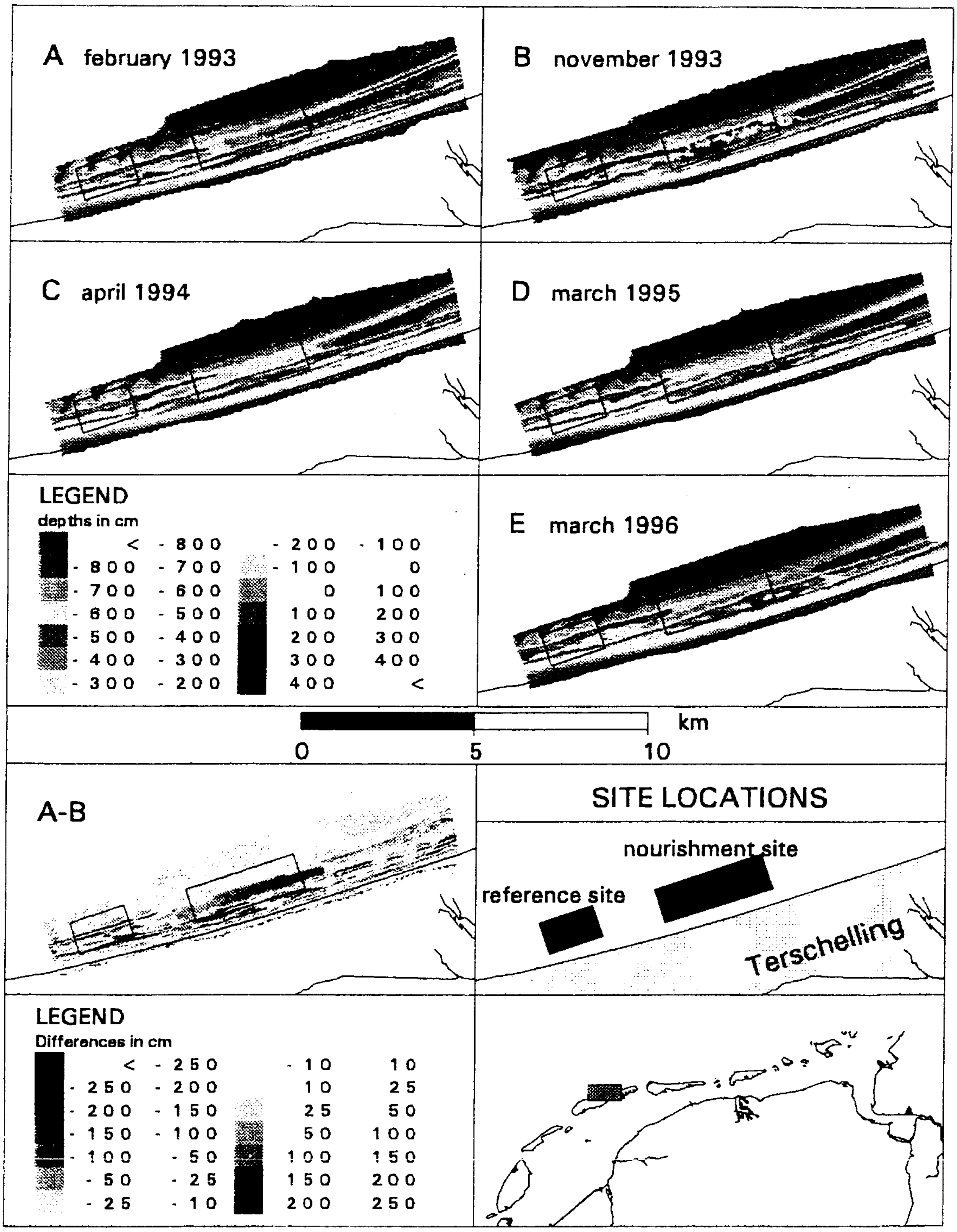


Figure A-7

Batymetric maps and sedimentation/erosion map of the nourishment and reference area North off Terschelling.



In the nourishment area, the median grain size increased with 17 - 57 μm due to the import of coarser sands from the extraction area. However, within 6 month after completion of the nourishment grain size distribution of the sediment had become almost identical to the one present in the pre-nourishment situation (GUILLÉN, 1995).
The composition of the sediment changed with respect to the contents of $CaCO_3$, mud (fraction <53 μm) and organic material (Fig. A-8). The patterns of change of these abiotic parameters over time were rather similar for the North and Trough strata both in the nourishment and reference area.
$CaCO_3$ contents were significantly higher in the 1994 (T1 and T2 survey) than in 1993 (T0 survey) (Fig. A-8a). Low values were observed in spring 1995 (T3 survey), to increase to values comparable to those of the T0 survey in autumn 1995 (T4 survey).
After the nourishment, *i.e.* in the T1 survey, the mud content had increased significantly only in the North stratum of the nourishment area (Fig. A-8b). From the T1 survey (April 1994) to the T3 survey (April 1995), mud contents showed a strong decrease in both North strata (nourishment and reference area) and in the Trough stratum of the reference area.
With regard to the organic matter content of the sediment all strata showed a similar development (Fig. A-8c). In the T1 survey (April 1994) significantly lower values were observed than in spring 1993. After spring 1994, organic matter contents stayed low, without showing any trend.

3.2 Macrozoobenthos

3.2.1 Species richness

Appendix A presents an overview of all species found in the nourishment and reference area and of their presence (average numerical density) in each of the surveys.
Before nourishment (T0 survey) differences in species richness were found between the geomorphological strata of the seabed. The highest number of species were found in the North (mean: 12.5 species/sample) and Trough (9 species/sample) strata of the nourishment area, followed by the two strata of the reference area (ca. 8 species/sample). The South stratum of the nourishment area had the lowest number of species (mean: 7.2 species/sample).
After the nourishment was carried out, the T1 survey showed lower species richness in the nourishment area (in both North and Trough stratum) than in the pre-nourishment situation (T0 survey), whereas no significant differences were found in the strata of the reference area (Fig. A-9).
In the North strata of both nourishment and reference area, species richness in the T2 and T2 survey was higher than in the T1 survey. In the T4 survey, these strata had a species richness comparable to that of the T0 survey (nourishment area) or slightly higher (reference area).
In the Trough strata a significantly higher species richness was found in the T2 and T3 survey; in the T4 survey species numbers were again similar to those present in the pre-nourishment (T0) survey (Fig. A-9).

Figure A-8

Box and whisker plots of CaCO$_3$ content (a), mud (fraction < 53 μm) content (b), and organic matter content (c) of the sediment in the North and Trough stratum, in the nourishment (N) area and reference (R) area, as measured in five successive surveys.

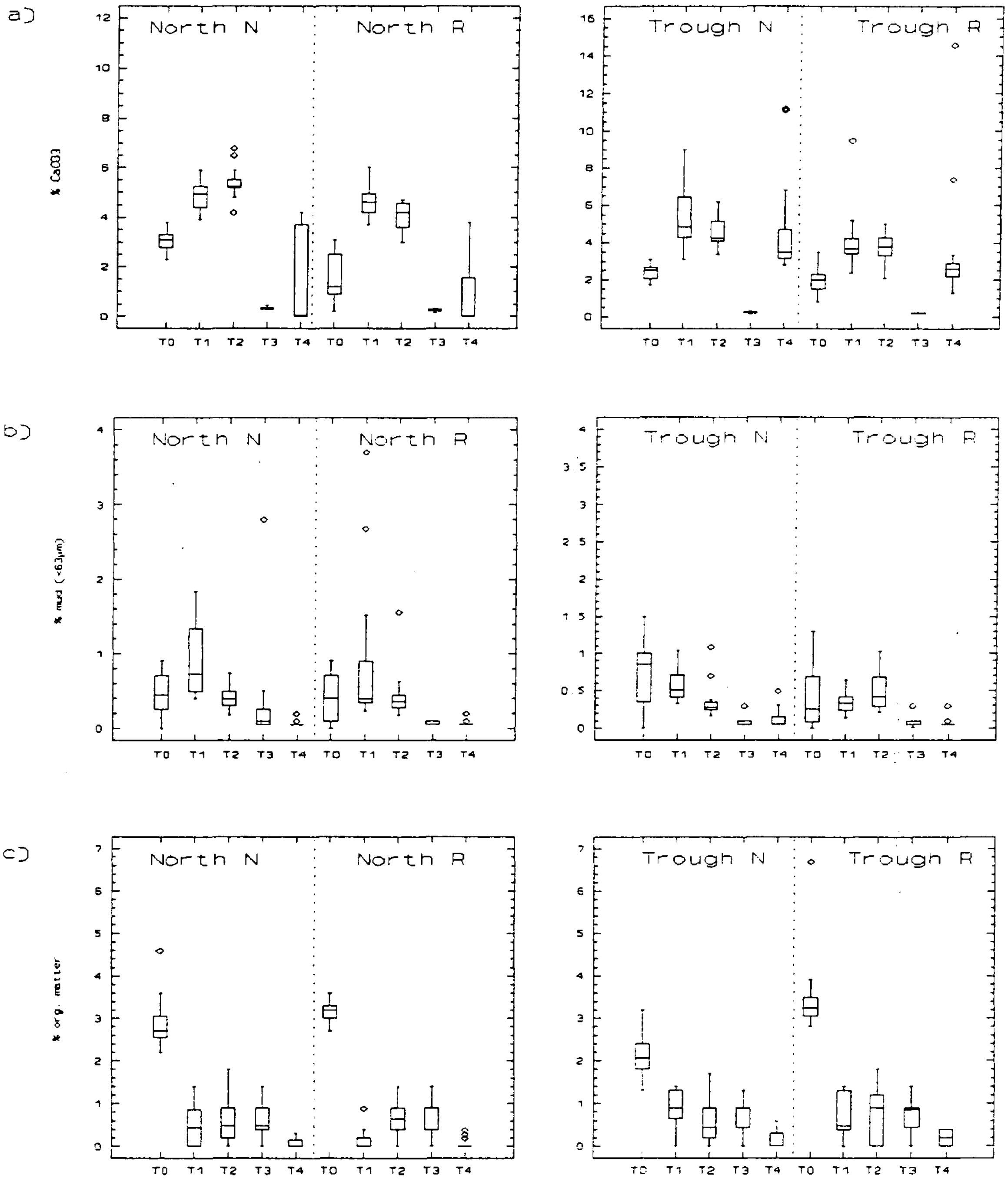
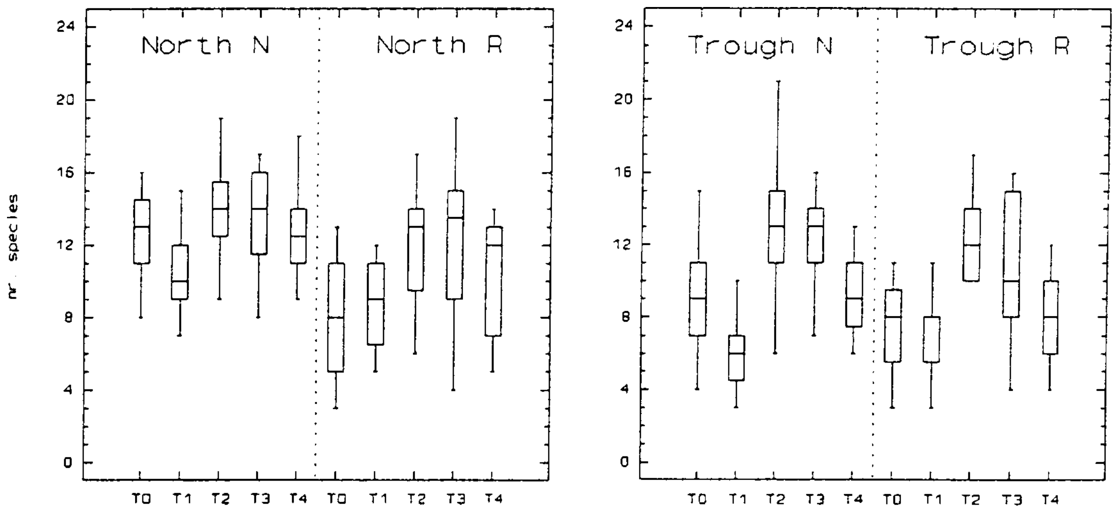


Figure A-9

Box and whisker plots of species richness (nr. of species/sample) in the North and Trough stratum, in the nourishment (N) area and reference (R) area, as measured in five successive surveys.



3.2.2 Diversity and evenness

In the North stratum of the nourishment area the diversity of the benthic community, expressed by the Shannon-Wiener index, decreased significantly after completion of the nourishment. This decrease in diversity even continued till the T2 survey, after which the diversity index remained more or less stable at a significantly lower level than before the nourishment (Fig. A-10). In the North stratum of the reference area no significant changes in Shannon Wiener index occurred.

In the Trough stratum, a decreasing trend was also observed from the T0 survey to the T2 survey. In the T3 and T4 surveys, however, the Shannon-Wiener index had increased to a significant higher level than before the nourishment. In the Trough stratum of the reference area no significant changes in the diversity index were found (Fig. A-10).

Heips index of evenness had moderate values before (T0 survey) and after (T1 survey) the nourishment, indicating a rather evenly distributed abundance of the different species forming the benthic community (Fig. A-11). During 1994 (between the T1 and T2 survey), all strata showed a strong decrease in Heips index, indicating a shift over summer towards a community dominated by rather a few species. In the following surveys, a gradual return towards a more evenly composed community occurred in all strata studied (Fig. A-11).

Figure A-10

Box and whisker plots of Shannon-Wiener diversity (H') per sample in the North and Trough stratum, in the nourishment (N) area and reference (R) area, as measured in five successive surveys.

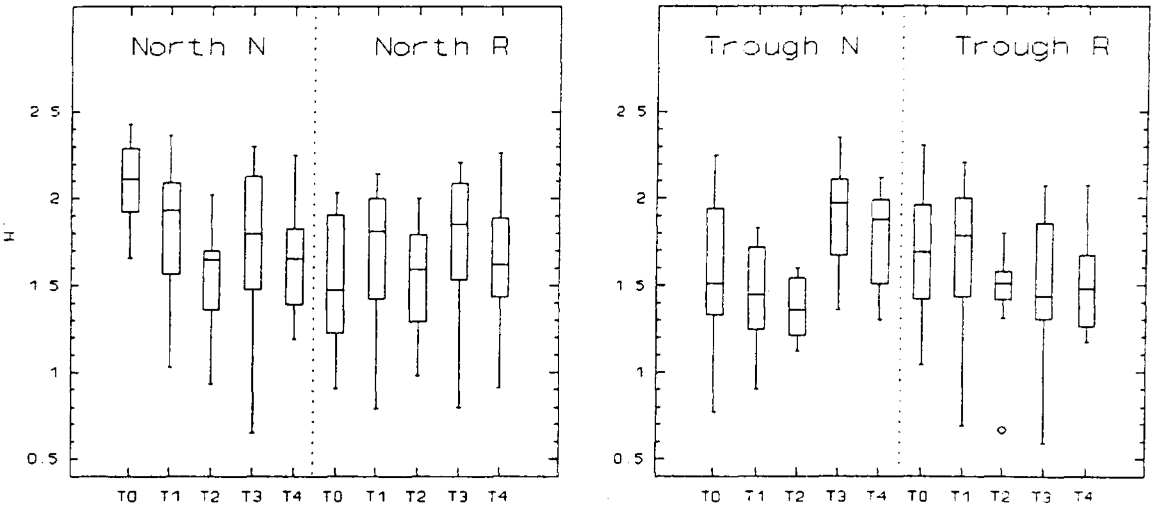
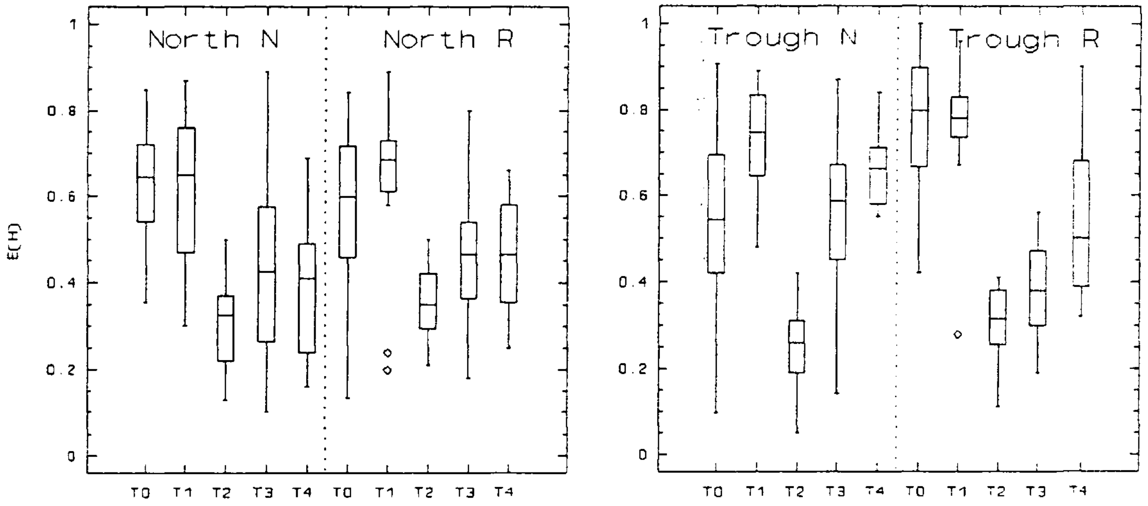


Figure A-11

Box and whisker plots of Heip's Index of Evenness [E(H)] per sample in the North and Trough stratum, in the nourishment (N) area and reference (R) area, as measured in five successive surveys.

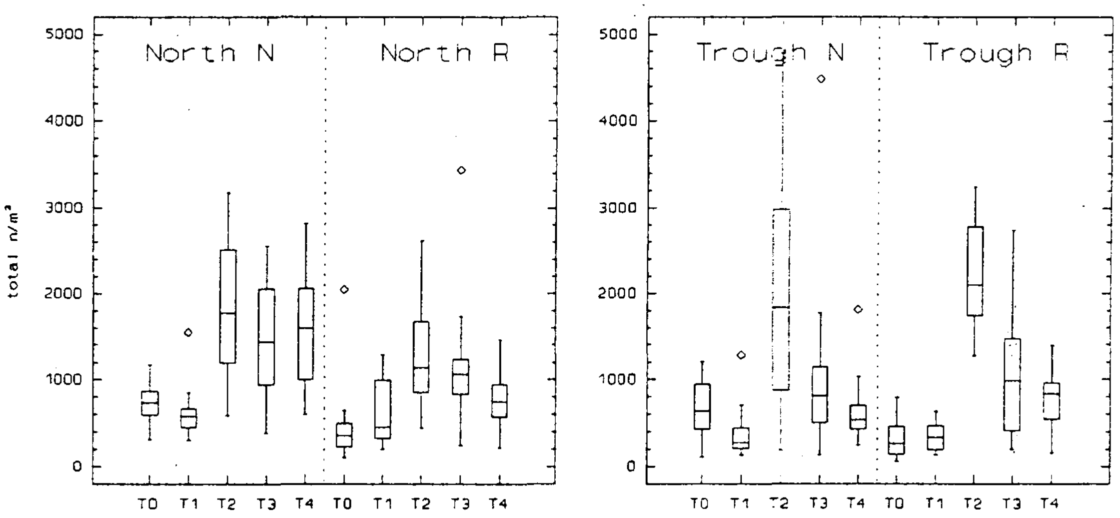


3.2.3 Abundance of macrozoobenthos

The total density of macrofauna in the North and the Trough stratum of the nourishment site after nourishment (T1 survey) was significantly lower than before (T0 survey), whereas no changes in total density were found in the comparable strata in the reference area (Fig. A-12).
Subsequently, over the summer of 1994 a striking increase of macrofauna abundance was found in all North and Trough strata at the autumn survey of 1994 (T2 survey). From then on the strata showed a different development in macrofauna abundance. In the North stratum of the nourishment area abundances remained much higher than in the pre-nourishment (= T0) survey, whereas in the Trough stratum of the nourishment area abundances declined. Also in the strata of the reference area a gradual decline of total macrofauna abundance towards pre-nourishment values was found. Eighteen months after completion of the nourishment, macrofauna abundance in the nourished Trough stratum did not deviate significantly from the abundance values found in the T0 survey.

Figure A-12

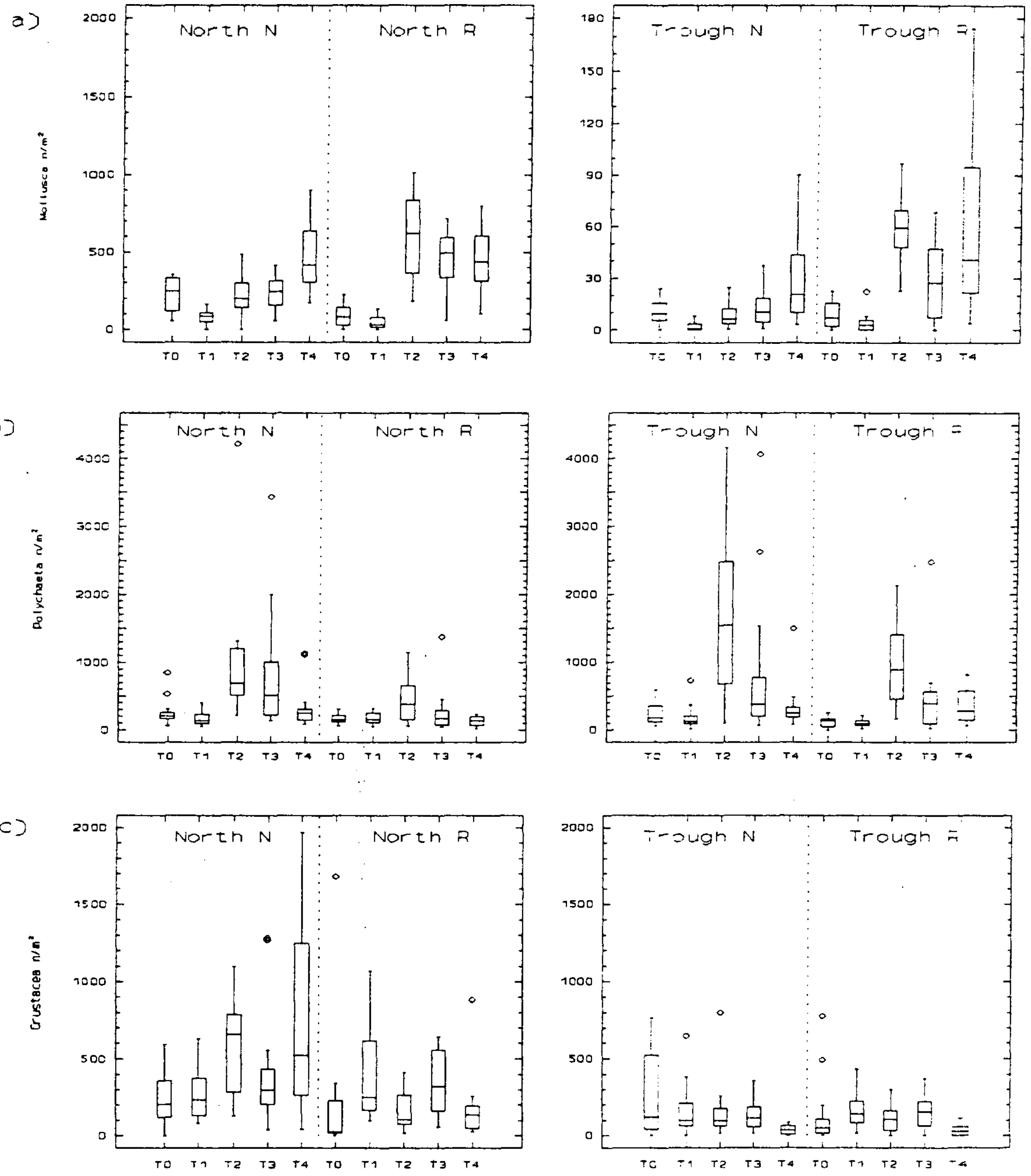
Box and whisker plots of total macrozoobenthos abundance in the North and Trough stratum, in the nourishment (N) area and reference (R) area, as measured in five successive surveys.



The decrease in total macrofauna abundance in the nourished area observed shortly after completion of the nourishment (T1 survey) is mirrored in the abundance of molluscs (Fig. A-13a). In the Trough of the reference area, however, abundance of molluscs also decreased. After the T1 survey, the abundance of molluscs in the reference area (both in North and Trough stratum) increased strongly. In fact, this increase was much stronger than in both strata of the nourishment area. By October 1995 (T4 survey), however, mollusc abundances in the nourishment and reference areas were no longer significantly different.
In both strata of the nourishment area polychaete abundances had increased four- to fivefold at the T2 survey, to be followed by a decline of abundances during the next year (from T2 to T4 survey) (Fig. A-13b).

Figure A-13

Box and whisker plots of abundance (n/m²) of molluscs (a), polychaetes (b), and crustaceans (c) in the North and Trough stratum, in the nourishment (N) area and reference (R) area, as measured in five successive surveys.

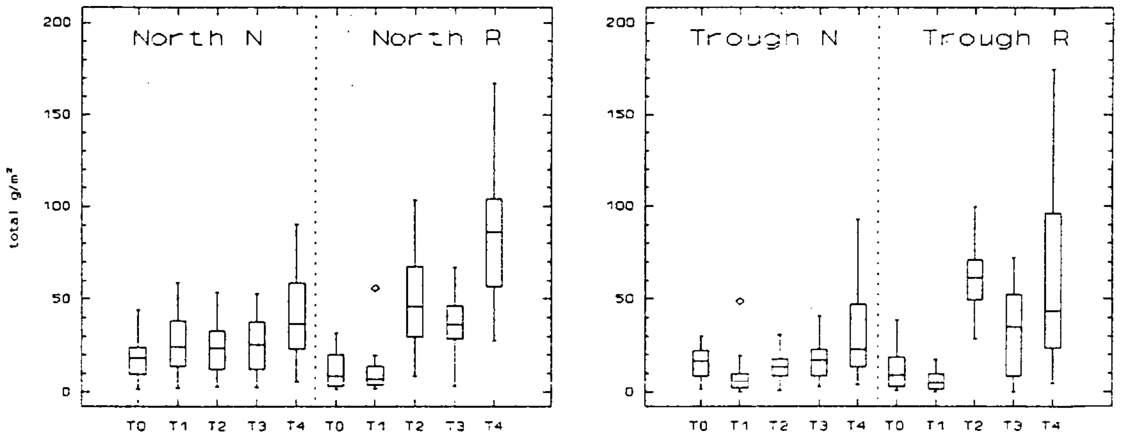


This decline was also observed in the Trough stratum of the reference area. In the North stratum of the reference area, polychaete abundances varied less, but also showed higher values in the T2 survey.
The abundance of crustacea in the Trough stratum of the nourishment area did not change significantly in the course of the surveys (Fig. A-13c) and densities in the T1 and T3 survey of both Trough and North strata of the nourishment area were similar to those found in the T0 survey. In the Trough of the reference area, however, densities in the spring surveys T1 and T3 were higher than in the T0 survey. A similar density pattern was found in the North stratum of the reference area.

3.2.4 Biomass of macrozoobenthos

Before the nourishment, *i.e.* in the T0 survey, the North stratum of the nourishment area had a high total biomass in comparison with the other strata. This was caused by the occurrence of *Echinocardium cordatum*, most of which were large (adult) specimens. The South stratum was characterised by a low total biomass.
After completion of the nourishment, a lower total biomass was found in both Trough strata of the nourishment and the reference area. This difference was only significant in the nourishment area (Fig. A-14).
In the North stratum of the nourishment area a gradual increase of mean total biomass (from 17.5 g/m^2 (T0 survey) to 39.7 g/m^2 (T4 survey) is visible. The North stratum of the reference area shows a similar trend, but here the increase is much stronger (from 11.9 to 86.5 g/m^2) (Fig. A-14).
In both Trough strata, from the T2 survey (Oct. 1993) onwards, the total biomass of macrofauna also increased. Again, this increase was more pronounced in the reference area. In both strata of the reference area a seasonal fluctuation pattern of total biomass, i.e. lower values in spring (T1 and T3 survey) and higher values in autumn (T2 and T4 survey) is clearly present, whereas this is not apparent at the nourishment area.

Figure A-14
Box and whisker plots of total macrozoobenthos biomass (gram AFDW per m^2) in the North and Trough stratum, in the nourishment (N) area and reference area, as measured in five successive surveys.

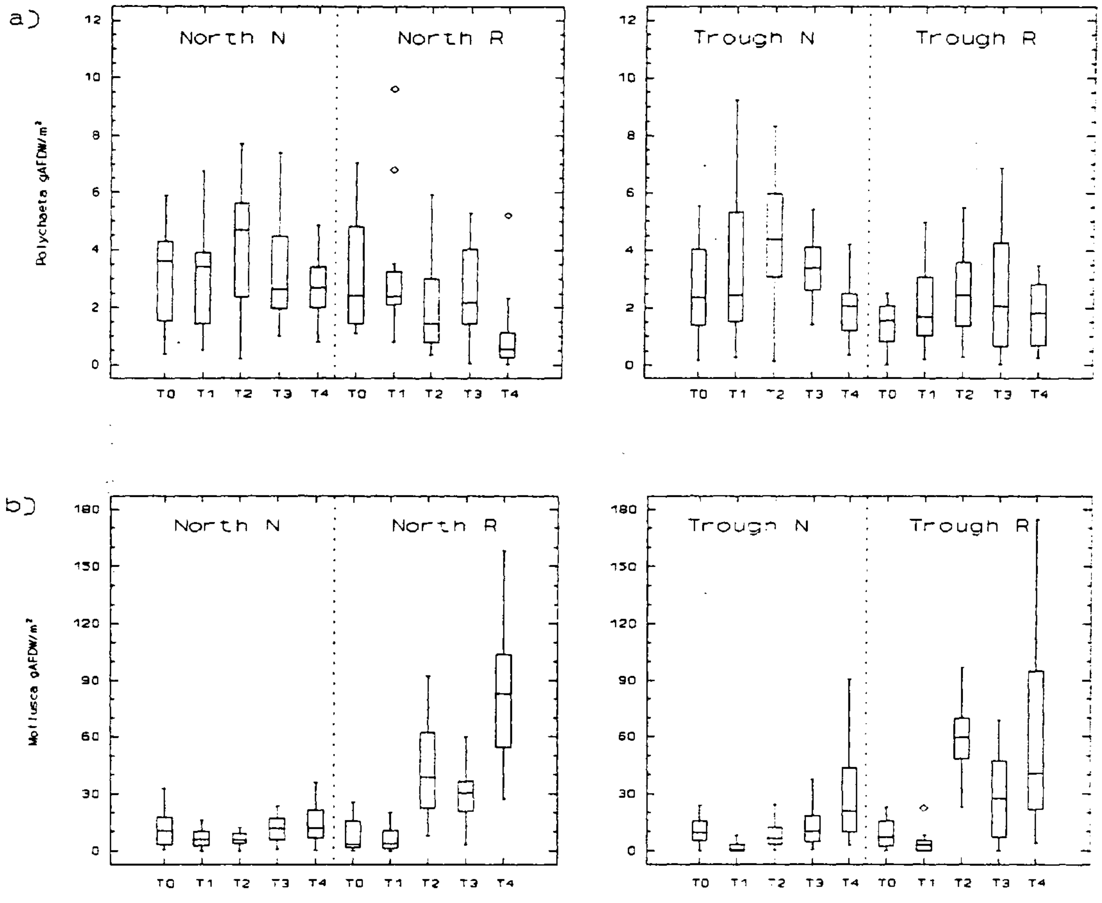


The biomass of polychaetous worms as present before (T0 survey) and after (T1 survey) the nourishment operation was not significantly different (Fig. A-15a). No significant change in polychaete biomass was observed during the successive surveys, neither in the strata of the nourishment area nor at the strata of the reference area.

The development of the biomass of the molluscs in the nourishment area was rather different from that in the reference area (Fig. A-15b). Both in the North and Trough stratum of the reference area significantly higher values were found from the T2 survey onwards. This is in strong contrast to the nourishment area where biomass remained low. In neither stratum of the nourishment any significant recruitment occurred in 1994 (T2 survey) nor in 1995 (T4 survey).

Figure A-15

Box and whisker plots of biomass (gram AFDW per m²) of polychaetes (a) and molluscs (b) in the North and Trough stratum, in the nourishment (N) area and reference (R) area, as measured in five successive surveys.

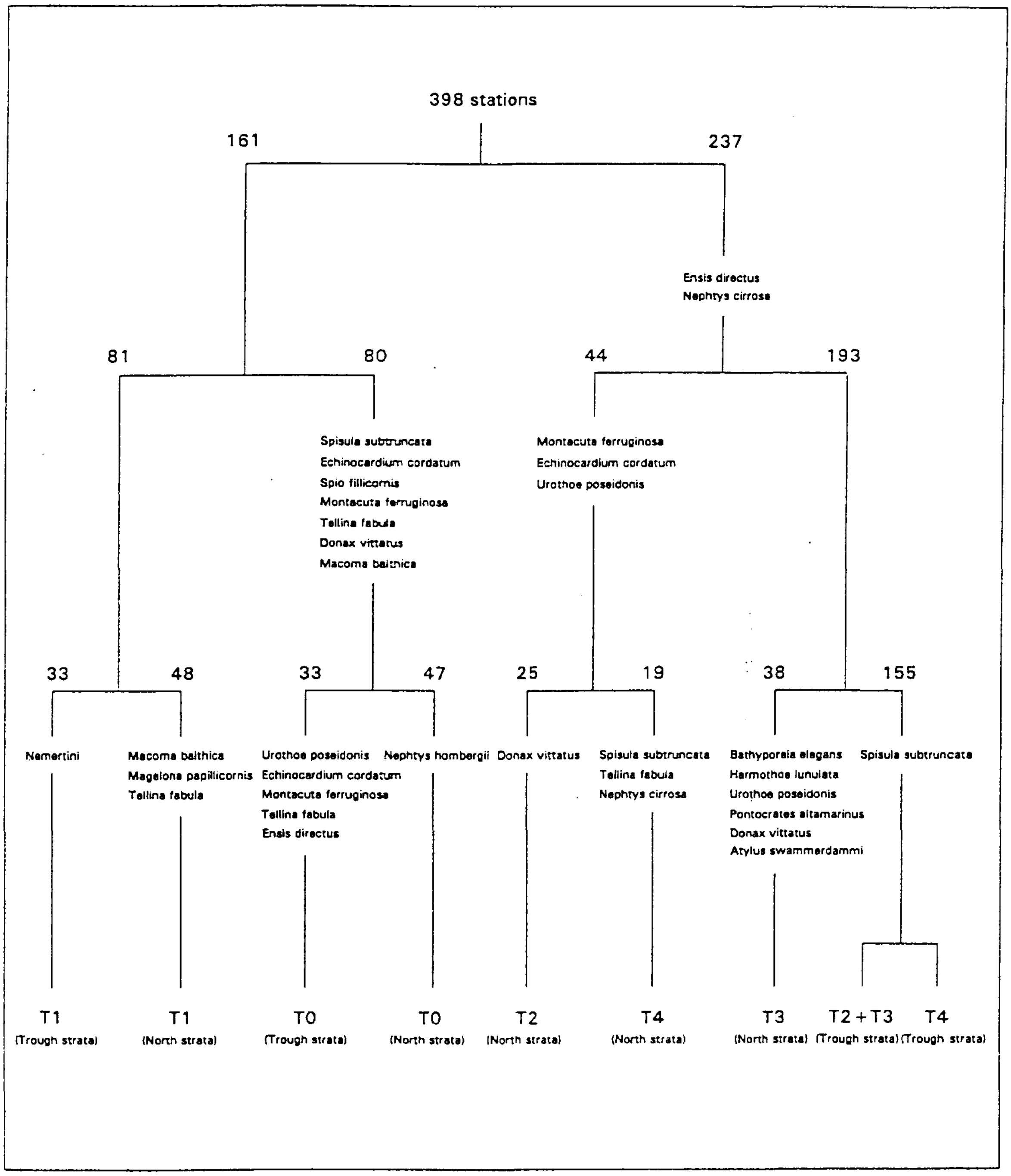


3.2.5 *Community structure*

*** *TWINSPAN cluster analysis.***
A TWINSPAN cluster analysis was performed on two different sets of data. This was due to the limited number of stations (up to 400) that could be handled by the available version of the TWINSPAN program. For the first analysis all data from the South stratum were omitted leaving a total of 398 stations, being all five surveys in the four remaining strata (North and Trough in nourishment and reference area). The second analysis dealt with all data (296 stations, including the South stratum) of the three spring surveys (T0, T1, T3).
The first cluster analysis, *i.e.* on all data except those from the South stratum, resulted in a separation of the stations of the T0 and T1 survey from those of the T2 - T4 surveys (Fig. A-16). This separation was strongly based on the appearance in the study area (in autumn 1994; T2 survey) of the American jack-knife clam *Ensis directus* and the polychaete *Nepthys cirrosa*. A separation of the stations of the T0 and T1 surveys was made in the second division of the cluster analysis. In the second division no clear separation of either surveys or strata was obtained, indicating no major difference in macrobenthic community structure between these surveys or strata.
Within the T0 and the T1 survey the stations of the North and Trough strata (of both nourishment and reference area) got reasonable well separated in the third division.

The second cluster analysis, using the data of the spring surveys (T0, T1, T3) only, also showed a general pattern of clustering of the stations per survey (Fig. A-17). In this case, however, the stations of the T1 survey were divided into two different clusters roughly separating the stations of both North strata from those of the two Trough strata and the South stratum. Also in this cluster analysis, the appearance of *Ensis directus* and *Nephtys cirrosa* in autumn 1994 defines the separate position of the T3 survey in the second division, whereas the strong decrease of densities of *Donax vittatus*, *Spisula subtruncata* and *Spio filicornis* following the nourishment operation demarcates the differences in benthic community between the T0 to the T1 surveys.

Figure A-16
TWINSPAN generated dichotomy of sampling stations (North and Trough strata; all five surveys) based on numerical density of macrofauna species. Indicator species and number of stations are indicated.



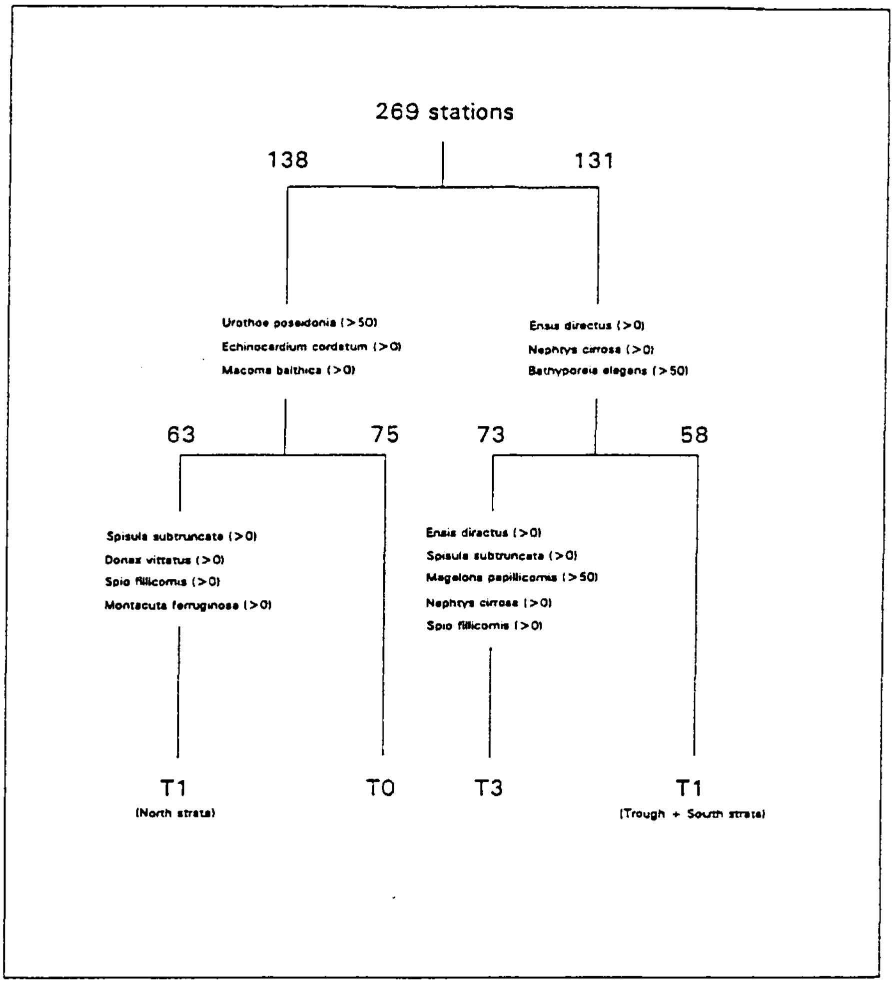
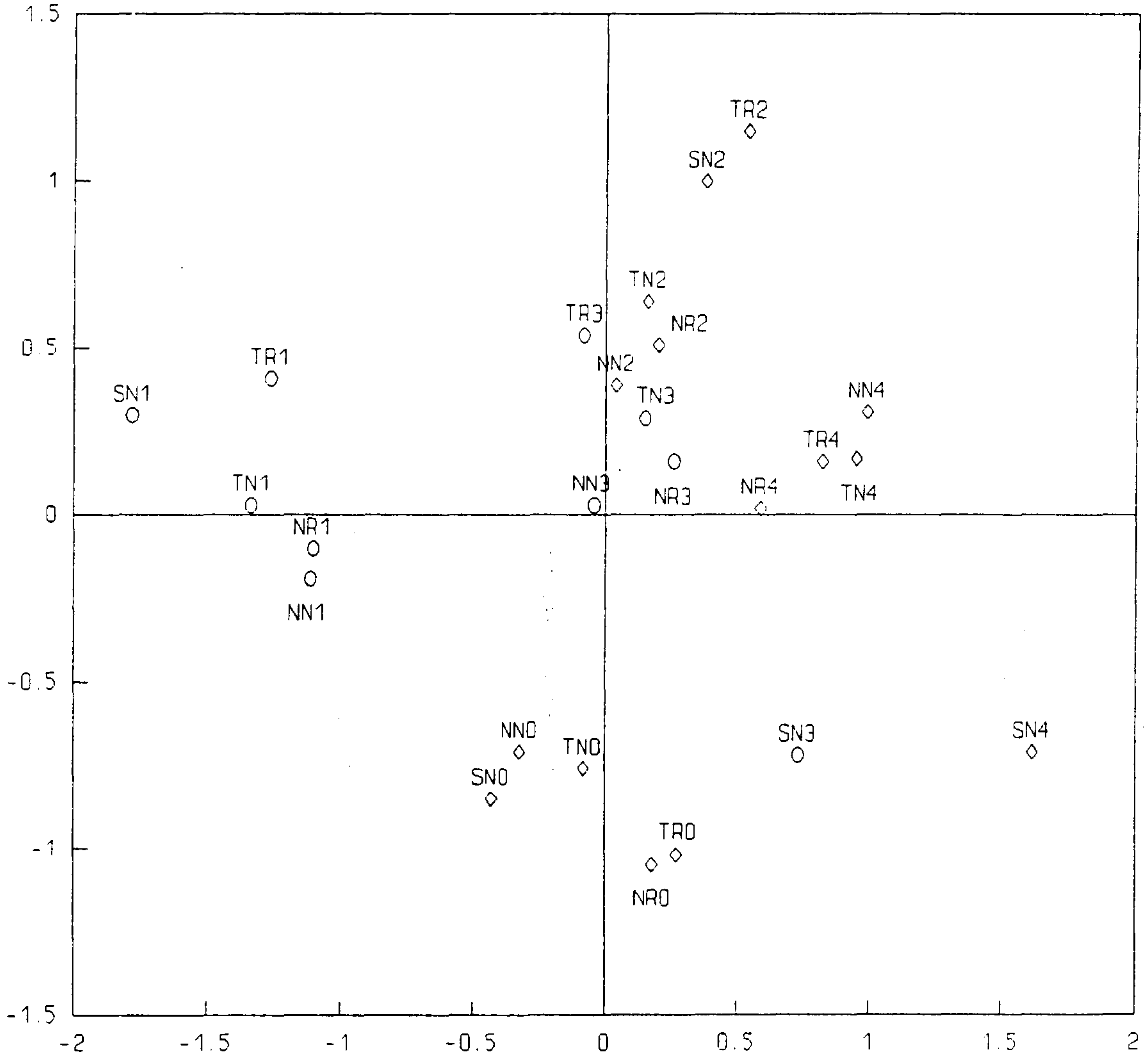


Figure A-17
TWINSPAN generated dichotomy of sampling stations (all strata; spring surveys T0, T1 and T3) based on numerical density of macrofauna species. Indicator species and number of stations are indicated.

**** MDS ordination***
An MDS ordination was carried out using the average species abundance data per stratum for each of the five successive surveys (Fig. A-18). The ordination reveals a reasonably well clustering of the different strata and the different surveys (stress factor = 0.166). The five strata of the T0 survey as well as the strata of the T1 survey are grouped in two distinct clusters. A third cluster is formed by the strata of the T2, T3 and T4 surveys, except for the South strata of booth the T3 and T4 survey.
The MDS analysis clearly showed that the community structure in the different surveys is distinct, though it is similar in the T2, T3 and T4 surveys. The community structure shifted from survey to survey, and did so most strongly between the T0 and the T1 survey, and after the T1 survey. The ordination of the abundance data does not show an effect of the nourishment 'treatment' on the community structure as the differences between the surveys apply to all strata equally without pointing towards the nourished Trough stratum as behaving differently.

Figure A-18

MDS ordination of the different strata per sampling survey in the nourishment and reference area North off Terschelling. Based on double-square-root-transformed average macrozoobenthos abundance per stratum. Strata: S = South , T = Trough, N = North. NN1 = North stratum of nourishment area in the T1 survey; NR1 = North stratum of reference area in the T1 survey, etc.



*** Canonical correspondence analysis (CCA)***

A canonical correspondence analysis (CCA) was carried out using the abundance data from both Trough strata of all five surveys (199 samples) (Fig. A-19).

Survey number is correlated with the first axis, indicating the importance of temporal development in the community. No significant correlation was found between the ordination of the samples and the abiotic parameters, not even for organic matter content of the sediment. Total biomass of macrozoobenthos was highly correlated with the numerical density of filter feeding species (this group included *Macoma balthica*). This is no surprise as the group of filter feeders consisted of bivalves only, which accounted for most of the total macrofaunal biomass.

The T0, T1 and T3 surveys are grouped along the first axis (X-axis; eigenvalue 0.386), whereas the stations of the T2 and T4 surveys are vertically spread along the second axis (Y-axis; eigenvalue 0.251) (Fig. A-20). The nourishment and reference stations of T1 survey are separated within their cluster (Fig. A-20). For the T2 survey, the ordination shows a much more distinct separation between the stations of the nourishment and reference area (Fig. A-19). This indicates a different development of the benthic community in terms of abundance in both Trough strata in the first year after the nourishment. The figure indicates that in the T3 and T4 surveys the benthic communities in both strata again have become more similar.

The effect of having sampled in different seasons of the year is visible in the different position in the ordination of stations of the two autumn surveys (T2 and T4; spread along axis 2) as compared to the stations of the T0, T1 and T3 surveys (spread along axis 1).

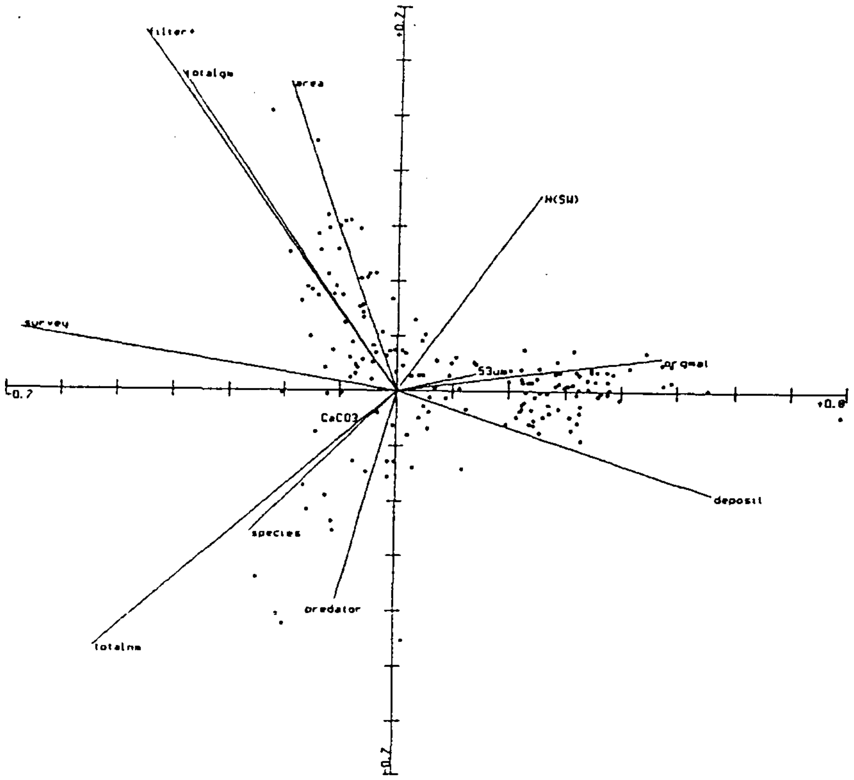
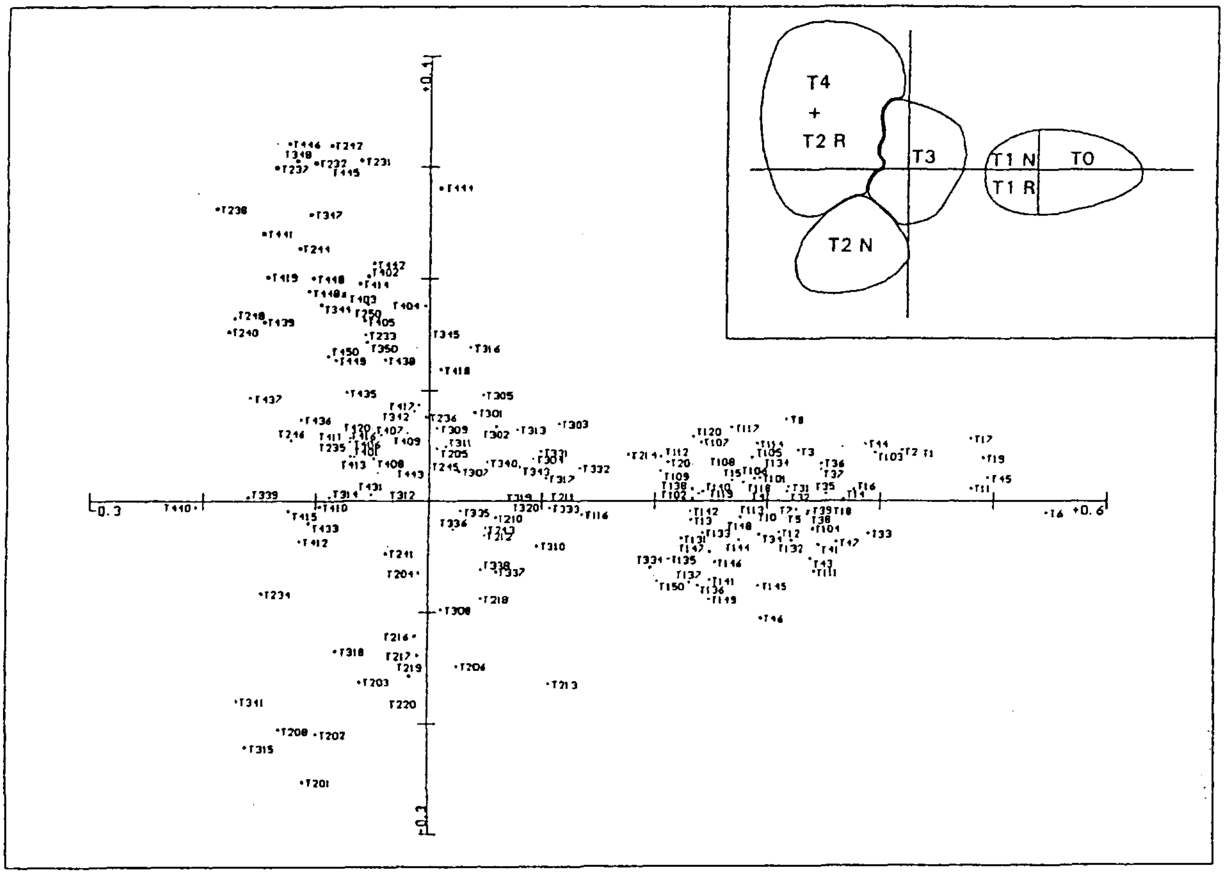


Figure A-19

CCA-ordination diagram of sampling stations and environmental variables of the Trough strata of nourishment and reference area in five successive surveys North of Terschelling, based on species abundance data. The environmental variables are represented by arrows: orgmat = % organic matter in the sediment; 53 μm = mud content (fraction < 53 μm); $CaCO_3$ = $\%CaCO_3$ in the sediment; depth = depth below NAP; survey = survey number; area = nourishment or reference area; species = number of species per station; totalgm = total biomass (g AFDW/m^2); totalnm = total macrofauna density (n/m^2); predator = total predator density (n/m^2); deposit = total density of deposit feeders (n/m^2); filter = total density of filter feeders (n/m^2); H(SW) = Shannon-Wiener diversity index. The CCA biplot does not show all samples as some are overlapping.

Figure A-20

Central part of figure 19 in more detail. Envelopes of survey station groups are drawn. A schematic grouping of the stations of the five surveys is given in the right corner above.



** Age composition*

The nourishment caused a covering of the macrofauna with a layer of sand. Therefore, a decline in macrofauna abundance was predicted as described in chapter 3.2.3. Especially the less mobile species (*e.g.* bivalves), were expected to be affected. However, in the T1 survey a decline in bivalve density was observed in both nourishment and reference areas. In the following surveys an increase in abundance was found which was much larger in the reference area than in the nourishment area. To investigate whether within a species groups of individuals of different age were more affected than others the abundance of different length classes was compared before and after the nourishment (VAN ESSEN, 1996a).
After the nourishment (T1 survey, April 1994), the population of *Spisula subtruncata*, mainly consisting of older specimens (25-35 mm), had disappeared almost completely in all strata of the nourishment and reference area (Fig. A-21). In the autumn of 1994 (T2 survey) this species reappeared with densities (of small animals; not shown in Fig. A-21) that were much higher in the reference area than in the nourishment area.
After the T2 survey densities of *Spisula subtruncata* remained high. The T3 survey (April 1995) showed a dominating abundance of 15-25 mm large specimens, supposed to be mainly of year class 1994. The lower densities in the nourishment area as compared with the reference area may relate to the nourishment.
Ensis directus was absent before (T0 survey) and directly after the nourishment (T1 survey), but showed a considerable population growth during 1994 (T2 survey), resulting in 30-60 mm large specimens to be present in April 1995 (T3 survey) (Fig. A-22). As in *Spisula subtruncata*, the highest abundances were reached in the reference area.
For the bivalves *Donax vittatus*, *Tellina fabula*, *Tellina tenuis* and *Macoma balthica*, no changes in densities of the different size classes were found that could be related to the nourishment nor was there a difference in development between the nourishment and the reference area. This is illustrated for *Tellina fabula* in Fig. A-23.

Figure A-21
Abundance (n/m²) of different size classes (shell length; mm) of *Spisula subtruncata* in the Trough stratum of the nourishment area (top panels) and the Trough stratum of the reference area (bottom panels) in March 1993 (T0), April 1994 (T1) and April 1995 (T3).

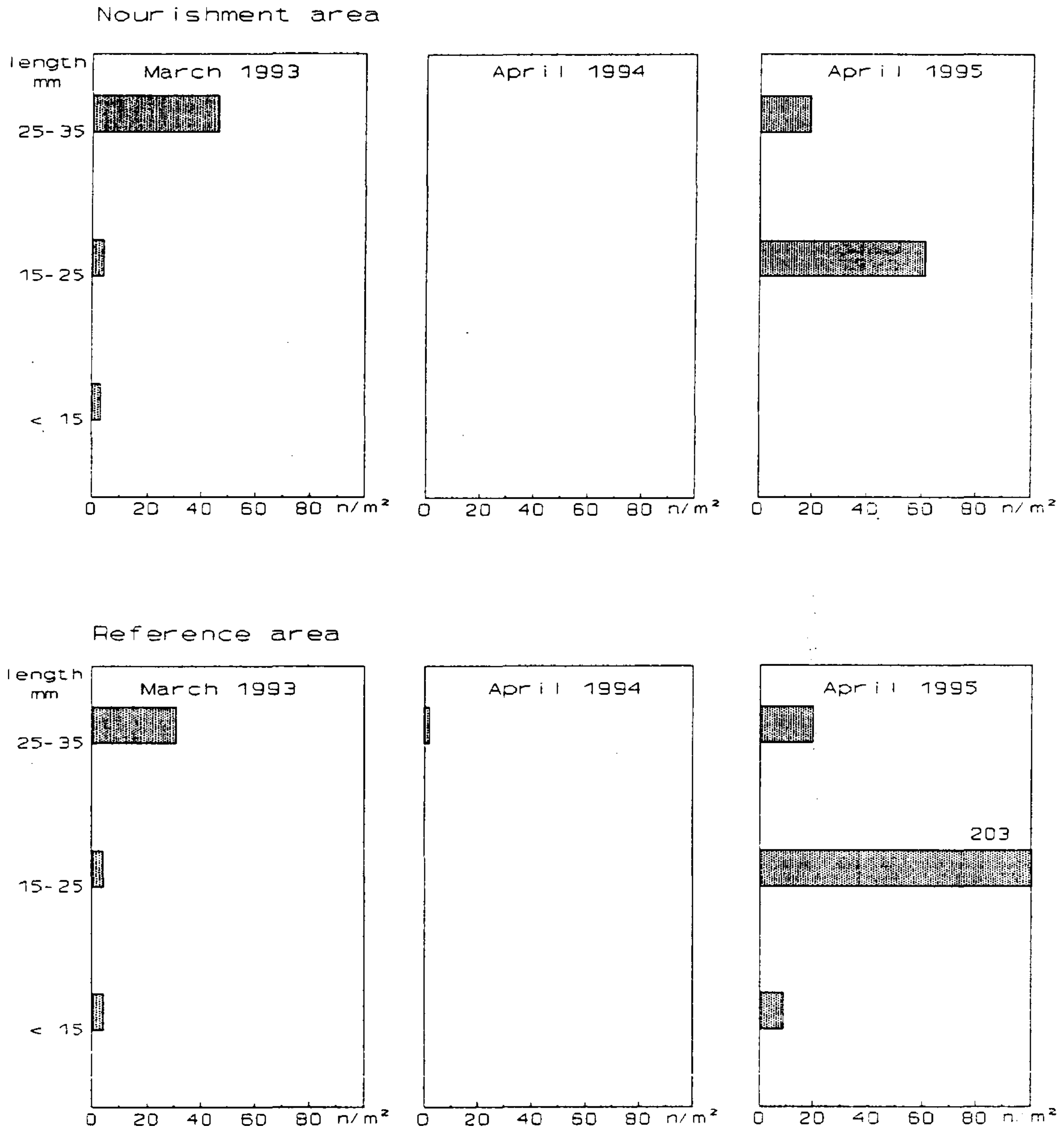


Figure A-22
Abundance (n/m²) of different size classes (shell length; mm) of *Ensis directus* in the Trough stratum of the nourishment area (top panels) and the Trough stratum of the reference area (bottom panels) in March 1993 (T0), April 1994 (T1) and April 1995 (T3).

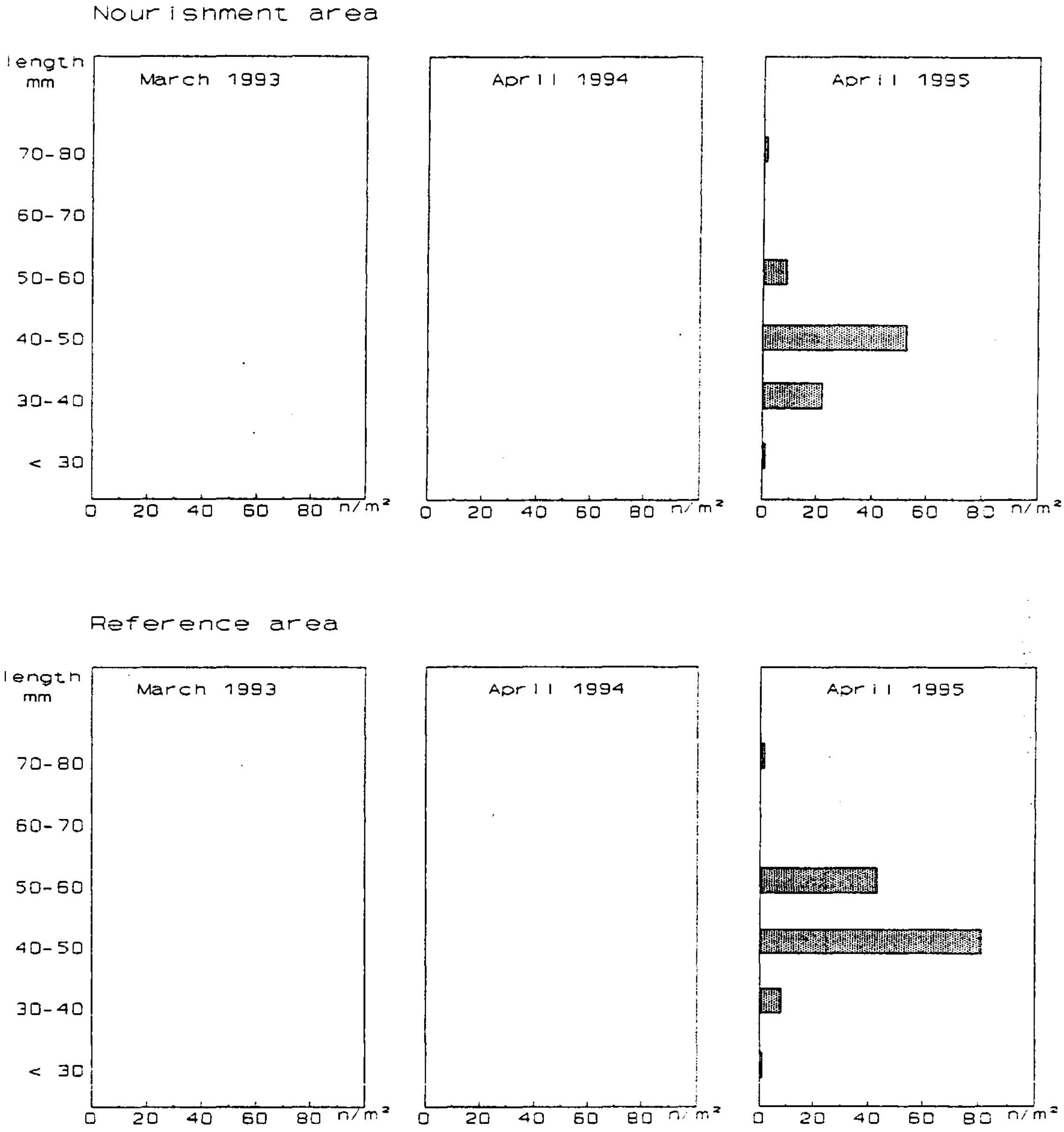
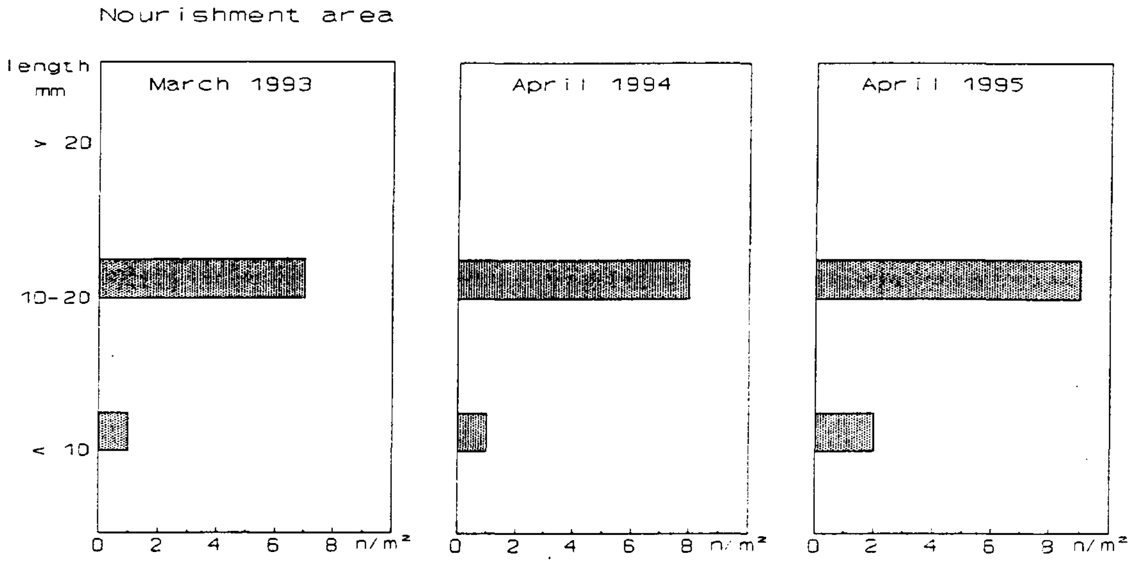
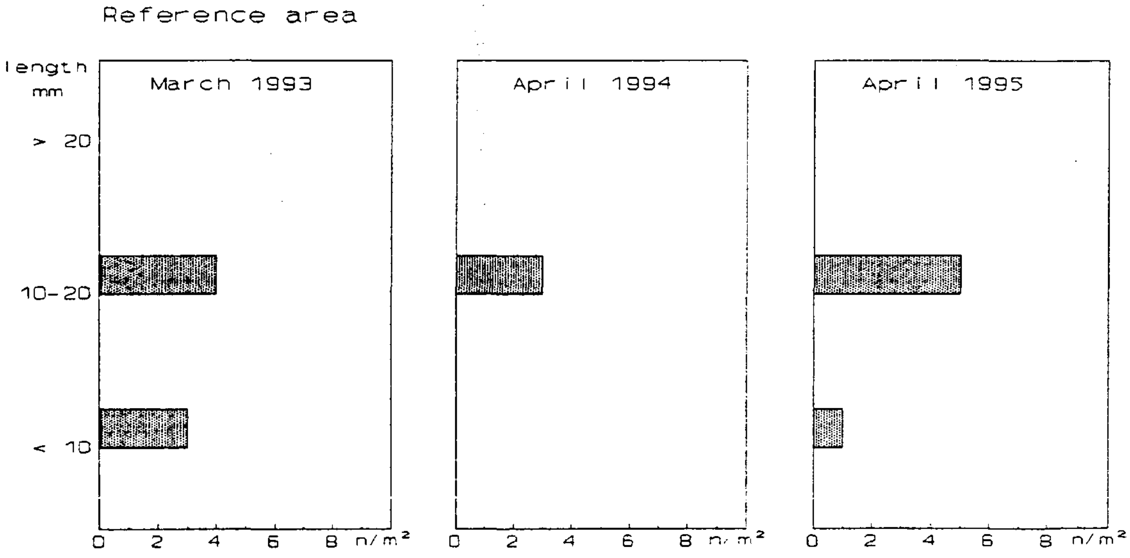


Figure A-23
Abundance (n/m²) of different size classes (shell length; mm) of *Tellina fabula* in the Trough stratum of the nourishment area (top panels) and the Trough stratum of the reference area (bottom panels) in March 1993 (T0), April 1994 (T1) and April 1995 (T3).





*** Functional groups***

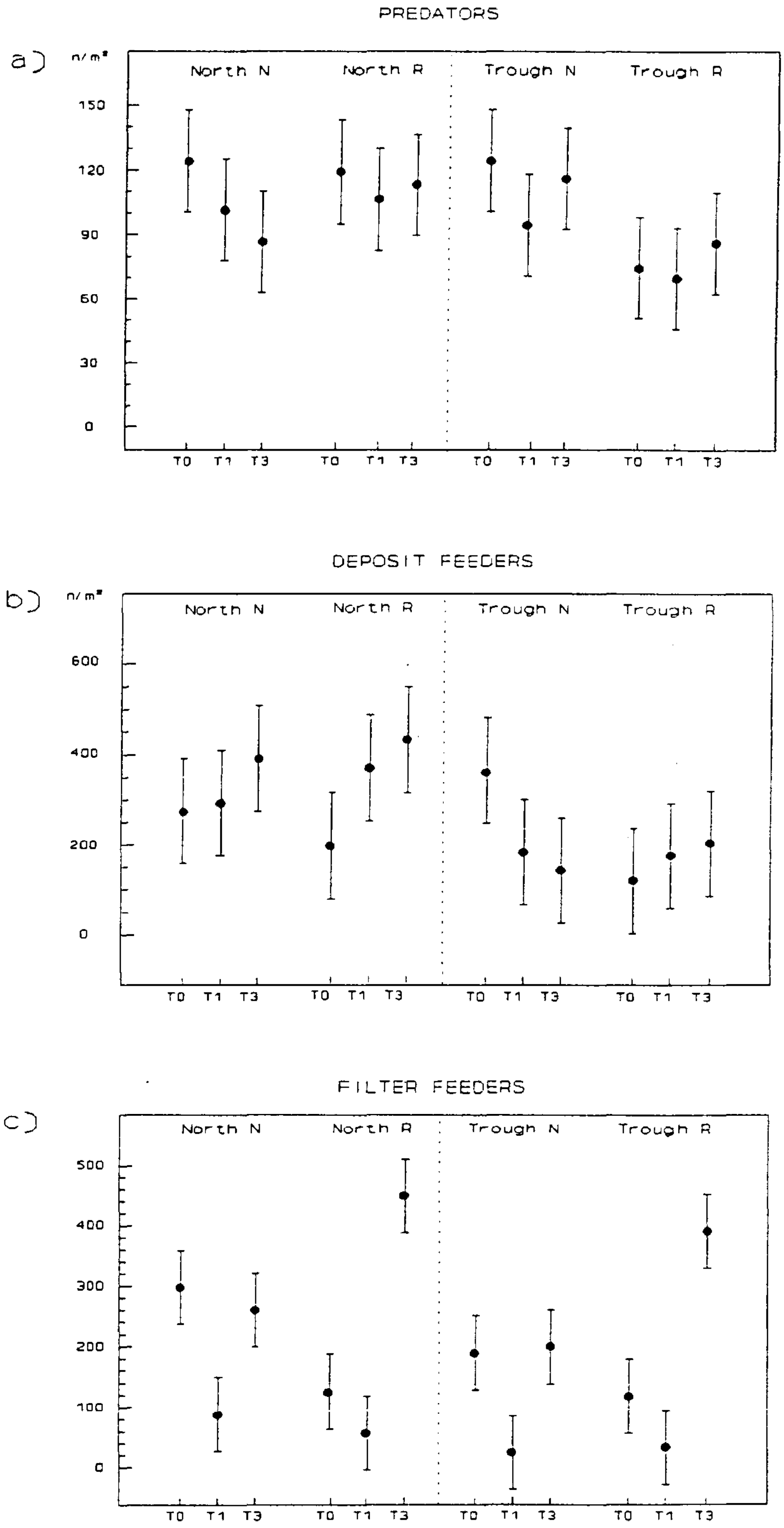
To investigate whether different feeding groups among the macrozoobenthos were affected differently by the nourishment the benthic fauna of the nourishment area was classified into predators (mainly consisting of polychaetes), deposit feeders (polychaetes and crustaceans) and filter feeders (mainly bivalve molluscs). Classification according to feeding type was possible for 63 species of the total of 75 species encountered (see Appendix A). Of these 63 species 15 were classified as predators, an other 15 as deposit feeders or grazers and 17 species as filter feeders. The remaining 16 species had a mixed feeding type and were therefore excluded from the analysis.

No significant changes in predator abundance were found in the nourishment nor in the reference area (Fig. A-24a). The deposit feeders decreased in the Trough stratum of the nourishment area from T0 survey to the T1 survey and their density remained low at the T3 survey, whereas at the North and Trough strata of the reference area a significant increase of densities was found from the T0 to the T3 surveys (Fig. A-24b).

The filter feeders decreased significantly in the nourishment area (both in Trough and North stratum) from the T0 survey to the T1 survey. A recovery of the filter feeder abundance to pre-nourishment values was found from T1 to T3 survey (Fig. A-24c). In the reference area a decrease in the abundance of filter feeders (bivalves) was observed from the T0 to the T1 survey. One year later, this group had strongly increased again in the T3 survey in both strata of the reference area.

Figure A-24

Average densities (n/m²) and standard error of predators (a), deposit feeders (b) and filter feeders (c) among the macrozoobenthos in the different strata as found in three spring surveys (March 1993; T0, April 1994; T1 and April 1995; T3).



4 Discussion

4.1 Methodology

No results were presented of the South stratum of the nourishment area. The reason for this is the absence of the proper possibility for comparison with a similar stratum in the reference area. The benthic fauna in the South stratum, however, has been more or less stable throughout the five surveys. The shallowness of this stratum and its position near the beach makes this stratum probably the most dynamic in the system studied. The relative poor benthic community in this stratum is likely to be well adapted to the high dynamics of the system and seems not to fluctuate much. This is in agreement with MARGALEF (1968) who was of the opinion that in physically unstable conditions only a limited number of species can be successful.

During the period of investigation a clear effect of the sampling season (spring *vs.* autumn) can be seen in the data. In the autumn surveys T2 and T4 an overall increase of macrofauna density biomass was found. The surveys can therefore not directly be compared with the T0 survey which was conducted in early spring, but may be used to describe the effects of the nourishment on settlement and other recovery processes.

4.2 Short-term effects

4.2.1 Abiotic changes

The nourishment changed the seabed morphology of the Trough stratum of the nourishment area because of a reduction of depth. The import of sand from the extraction area resulted in a sediment which was coarser and less well sorted than the original sediment at the nourished area (GUILLÉN, 1995). However, redistribution of the sediment by natural processes resulted in a fast restoration of the sediment structure. Six months after the nourishment was completed, the grain size distribution and the median grain size showed no significant changes with pre-nourishment situation (GUILLÉN, 1995).

4.2.2 Changes in biota

The relationship between macrofauna distribution and sediment composition has been the subject of several publications (e.g. DANKERS & BEUKEMA, 1981; SALZWEDEL *et al.*, 1985; KÜNITZER *et al.*, 1992; MACKIE *et al.*, 1995). Often high correlations of community structure and species distribution with the sediment composition were found. Gross differences in sediment type (gravel, sand, silt) are mostly related to

different communities, whereas within a certain sediment type, distributional ranges of macrofauna may be rather large (*cf.* WOLFF, 1973; DANKERS & BEUKEMA, 1981).
In this study, changes in the composition of the sediment were found for the contents of $CaCO_3$ and organic material. The changes that were observed, however, occurred in both nourishment and reference area and therefore must have a natural origin.
The major effects of the nourishment on the macrofauna community are likely to be caused by the sudden sediment deposition during the actual nourishment operation. Estimations of the sedimentation rates during this nourishment operation ranged from 1.5 meter per 120 hours up to 1.5 meter per 30 hours (TYDEMAN, 1994). At the lower sedimentation rate certain species would be able to survive by crawling upward into the new layer of sand (cf. BIJKERK, 1988; ESSINK, 1997). Survival of species can therefore not be excluded. A small-scale survey conducted in November 1993 (TYDEMAN, 1994) showed that shortly after completion of the nourishment some benthic fauna was already present. This indicates that recovery of the benthic community started immediately, probably through survival of the original fauna and immigration of organisms from the surrounding areas. Finally, import of species from the extraction area cannot be completely excluded (TYDEMAN, 1994).

No evidence was found for a rapid colonisation of the 'open space' in the nourished sand by opportunistic species. In contrast, in the T1 survey known opportunists as *Spiophanes bombyx* and *Spio filicornis* were reduced in abundance (see further explanation below). *Spio filicornis* reappeared in large densities only in the T2 survey.
Directly after the nourishment (T1 survey), in the nourished area a decline was found in the density of deposit feeders (*e.g. Urothoe poseidonis* and *Echinocardium cordatum*) and filter feeders (*e.g. Macoma balthica*). Also species richness and diversity had decreased. These changes were not seen at the reference area, and may therefore be attributed to the nourishment operation.

4.3 Longer term effects

4.3.1 Abiotic changes

At the nourishment site the sea bed morphology changed after completion of the nourishment operation. A new trough developed in the nourished area leading towards a restoration of the original system of breaker bars and troughs in between (BIEGEL *et al.*, 1995a; HOEKSTRA *et al.*, 1996).
The mud- and $CaCO_3$-content of the sediment had decreased significantly since the T0 survey, not only in the nourishment area but also in the reference area. This lasting change in sediment structure in the nourishment area is in contrast with the results of sediment analysis of NOURTEC showing that six month after completion of the nourishment the grain size composition in the nourished area did not longer differ (GUILLÉN, 1995).
As the changes in sediment composition showed similar patterns in the nourishment and the reference area, it has to be concluded that the

natural local hydrodynamic processes play an overriding role in the morphodynamics and sediment dynamics of the foreshore of Terschelling. No clear lasting effect of the nourishment on the sediment parameters was found.

4.3.2 Changes in biota

After the nourishment (T1 survey) the average number of species per sample at the nourishment site had decreased as compared to the T0 survey. This short-term impoverishing effect of the nourishment had disappeared by the T3 survey, when species numbers as present in the T0 survey had re-established. From the T0 survey to the T3 survey, there has been a general increase of the total number of species found, at the nourishment site as well as at the reference site. Therefore, the increase in species number at the nourishment site cannot be considered as a response of opportunistic species to a disturbance of the benthic habitat; it has to be considered as a natural fluctuation in the dynamic shoreface system.

*** Species abundance and biomass**

Some of the more abundant species at the nourishment area in the T0 survey had decreased in numbers in the T1 survey, *viz. Spiophanes bombyx, Urothoe poseidonis, Macoma balthica* and *Echinocardium cordatum*. Other species had disappeared (*e.g. Spio filicornis* and *Spisula subtruncata*), but reappeared in the T2 survey. In *Spisula subtruncata* decreased densities and biomass were found in the T1 survey in April 1994. This is in agreement with the very strong decline in this species found all along the Dutch coast between 1993 and 1994 (LEOPOLD, 1996a) which is partly due to fishery for this bivalve and partly due to heavy predation by sea ducks. In the summer of 1994, however, a good settlement of spat of *Spisula subtruncata* occurred, followed by a remarkable growth of these juveniles during autumn (LEOPOLD, 1996). Also in *Spio filicornis*, natural fluctuations must be considered as the explaining factor for its decrease in the nourishment area, as this species simultaneously disappeared also in the reference area. In *Urothoe poseidonis, Macoma balthica* and *Echinocardium cordatum*, however, the observed decline may be a result of the nourishment operation. In his overview of the effects of increased sedimentation on some benthic organisms BIJKERK (1988) described an increased mortality of the latter two species if confronted with a sudden sand coverage of 30 cm or more. Such a sudden sediment coverage may be easily met by the use of split hopper dredges releasing their cargo in a very short instance of time. In the Trough stratum of the nourishment area the density of *Urothoe poseidonis, Macoma balthica* and *Echinocardium cordatum* remained low in the successive surveys when compared to the other strata.

The total abundance and biomass of the macrofauna in the nourishment area in April 1995 (T3 survey showed a recovery towards the pre-extraction values of the T0 survey (March 1993). This recovery of macrofauna abundance can be explained by the strong growth of the populations of *Magelona papillicornis* and *Spio filicornis*, particularly in the nourishment area, whereas *Bathyporeia elegans, Nephtys cirrosa* and the molluscs *Ensis*

directus and *Spisula subtruncata* showed a much higher population growth in the reference area.
Following the nourishment, the total biomass in the Trough stratum decreased, both in the reference area (not significant) and in the nourishment area (significant) (see Fig. A-14). After having excluded *Spisula*, which showed an overall increase, the biomass decrease in the Trough stratum of the nourishment area remained significant. So, a negative effect of the nourishment operation on the development of total biomass is evident in the Trough stratum of the nourishment area.
From the T2 survey onward, biomass in the Trough stratum of the nourishment area had about the same values as in the T0 survey. This was due to the appearance of *Ensis directus* and *Spisula subtruncata* in 1994. In the Trough of the reference area, however, a much larger increase of *Ensis directus* and *Spisula subtruncata* occurred. It is difficult to say whether this difference in development of these two bivalve species is a delayed effect of the nourishment or is caused by chance.
So, a differential development of the benthic community in the nourishment and reference area occurred. Possibly, the nourishment has changed the area in such a way that spatfall and survival of *Spisula subtruncata* and *Ensis directus* were not as successful in the nourishment area as in the reference area, while the opposite is true for some (opportunistic) polychaetes such as *Magelona papillicornis* and *Spio filicornis*.

A most striking development in the macrobenthos abundance is the strong increase in 1994 (from T1 to T2 survey). This was observed both in the nourishment and the reference area. Therefore, this development has to be considered merely as the result of a successful reproduction season.
With regard to biomass a striking increase in 1994 was only observed in the reference area, mainly due to the already discussed increase of *Ensis directus* and *Spisula subtruncata*.

• Community structure
The TWINSPAN analyses performed on each spring survey separately, showed that from the T0 to the T1 survey the community structure of the Trough stratum of the nourishment area shifted towards that of the relative poor South stratum. In the T3 survey, the community structure of the Trough stratum had changed backward to the pre-extraction situation (VAN DALFSEN & PINKHAM, 1994; VAN DALFSEN & DUYTS, 1995; VAN DALFSEN & BUNT, 1996). When the data of all five surveys were used (except the South stratum) this development in the Trough stratum is no longer visible due to the overriding role in the TWINSPAN divisions of the strongly increasing numbers of *Spisula subtruncata* and *Ensis directus* in the reference area.

The CCA ordination showed the following development of the benthic communities in the area studied. Firstly, in the T1 survey a difference between the nourishment and reference area started to develop. Secondly, this difference has become more pronounced in the T2 survey, possibly as a result of different reproduction success in the different areas. In the T3 survey, however, the difference between nourishment and reference area

has disappeared, indicating the recovery of the community in the nourishment area.
No clear impact of the nourishment on the age composition of bivalves could be demonstrated, mainly due to the low abundance of most bivalve species investigated.
No changes in the abundance of predators or deposit feeders were found between the T0 and T3 at the nourishment area. The striking difference between the nourishment and the reference area in the density of filter feeders at the T3 survey is entirely explained by the different development *Spisula subtruncata* and *Ensis directus*.

4.4 Effects on consumers of benthos

For diving ducks, especially *Spisula subtruncata* is an important food source when concentrated in large *Spisula* banks. These banks did exist along the Dutch coast. Off Terschelling large *Spisula* banks were located just North of the nourished area (M.F. Leopold, personal comm.). Therefore, no direct impact of the nourishment on these banks is likely to have occurred. New banks of *Spisula subtruncata* do not necessarily develop at the same locations as old ones (*cf.* LEOPOLD, 1996; LEOPOLD & VAN DER LAND, 1996). Therefore, there is a fair chance that any future shoreface nourishment will indeed affect *Spisula* banks as food source for sea ducks and/or as exploitable stock for fishermen.

As diving ducks feeding for molluscs are very sensitive to disturbance, the ships transporting the sand from borrow area to the nourishment site may affect these birds. Such an effect, however, is not very likely as the majority of the ducks are wintering guests present from September till May, whereas the nourishment activities were carried out for only a short time within this period.

The shallow coastal zone between 2 and 10 m depth is of importance as a nursery for plaice (*Pleuronectes platessa*) and sole (*Solea solea*) (VAN BEEK *et al.*, 1989) and also for dab (*Limanda limanda*), brill (*Scophthalmus rhombus*) and turbot (*Psetta maxima*) (KNIJN *et al.*, 1993). For plaice it was found that the coastal zone of the island of Texel (ca. 20 km SW of Terschelling) is of similar importance as nursery as the well documented Balgzand area inside the Dutch Wadden Sea (MENGEDOHT, 1995). These juvenile flatfish mainly feed on amphipods, polychaetes and small bivalves.
Earlier in this report, it was shown that density of crustaceans and biomass of polychaetes did not really change from survey to survey, not even in the Trough stratum of the nourishment area where all sand was deposited (see Figs. 13c and 15a). Nourishment did only affect the total bivalve biomass (Fig. A-15b), mainly as a consequence of a decrease in abundance of larger specimens. This decrease from T0- to T1 survey was calculated to equal a loss of bivalve biomass of approx. 4000 kg ash-free dry weight (in 1.7 km^2 nourished area). Therefore, a longer term decrease of food availability to juvenile flatfish due to nourishment is not very likely. Only very short-term effects for juvenile flatfish may be expected to occur

during the actual nourishment operation due to local disturbance and burial of local benthos. As the nourishment area is 1.7 km^2 this is only 0.5% of the ca. 350 km^2 large 2 - 10 m deep coastal zone North of the Dutch Wadden islands. Even if three nourishment operations of 5 km^2 each were carried out at the same time this would affect not more than 2.5% of the nursery function of this coastal habitat for a very short time.

5 Conclusions

The effects of sand nourishment on the benthic fauna as observed in the case off the island of Terschelling are relatively small. Short-term as well as longer term effects can be discriminated regarding the benthic community, and also effects on consumers of the benthic fauna.

5.1 Short-term effects

The direct effect of deposition of a body of sand was restricted mainly to the trough that had been filled up. Here, a short-term reduction of bivalve abundance and biomass of bivalves and sea urchins (*Echinocardium cordatum*) was the most conspicuous effect, which was mainly due to the disappearance of older specimens from the population. No evidence was found for a quick development of opportunistic species colonizing the nourished sand body.

5.2 Longer term effects

After completion of the nourishment operation, the sea bed started to restore its original morphology with troughs and breaker banks. To a very large extent, recovery of the seabed morphology and of the benthic fauna took place within two years time. Only the recovery of the total biomass was not completed in this period as this is linked to the growth of long living species as molluscs and echinoderms.

Differences in the development of the benthic community did occur between the nourished and the reference area, but these differences could not easily be related to the nourishment activity. The natural hydrodynamic processes in this highly dynamic coastal system seem to be of major importance to the development of the local benthic community.

5.3 Risk to fish and birds

The shallow coastal zone between 2 and 10 m depth is of importance as a nursery for various species of flatfish. As benthic prey species of these juvenile flatfish are likely to be affected by deposition of a body of sand shoreface nourishment poses a potential risk to the nursery function of the shallow coastal zone. It was shown, however, that nourishment mainly caused a relatively small and short-term decline of bivalve biomass. Part of this decline, however, was due to disappearance of larger bivalves that are not important as prey to most of the juvenile fish. Therefore, it is concluded that the nursery function of this coastal habitat is only slightly affected for only a very short time.

The nourishment North of Terschelling did not affect food resources (*Spisula subtruncata*) of diving ducks such as common scoters (*Melanitta* *nigra*). These birds are known to feed especially on *Spisula* banks. Such banks were not present in the nourished area. In other instances, however, shoreface nourishment may very well strike important *Spisula* banks, and then pose a serious risk to the survival of wintering sea ducks.

Appendix A.

List of macrobenthos species collected during the RIACON project in the shoreface nourishment and reference area off the island of Terschelling between March 1993 and October 1995, and the number of stations were the species were found for each of the surveys.

Species indicated with an asteriks (*) were excluded from the data analyses (see 2.7).

Phylum codes:

1 Mollusca
2 Crustacea
3 Annelida
4 Echinodermata
5 Nemertinae

Taxon codes:

A Amphipoda
B Bivalva
D Decapoda
E Echinoidea
G Gastropoda
I Isopoda
M Mysidacea
N Nemertinea
O Ophiuroidea
P Polychaeta
S Asteroidea
U Cumacea

Feeding type codes:
1 scavenger & omnivore
2 omnivore & predator
3 filter feeder
4 filter feeder and selective deposit feeder
5 non-selective deposit feeder
6 non-selective deposit feeder & predator
7 predator
8 predator & omnivore
9 selective deposit feeder or grazer
10 selective deposit feeder or grazer & filter feeder
11 (non)-selective deposit feeder or grazer
12 predator & filter feeder
13 predator & grazer

Assignment of species to feeding type was done according to: FAUCHALD & JUMARS (1979); HARTMANN-SCHRÖDER (1969); HOLTMANN *et al.* (1996); MULDER *et al.* (1988); NAYLOR (1972); PLEIJEL & DALES (1991); RUPPERT & BARNES (1994); SEIP & BRAND (1979) and STECHER & DÖRJES (1993).

Species	Abreviation	Phylum	Taxon	Feeding type	present in n stations (total nr. of stations) T0 1993 (89)	T1 1994 (90)	T2 1994 (90)	T3 1995 (90)	T4 1995 (89)
Abra alba	ABRAALBA	1	B	9			1		1
Donax vittatus	DONAVITT	1	B	3	43	9	25	20	12
Ensis arcuatus	ENSIARCU	1	B	3	1		2	8	
Ensis directus	ENSIDIRE	1	B	3	10	11	84	77	69
Ensis siliqua	ENSISILI	1	B	3			8		
Lunatia catena	LUNACATE	1	G	7		1			
Macoma baltica	MACOBALT	1	B	10	59	36	39	32	24
Mactra corallina	MACTCORA	1	B	3	3		13	7	5
Montacuta ferruginosa	MONTFERR	1	B	3	30	8	22	18	18
Mysella bidentata	MYSEBIDE	1	B	3		3	6	6	3
Spisula solida	SPISSOLI	1	B	3		2	2		
Spisula subtruncata	SPISSUBT	1	B	3	63	10	75	74	82
Tellina fabula	TELLFABU	1	B	10	45	35	45	45	41
Tellina tenuis	TELLTENU	1	B	4	39	37	33	29	28
Atylus falcatus	ATYLFALC	2	A	9		12	2		
Atylus swammerdami	ATYLSWAM	2	A	9		26	20	17	13
Bathyporeia elegans	BATHELEG	2	A	9	45	67	54	70	31
Bathyporeia guilliamsoniana	BATHGUIL	2	A	9		15	10	16	5
Corophium volutator	COROVOLU	2	A	11			1	1	
Crangon allmanni*	CRANALMA	2	D	8				5	
Crangon crangon*	CRANCRAN	2	D	8	8	2	16	1	
Crustacea larvae*	CRUSLARV	2	D	8		7			
Diastylis lucifera	DIASLUCI	2	U	9		1			
Diogenus pugilator	DIOGPUGI	2	D				2		1
Eurydice pulchra	EURYPULC	2	I	7				1	1
Gammarus duebeni	GAMMDUEB	2	A	9	6				
Gammarus salinus	GAMMSALI	2	A				1		
Gastrosaccus spinifer*	GASTSPIN	2	M	8		1		5	
Idotea linearis	IDOTLINE	2	I	9		2		5	
Liocarcinus holsatus*	LIOCHOLS	2	D	7		1	7	3	4
Liocarcinus marmoreus*	LIOCMARM	2	D			3	1		
Liocarcinus pusillus*	LIOCPUSI	2	D						2
Microprotopus maculatus	MICRMACU	2	A	7			17	10	1
Mysis species*	MYSISPEC	2	M			6		2	
Neomysis integer*	NEOMINTE	2	M		2		1	1	
Orchomene nana	ORCHNANA	2	A				1		
Pagurus bernhardus	PAGUBERN	2	D	2			1	2	
Pariambus typicus	PARITYPI	2	D					1	
Pinnotheres pisum	PINOPISU	2	D		1				
Pontocrates altamarinus	PONTALTA	2	A	9	38	74	35	66	1
Pontophilus trispinosus*	PONTTRIS	2	D				3		15
Portumnes latipes	PORTLATI	2	D	1	6		2		
Pseudocuma longicornis	PSEULONG	2	U	9			1		

					present in n stations (total nr. of stations)				
Species	Abreviation	Phylum	Taxon	Feeding type	T0 1993 (89)	T1 1994 (90)	T2 1994 (90)	T3 1995 (90)	T4 1995 (89)
Schistomysis kervillei*	SCHIKERV	2	M	8	8		2		
Syriella armata*	SYRIARMA	2	M				1		
Urothoe poseidonis	UROTPOSE	2	A	9	65	63	73	65	64
Anaitides maculata	ANAIMACU	3	P	7	2	1	1	1	
Anaitides mucosa	ANAIMUCO	3	P	7				1	
Anaitides subulifera	ANAISUBU	3	P	7			3		1
Autolytus prolifer	AUTOPROL	3	P	13			2		
Capitella capitata	CAPICAPI	3	P	5			34	16	11
Chaetozone setosa	CHEASETO	3	P	9			1	1	
Eteone longa	ETEOLONG	3	P	7		1	1		
Eumida sanguinea	EUMISANG	3	P	7		5	12	6	3
Eumida species	EUMISPEC	3	P	7		2			
Harmothoe ljungmani	HARMLJUN	3	P	7		1			14
Harmothoe lunulata	HARMLUNU	3	P	7	6	10	18	28	
Lanice conchilega	LANICONC	3	P	10	25	31	17	19	22
Magelona papillicornis	MAGEPAPI	3	P	4	43	50	83	76	78
Nephtys caeca	NEPHCAEC	3	P	2		17	25	21	1
Nephtys cirrosa	NEPHCIRR	3	P	2			32	47	85
Nephtys hombergii	NEPHHOMB	3	P	2	80	85	82	82	65
Nephtys longosetosa	NEPHLONG	3	P	2			1		1
Nereis longissima	NERELONG	3	P	5				1	
Paraonis fulgens	PARAFULG	3	P	11			1		
Pectinaria koreni	PECTKORE	3	P	9	1				
Pygospio elegans	PYGOELEG	3	P	9			1	2	
Scolelepis bonnieri	SCOLBONN	3	P	7		7		1	
Scolelepis foliosa	SCOLFOLI	3	P	7	1				
Scolelepis squamata	SCOLSQUA	3	P	10	2	4	4	4	3
Scoloplos armiger	SCOLARMI	3	P	5		2			
Sigalion mathildae	SIGAMATH	3	P	7				1	1
Spio filicornis	SPIOFILI	3	P	4	50		82	59	61
Spiophanes bombyx	SPIOBOMB	3	P	9	16	6	28	25	33
Echinocardium cordatum	ECHICORD	4	E	5	35	16	23	19	19
Ophiura texturata	OPHITEXT	4	O	12				1	
Nemertinae species	NEMERTIN	5	N	7	50	38	60	38	36

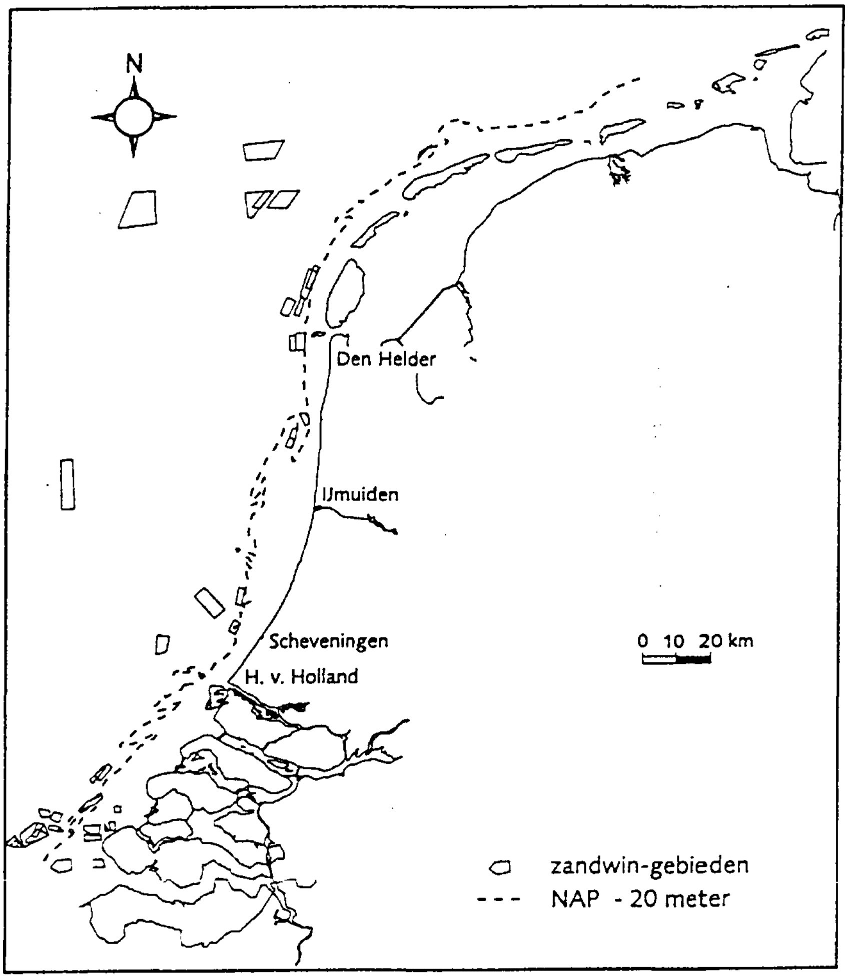
PART B

THE ECOLOGICAL EFFECTS OF SUBAQUEOUS SAND EXTRACTION NORTH OF THE ISLAND OF TERSCHELLING

1 Introduction

For many years, marine sand needed for various purposes was extracted in the shallow Dutch coastal waters (Fig. B-1). In The Netherlands circa 6 to 7 million m^3 sand is needed per year to compensate for sand losses in erosive coastal sections of the nearshore zone (DE RUIG, 1995a, b). Due to sea level rise almost twice this amount of sand will be needed. The exploitation of marine sand deposits for other purposes has increased from 2-3 million m^3 per year in the 1970s to ca. 12 million m^3 per year since 1990. This sand is used primarily for coastal nourishment and large construction works. Future reduction of exploitation of land based deposits together with an increasing demand for nourishment will lead to an increasing exploitation of marine sands (DE RUIG, 1995a).

Figure B-1
Position of sand extraction areas ('zandwin-gebieden') along the Dutch North Sea coast. From: DE RUIG, 1995a.
NAP ≈ mean sea level.



Because of arisen concern regarding the effects of continuous sand extraction a first integrated hydrographical, sedimentological and ecological study of the effects of sand extraction was carried out in the Dutch Wadden Sea in the 1970s (ANONYMOUS, 1981). More recently, acceleration of sea level rise due to global warming again focussed the attention to the significance of near-shore sand extraction. With respect to the Wadden Sea it was concluded that extraction of sand from the Wadden Sea would imply a risk of progressing erosion of the foreshore of the Wadden Sea islands, posing a threat to the continued existence of the barrier island type of coastline (LOUTERS & GERRITSEN, 1994). Since 1985, no sand for nourishment was extracted from the Dutch Wadden Sea any more.

With respect to the management of the Dutch sector of the North Sea new policy was developed, requiring increased protection of the coastal zone to favour the restoration of the North Sea ecosystem (ANONYMOUS, 1993a). This policy does not allow extraction of surface aggregates from the sea floor inshore of the 20 m depth contour, except for maintaining shipping fairways to Dutch ports (ANONYMOUS, 1993b).

In the North Sea, only little information is available on the environmental effects of sand extraction. Some studies have be performed on the effects of gravel extraction (VAN MOORSEL, 1994; KENNY & REES, 1994). Studies carried out in the Wadden Sea had shown that recovery of the benthic community at sand borrow sites was fast at locations with relatively high water and sediment dynamics, such as in tidal channels, and slow at intertidal flats (VAN DER VEER *et al.*, 1985).

The borrow area of sand used for the shoreface nourishment off Terschelling was located just below 20 m depth. Around 20 m depth in the North Sea, the dynamics of the sea-bed and also the composition of the benthic community is rather different from that in the coastal zone (*cf.* HOLTMANN *et al.*, 1996). Therefore, actual information on the effects of sand extraction at this location in the North Sea was considered to be relevant to corroborate the new policy of the Ministry of Traffic, Public Works and Water Management.

In contrast to the area of the shoreface nourishment itself (see Part A), studies of the NOURTEC project did not include the borrow site. In general, it was expected that the short-term effect of extraction of sand would be a serious impoverishment of the benthic fauna. Recovery was expected to proceed in two ways, by immigration of animals from the surroundings and by settlement of juveniles resulting from reproduction of benthos in the surrounding sea bed (*cf.* VAN DER VEER *et al.*, 1985). For long living species, recovery of a diverse composition of age groups was expected to take several years.

The purpose of this study was to assess the short-term impact of sand extraction on local macrobenthic fauna, to describe and quantify the recovery process after completion of the extraction, and to interprete these results in terms of risk of sand extractions to both the benthic community and benthos dependent species.

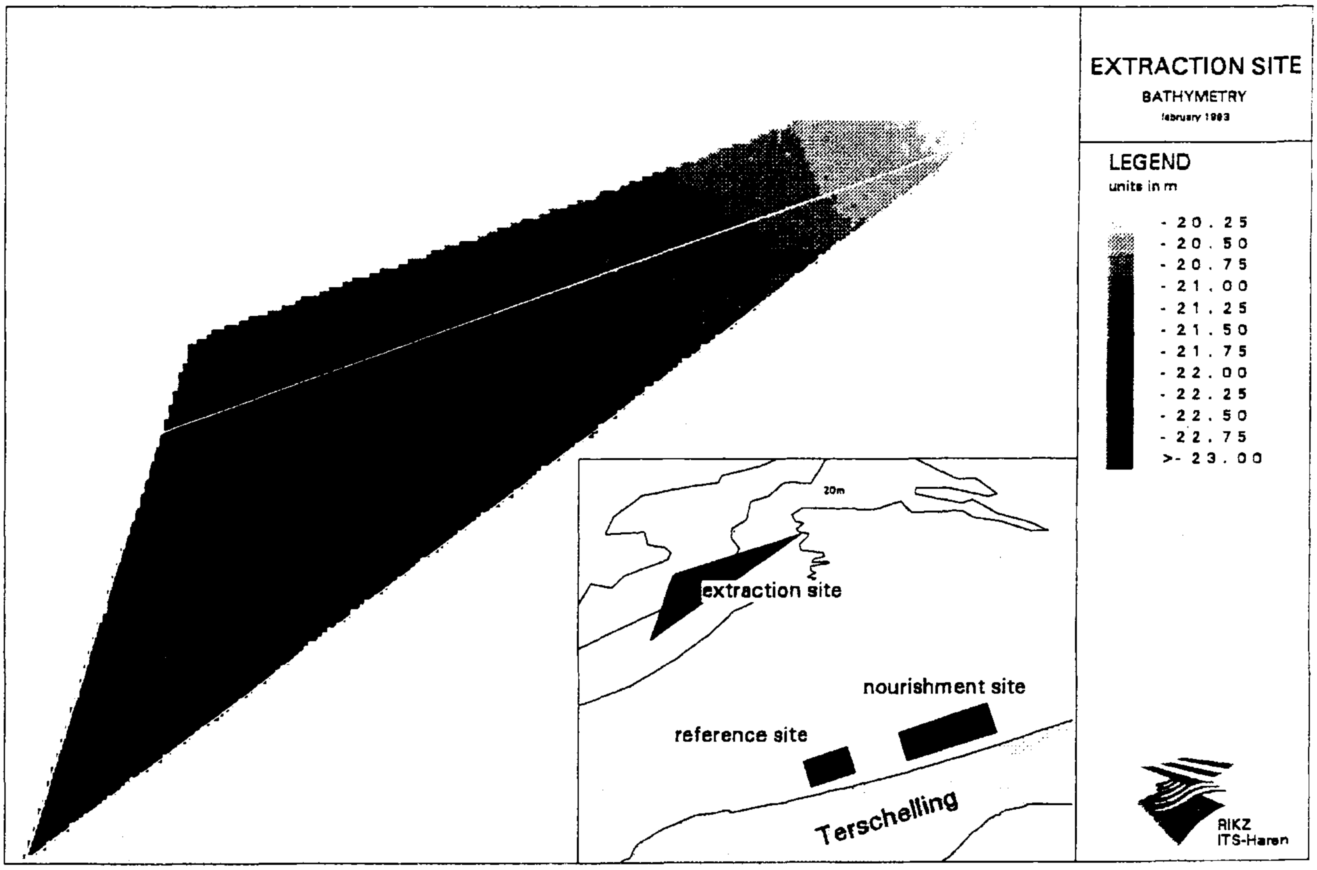
2 Methods

2.1 Study area

The triangular sand borrow area is situated approximately 8 km north of Terschelling at a depth between 20 m and 23 m below Dutch Ordnance Level (= NAP) (Fig. B-2). A bathymetric map of the borrow area was produced in February 1993, *i.e.* before the extraction of sand commenced. The median grain size of the sediment varied between 183 and 213 μm, with a sorting parameter D80/D20 of 1.32 - 1.40 (maximum 1.67). The D70/D30 ratio varied between 1.17 and 1.23 (maximum 1.35) (BIEGEL *et al.*, 1994). Eastward flowing flood currents are somewhat stronger than the westward ebb currents. Although in this coastal area of the North Sea the residual current runs from (south)west to (north)east (GOEDECKE, 1968) a reverse residual water transport occurs at times of northeasterly wind stress (BACKHAUS, 1984; RIEPMA, 1980; VAN DE KAMP, 1983).

The benthos in the Dutch coastal zone has been subject of a survey ("MILZON") in 1988-1989 commissioned by Rijkswaterstaat North Sea Directorate (HOLTMANN, *et al.*, 1996). The coastal zone off Terschelling area is characterised by a high species diversity. Macrofauna density ranges between 2,400 and 34,000 individuals individuals per m^2; biomass (ash-free dry weight of soft parts) was between 8 and 19 gram m^2. This benthos makes the coastal zone important as a nursery for flatfish species (VAN BEEK *et al.*, 1989).

Figure B-2
Map of the borrow area North off Terschelling surveyed in February 1993, with depth contours (in m below NAP = Dutch Ordnance Level ≈ mean sea level).

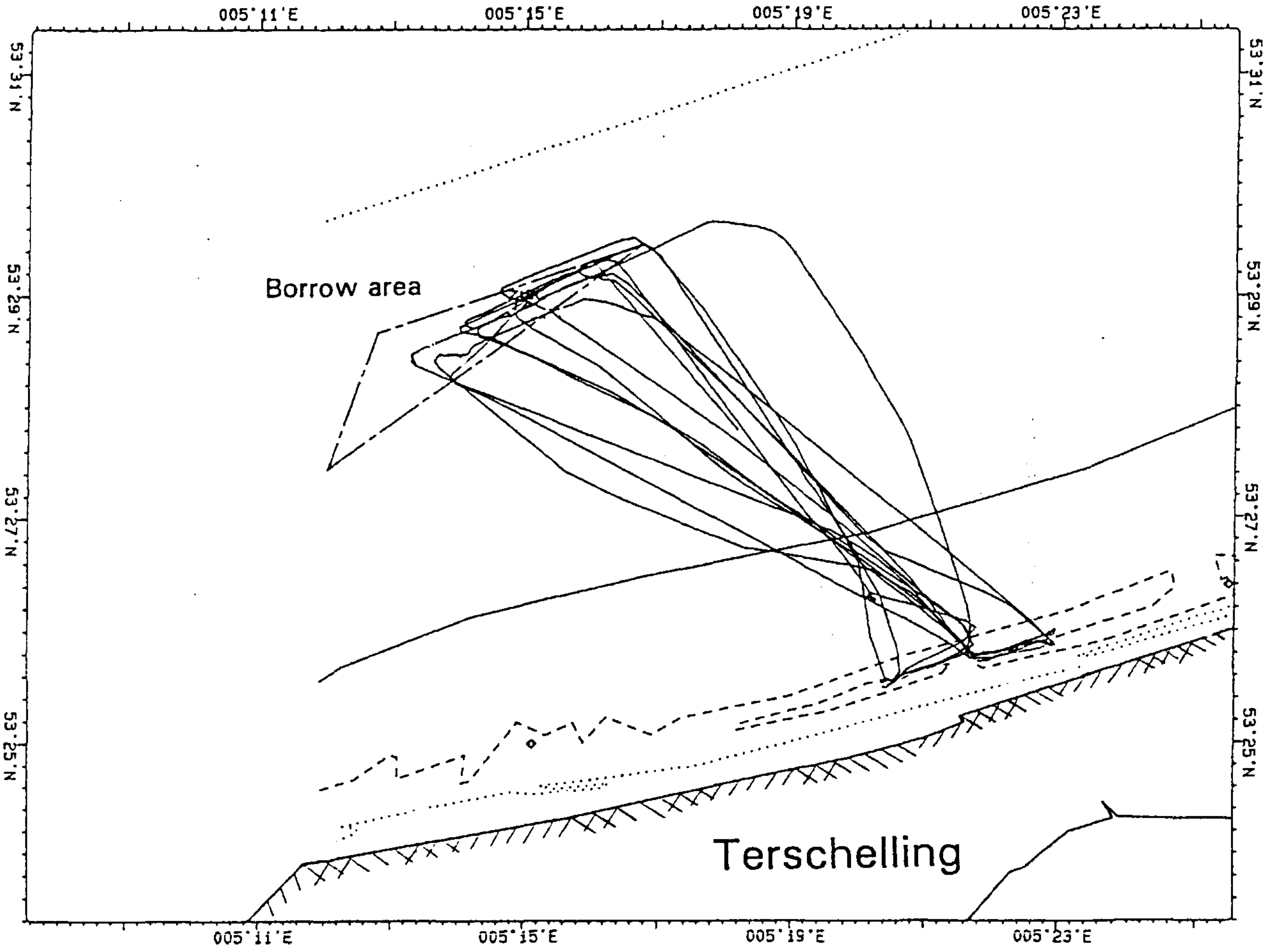


2.2 Sand extraction operation

The sand necessary for the shoreface nourishment was extracted from the borrow area with three split-hull hopper dredgers having capacities of 1,000 - 2,100 m^3. Borrowing of sand was done in the period April - November 1993. A total volume of 2.5 million m^3 of sand was extracted (HOEKSTRA *et al.*, 1994). Fig. B-3 shows a selection of tracks sailed by the hopper dredgers indicating that a major part of the borrow area has been effectively used for the extraction of sand.

Figure B-3

Map of the borrow area with tracks that hopper dredgers sailed at 29-06-1993.



2.3 Bathymetry and sampling of sediment

Bathymetric surveys of the borrow site were made by Rijkswaterstaat North Sea Directorate in February 1993, May 1994 and in October 1995. Surveys of benthos and sediment were made in March 1993 (T0-survey), in Sept./Oct. 1994 (T1-survey, one year after the end of sand extraction) and in October 1995 (T2-survey). For analyses of sediment small samples were taken from each box core sample taken for macrozoobenthos (see B.2.4.). Sediment samples were analysed for mud content (fraction <53 μm), $CaCO_3$ and organic matter (% weight of dried sample). Analyses were performed at the Middelburg laboratory of Rijkswaterstaat/RIKZ.

2.4 Sampling of macrozoobenthos

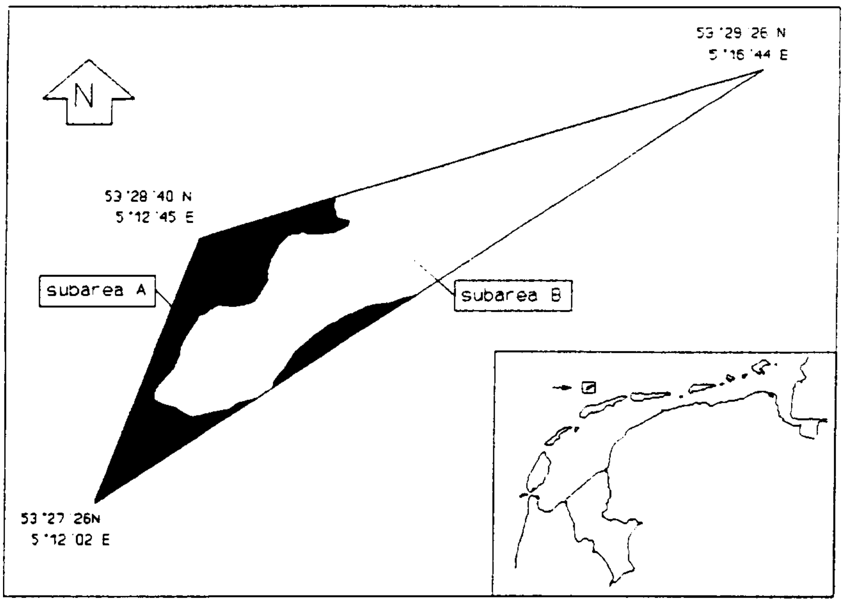
In March 1993 and October 1994 a total of 30 samples were taken, randomly distributed over the borrow area. In October 1995, 34 random samples were taken. The positions where the samples were taken are listed in the separate survey reports (VAN DALFSEN & OOSTERBAAN, 1995a, 1995b, 1996b).
Each sample was taken with a Reineck boxcorer (0.078 m^2). After taking a small sample for sediment analysis (see B.2.3) each sample was washed over a 1 mm mesh sieve on board of the ship and preserved with 4% formalin in sea water and stored in a freezer. In the laboratory the samples were stored at -20°C till further analysis to reduce loss of biomass (SALONEN & SARVALA, 1985).

Initially, for the investigation of the effects of sand extraction no reference area was designated. Comparison of bathymetric maps, made in February 1993 and May 1994, showed that a relatively small western part of the borrow area had not deepened. This suggests that this part of the borrow area was not intensively used for the extraction of sand. Therefore, two subareas were identified within the borrow area (Table B-1; Fig. B-4). As a working hypothesis, subarea A is considered as a reference area, and subarea B as the area affected by the sand extraction.

Table B-1
Change in depth of the sea floor between February 1993 (pre-extraction) and May 1994 (post-extraction) in two subareas of the borrow area north off Terschelling. See for areas A and B Fig. B-4.

Subarea	Change in depth
A ('reference')	+10 to - 10 cm
B ('disturbed')	-10 to -150 cm

Figure B-4
Map of the borrow area North off Terschelling. Two subareas are indicated: A = 'reference' and B = 'disturbed' (see Table B-1 and text).



2.5 Treatment of macrozoobenthos samples

Frozen samples were thawed and rinsed with tap water to remove formaldehyde using a 0.5 mm mesh sieve. The samples were then sorted with the aid of a low-power stereomicroscope.
Density (ind/m^2) was recorded at species level for as much as possible, or otherwise at a higher taxonomic level. In *Nephtys* species and *Echinocardium cordatum*, juveniles and adults were counted separately. In none of the other species such a discrimination was made. Bivalves were separated into length classes of 0.5 cm except for the small sized *Montacuta ferruginosa*.
Biomass was determined in grams ashfree dry weight (AFDW) per m^2. AFDW was determined by drying the organisms for 65 hours at 65°C. The animals were then weighed (dry weight) and incinerated at 570°C for a period of two hours and weighed again (ash weight).
For the major polychaetes *Nephtys hombergii* and *Magelona papillicornis* assessment of biomass was done for each species separately; for all remaining worms (polychaetes and nemertini) the combined biomass was determined. In bivalve molluscs biomass was determined per species. For echinoderms (mostly *Echinocardium cordatum*), only complete individuals were used for determination of an average individual AFDW, from which the biomass per m^2 was calculated. Discrimination was made between juvenile (<2 cm) and adult (>3.5 cm) *Echinocardium cordatum*. There was no determination of biomass of Crustacea.

2.6 Data analysis

Not all species found in the samples were considered. Mobile epibenthos (*e.g.* copepods, mysids, shrimps and crabs) were excluded, primarily because of inadequate sampling. Furthermore, is was agreed between RIACON-partners not to include Bryozoa, Hydrozoa, Nematoda and *Branchiostoma lanceolatus* in the data analysis. In Appendix B an overview is given of all species found in the samples, of those species included in the data analysis as well as assignment of species to feedings types. Average density, biomass, species diversity and evenness were calculated for the entire borrow site as well as for two distinguished subareas separately. The diversity of the macrobenthic fauna is expressed by the Shannon-Wiener index H' and the distribution of the numbers of individuals among the species by Heips index E(H) of evenness (HEIP, 1974).

$$H' = -\sum_{i=1}^{S} p_i (\ln p_i) \qquad \text{with } p_i = n_i / N$$

where N = Total number of individuals
n_i = number of individuals of species i
S = total number of species

$$E(H) = \frac{N_1 - 1}{N_0 - 1}$$

where $N_1 = e^{H'}$
N_0 = total number of species

Heip's Index $E(H) = 1$ if all species present are equally abundant.

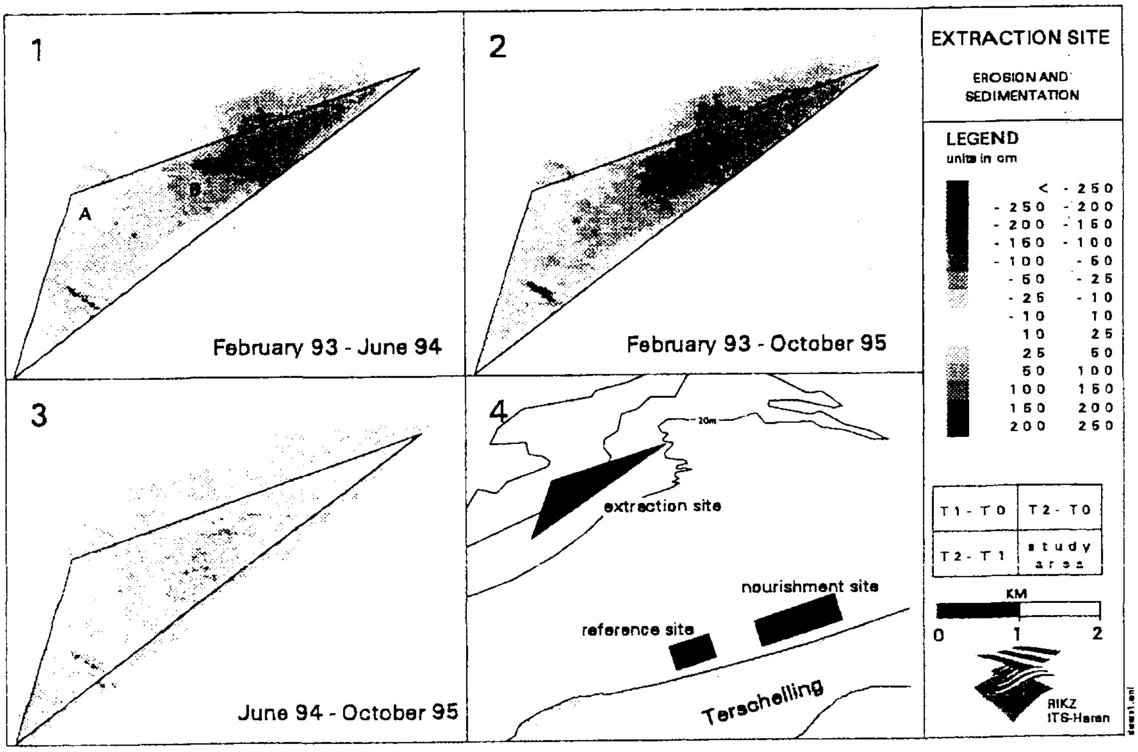
Statistical differences in abiotic parameters, species composition, abundance and biomass between the three successive surveys were tested, using the Mann-Whitney U-test. Within each survey, differences between the two subareas A and B were tested by an analysis of variance (ANOVA) using a 95 % Tukeys multiple range test.
The benthic community structure was analyzed using TWINSPAN cluster analysis (HILL, 1979) on the combined data set of the three successive surveys (*i.e.* a total of 94 samples). TWINSPAN analyses were performed on density data (cut levels for each species: 0, 1, 10 and 100 individuals per sample). Further data analysis included non-metric multi dimensional scaling ordination (MDS) (KRUSKALL & WISH, 1978) using a Bray-Curtis similarity matrix of log(N+1)-transformed species abundance (BRAY & CURTIS, 1957) and detrended correspondence analyses (DCA) also using log(N+1)-transformed species abundance.
Finally, data on feeding type of species (predator, deposit feeder, suspension feeder) and age structure (based on shell length measurements) of some bivalve species were used to investigate the effects of sand extraction.

3 Results

3.1 Seabed morphology and sediment characteristics

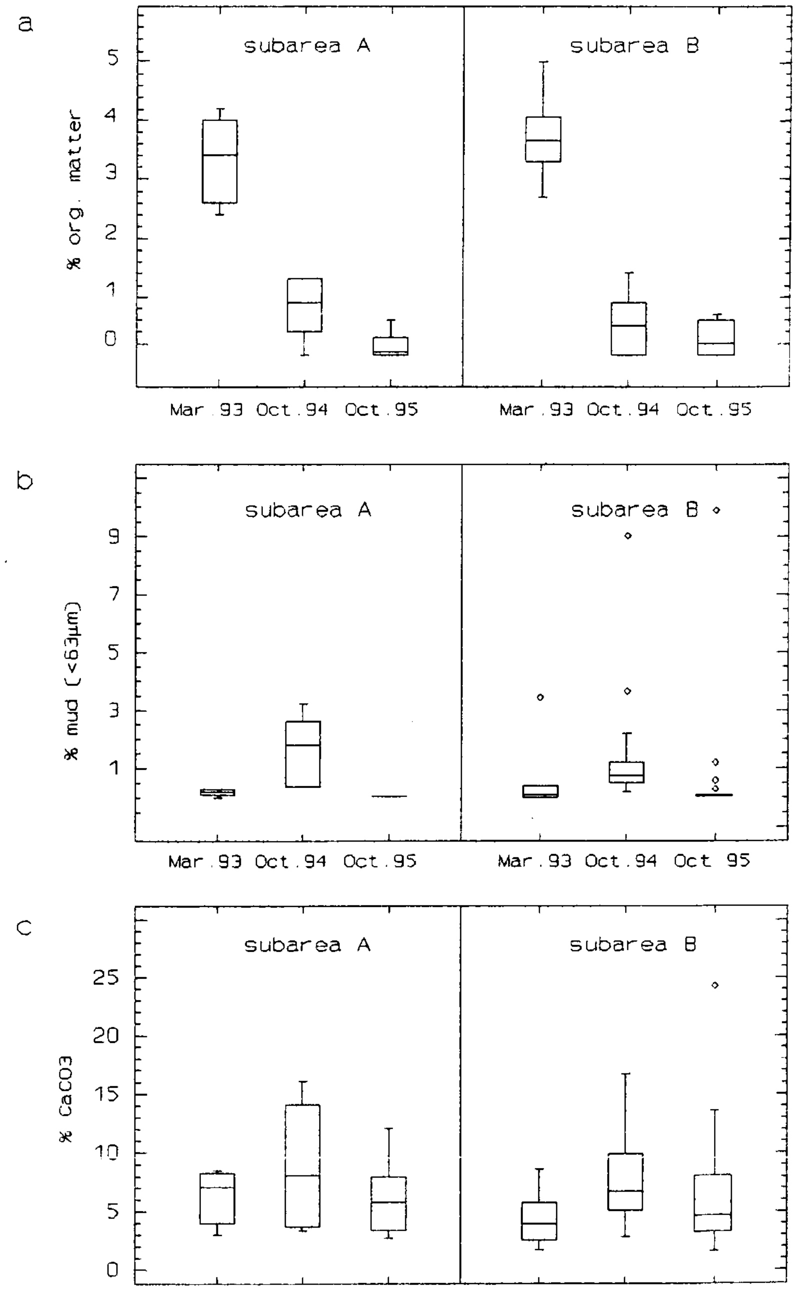
The bathymetry of the borrow area changed considerably as a result of the sand extraction. The sedimentation/erosion map (Fig. B-5[1]) indicates that in the period February 1993 - June 1994 a lowering of the sea bed of 0.25 - 1.5 m has occurred in approximately 1.4 km² in the eastern part of the borrow site. In the same period, however, some sedimentation took place in the northwestern corner of the borrow site. From June 1994 to October 1995 (Fig. B-5[3]) a further deepening of *c.* 0.10 m was observed in the borrow area. From hydrographic maps of the Ministry of Transport, Public Works and Water Management (Nederlandse Kustwateren, Noordblad Wadden; scale 1:100000) it is deduced that a general sedimentation took place in the surroundings of the borrow area between 1977 and 1987-1992. These hydrographic maps, however, are not detailed enough to allow proper comparison.

Figure B-5
Bathymetric difference map of the borrow area, showing sedimentation and erosion over the period February 1993 - October 1995.



The sediment composition in the borrow area changed between March 1993 (T0 survey) and October 1995 (T2 survey). The organic matter content of the sediment decreased significantly in the whole area (Fig. B-6). The percentage of mud (fraction <53 µm) and of $CaCO_3$ increased from March 1993 (T0) to Sept./Oct. 1994 (T1), to decrease to pre-extraction values in October 1995 (T2) (Fig. B-6). These patterns of change of abiotic parameters over time are similar for the two subareas A and B, irrespective of the differences in sedimentation/erosion between these subareas.

Figure B-6
Mean contents of organic matter (a), mud (fraction <53 µm; b) and $CaCO_3$ (c) in the sediment of the subareas A and B in March 1993 (T0), October 1994 (T1) and October 1995 (T2).

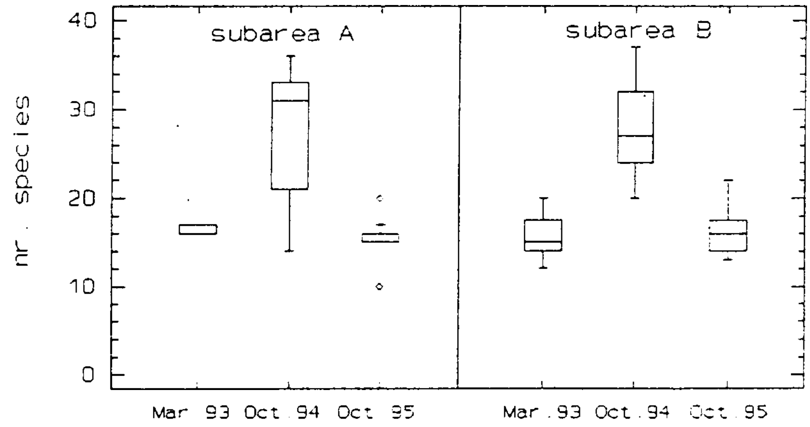


3.2 Biotic parameters

3.2.1 Species richness

Appendix B presents an overview of all species found in the borrow area and of their occurrence (number of stations at which present) in each of the surveys.
The number of species in the borrow area increased strongly from an average of 16 species per sample in March 1993 to 27 species per sample in October 1994, *i.e.* almost one year after completion of the sand extraction (Fig. B-7). In the final survey (October 1995), species numbers had fallen to the pre-extraction average of 16 species per station. In none of the surveys any significant difference in species numbers was found between the subareas A and B.

Figure B-7
Mean number of species per sample in the subareas A and B in March 1993 (T0), October 1994 (T1) and October 1995 (T2).



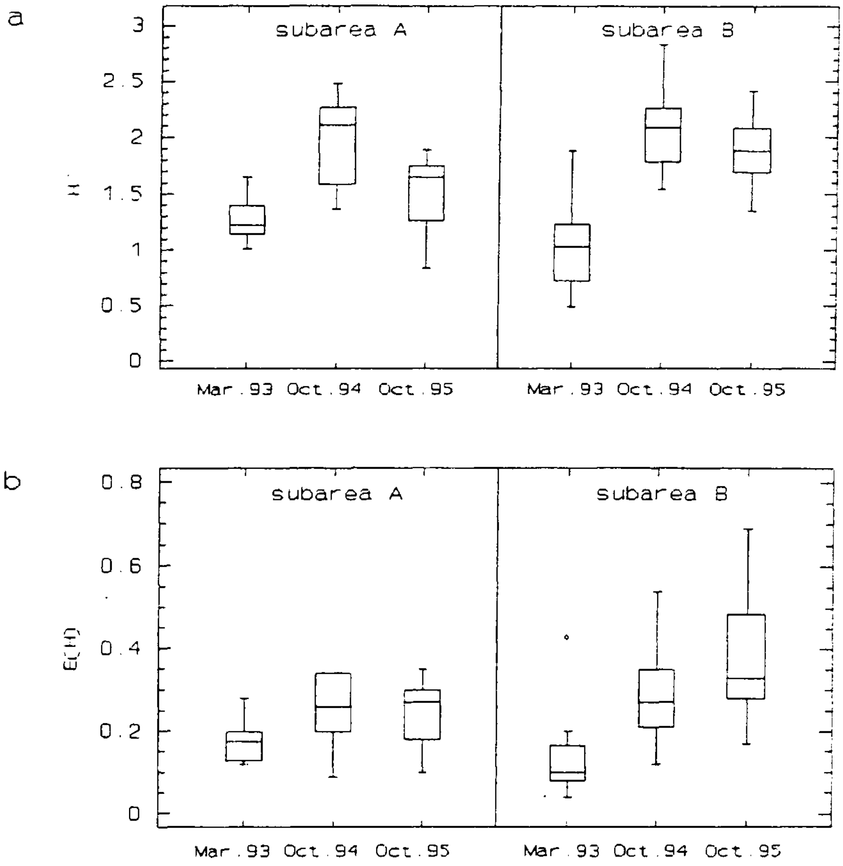
3.2.2 Diversity and evenness

One year after completion of the sand extraction (Sept/Oct. 1994), the diversity of the benthic community, expressed by the Shannon-Wiener index, was significantly higher than before (March 1993) (Fig. B-8a). In the disturbed area B the Shannon-Wiener index was found similarly high in the October 1995 survey, whereas in subarea A the diversity had significantly decreased to values similar to those found in March 1993 (T0 survey).
In March 1993, the benthic community was dominated by a few species, as may be concluded from the low value (<0.2) for Heip's index of evenness (Fig. B-8b). No significant changes in the index occurred in subarea A throughout the surveys. In subarea B ('disturbed'), however, Heips index had risen significantly in Sept/Oct. 1994 (T1 survey) to have increased even further in the October 1995 survey (Fig. B-8b).
In none of the surveys, except for the T2 survey, differences were found in Shannon-Wiener diversity between the two subareas A and B. For Heip's

index of evenness, in neither survey any difference between the subareas A and B was found.

Figure B-8

a) Mean Shannon-Wiener diversity index (H') and b) mean Heip's index of eveness (E(H) per sample in the subareas A and B in March 1993 (TO), October 1994 (T1) and October 1995 (T2).



3.2.3 *Abundance of macrozoobenthos*

A general decline in total macrofauna abundance was found to occur over time (Fig. B-9). In the 'disturbed' subarea B, this decrease is statistically significant. In the 'reference' subarea A, total abundance had only significantly decreased when comparing the March 1993 and the October 1995 survey. The numerical densities of polychaetes and crustaceans, being responsable for over 90% of total macrofauna numbers, showed the stronger decline in the 'disturbed' subarea B as compared with a more gradual decline in the 'reference' subarea A (Fig. B-10a,b). This applies especially to the polychaetes when comparing the T0 and T1 survey. The numerical density of molluscs (mainly consisting of bivalves) showed little variation over the years, neither in subarea A nor B (Fig. B-10c). Differences in mean density were not significant between surveys.
The numerical density of the *Echinocardium cordatum*, being the most abundant echinoderm, had not changed one year after the sand extraction. The October 1995 survey, however, showed that this species had

become significantly more abundant, but only in the 'disturbed' subarea B (see Fig. B-20).

Figure B-9
Mean total abundance of macrozoobenthos (ind. m^{-2}) per sample in the subareas A and B in March 1993 (T0), October 1994 (T1) and October 1995 (T2).

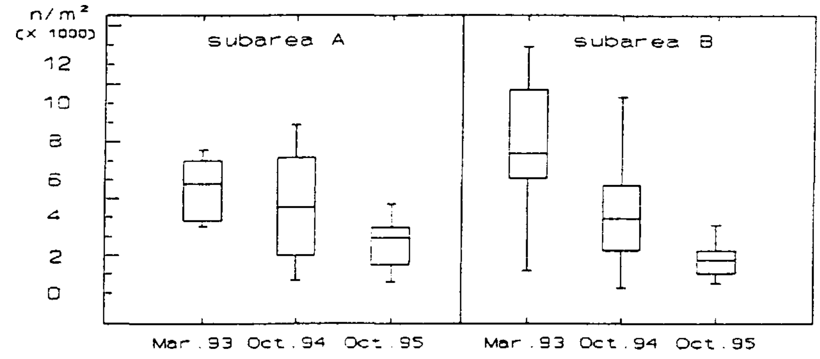
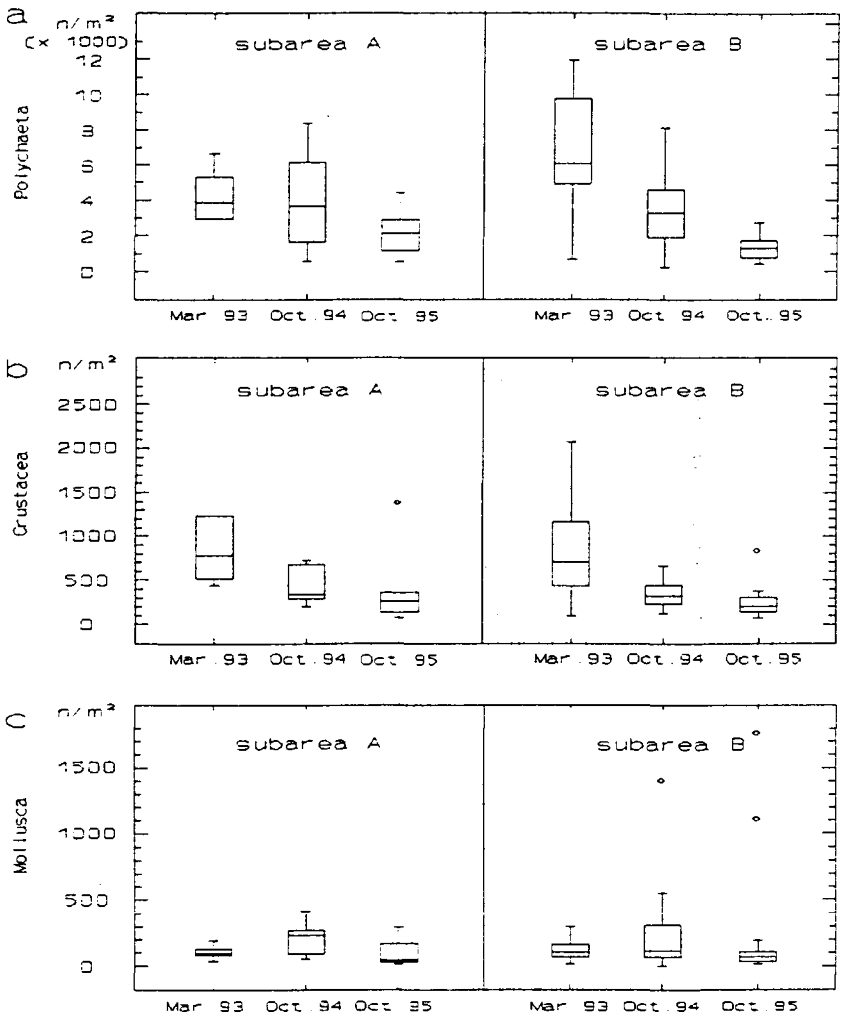


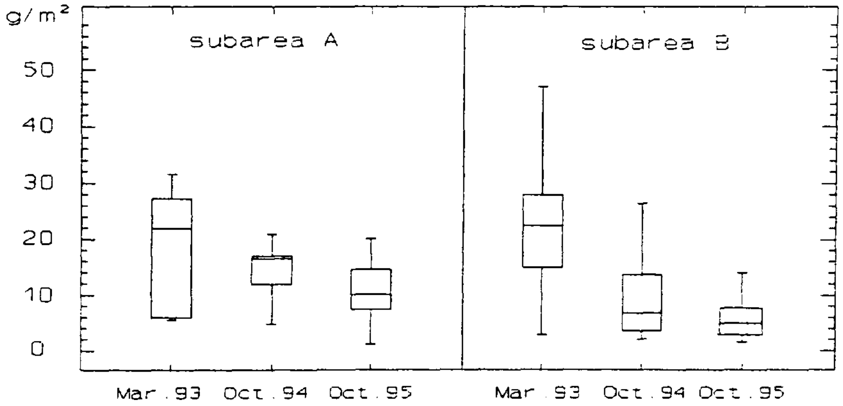
Figure B-10
Mean total abundance (n/m^2) of polychaetes (a), crustaceans (b) and molluscs (c) per sample in the subareas A and B in March 1993 (T0), October 1994 (T1) and October 1995 (T2).



3.2.4 Biomass of macrozoobenthos

The total biomass of the benthic fauna (biomass of crustaceans excluded because of their minor contribution) in the borrow area showed a decreasing trend from the March 1993 survey to the October 1995 survey (Fig. B-11). The biomass of the molluscs also decreased (Fig. B-12a). In subarea B this decrease was discontinued after the T1 survey. A similar development was observed regarding the biomass of polychaetes (Fig. B-12b). No change occurred in subarea A. In the 'disturbed' area B, there was a significant reduction, continuing till October 1995.

Figure B-11
Mean total biomass of macrozoobenthos (g AFDW m^2) per sample in the subareas A and B in March 1993 (T0), October 1994 (T1) and October 1995 (T2).



For mollusc biomass, no differences between the subareas A and B were found, neither before (March 1993) or after (October 1955) the sand extraction (Fig. B-12a). For polychaetes, biomass was different between the subareas A and B in March 1993. After the sand extraction, however, differences between these subareas were no longer significant (Fig. B-12b). In *Echinocardium cordatum*, the biomass was lower in the T1 survey than in the T0 survey, although densities had not really changed (see above). This decrease of biomass was significant only in subarea B, not in subarea A (Fig. B-13).

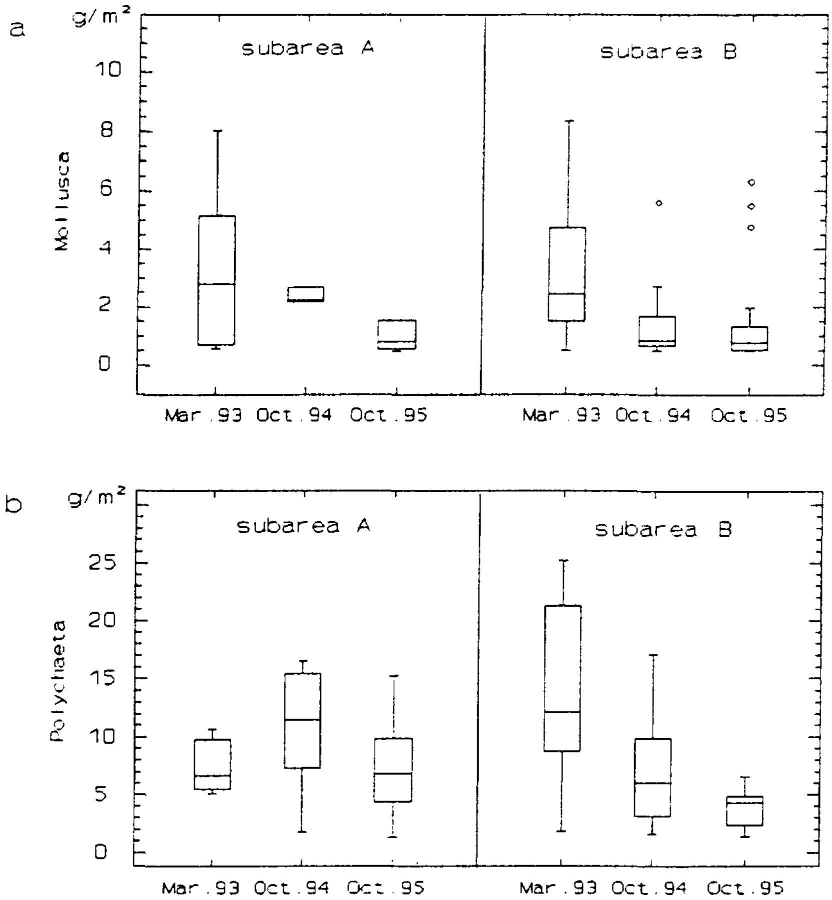


Figure B-12
Mean biomass (g AFDW m^{2}) of molluscs (a) and polychaetes (b) per sample in the subareas A and B in March 1993 (TO), October 1994 (T1) and October 1995 (T2).

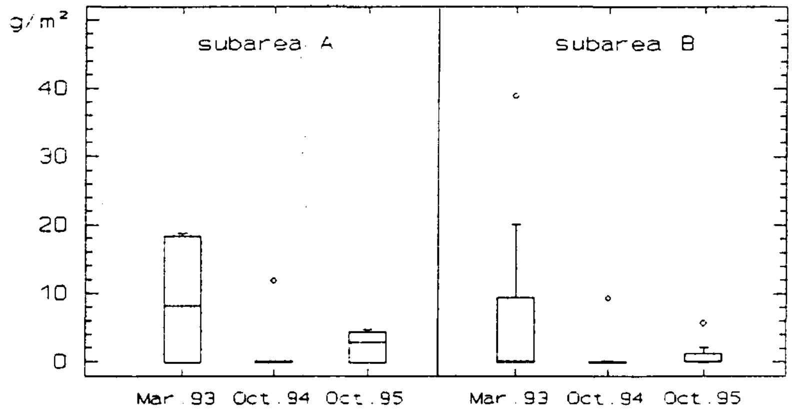


Figure B-13
Mean biomass (g AFDW m^{2}) of *Echinocardium cordatum* per sample in the subareas A and B in March 1993 (TO), October 1994 (T1) and October 1995 (T2).

3.2.5 Community structure

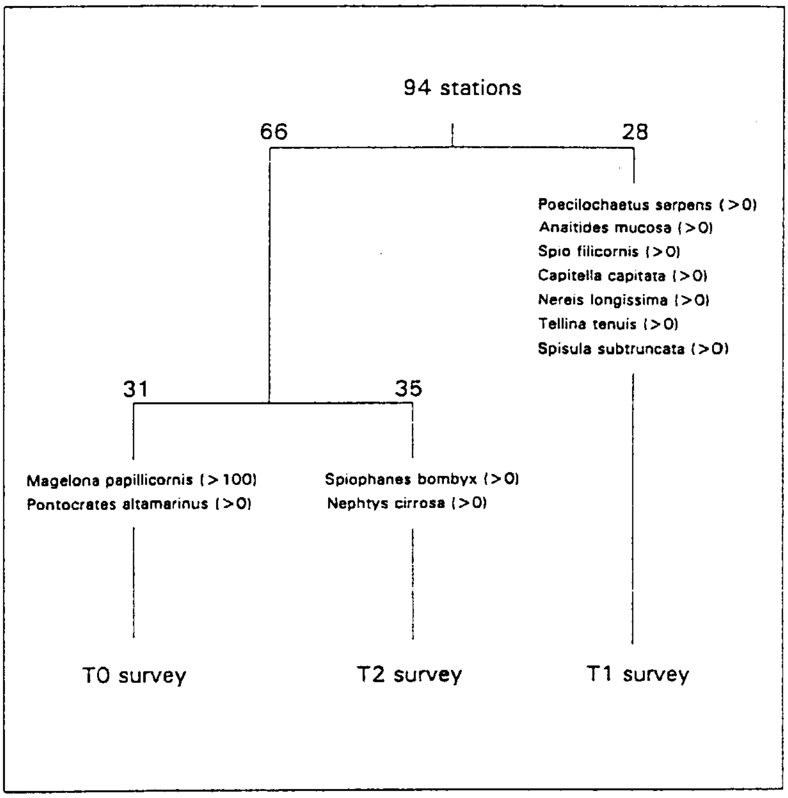
*** *TWINSPAN cluster analyses***

TWINSPAN analysis was performed for the three surveys combined, *i.e.* using the abundance data of 104 species found in 94 samples/stations. The outcome of the TWINSPAN cluster analysis is presented in Fig. B-14. The diagram shows a clear separation of the stations (= samples) of the three successive surveys. The subareas A and B cannot be distinguished as separate entities within each cluster, indicating a rather uniform distribution of the benthic fauna in each survey irrespective of the supposed areal differences in disturbance due to sand extraction. This finding is in agreement with the results of the TWINSPAN analysis per survey as documented in the reports on the separate survey reports (VAN DALFSEN & OOSTERBAAN, 1995a, 1995b, 1996b).

No relationship was found between the TWINSPAN clusters and any of the abiotic parameters measured, nor with the inferred differences in impact of sand extraction (subareas A and B).

The first division in the TWINSPAN dichotomy separates the stations of the T1 survey from those of the T0 and T2 survey, pointing to a higher resemblance of the benthos community in latter two surveys. The first division is based on the presence or absence of the indicator species given in Fig. B-14. The second division is based on the presence or absence of 3 species (*Spiophanes bombyx*, *Nephtys cirrosa* and *Pontocrates altamarinus*) and difference in abundance (more or less than 100 indiv. per sample) of *Magelona papillicornis*.

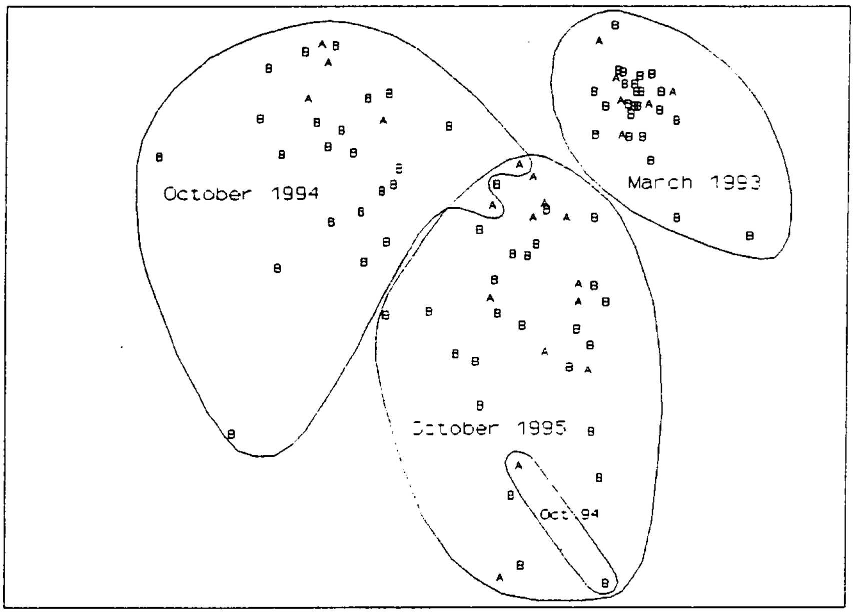
Figure B-14
TWINSPAN generated dichotomy of sampling stations based on presence/absence (>0) and differences in density (>100) of macrofauna species. Indicator species and number of stations are indicated.



* *MDS ordination*

As in the TWINSPAN cluster analysis, MDS ordination (stress factor 0.103) clearly separates the stations of the three different surveys (Fig. B-15). The stations of the T0 survey form a rather coherent cluster, indicating a rather homogenous fauna. The greater distance in the ordination between the stations of the T1 survey indicates a more heterogenous benthic fauna. In the T2 survey, the distances between the stations are somewhat reduced and spatial position of the T2 benthic community has shifted to the right, *i.e.* in the direction of the position of the T0 survey stations.

Figure B-15
MDS ordination of the sations of the three successive sampling surveys (T0, T1, T2) in the borrow area North off Terschelling. Numerical densities of species were log (N+1)-transformed. Stations of subareas A and B are indicated as 'A' and 'B'.



* *Redundancy analysis (RDA)*

The RDA ordination plot resulting from the correspondence analysis on log(N+1)-transformed numerical density data shows three distinct groups of stations (Fig. B-16). These groups correspond with each of the three surveys carried out. The stations of the T0 survey and the T1 survey are 'horizontally' separated along the first axis (eigen value 0.335) in the upper part of the RDA plot. The T2 survey of October 1995 is 'vertically' divided from the first and second survey along the second axis. This second axis is not much informative as it has a low eigen value (0.140). Differences in sediment characteristics do influence the ordination as the organic matter content is significantly correlated with the first axis. In the ordination, however, no segregation of the stations of the 'reference'and 'disturbed' subareas was found. The stations of neither subarea A nor B form separate clusters within the three large survey related clusters of stations shown in Fig. B-16.

Also significantly correlated with the first axis is the number of species per station, indicating differences in community structure between the three surveys.

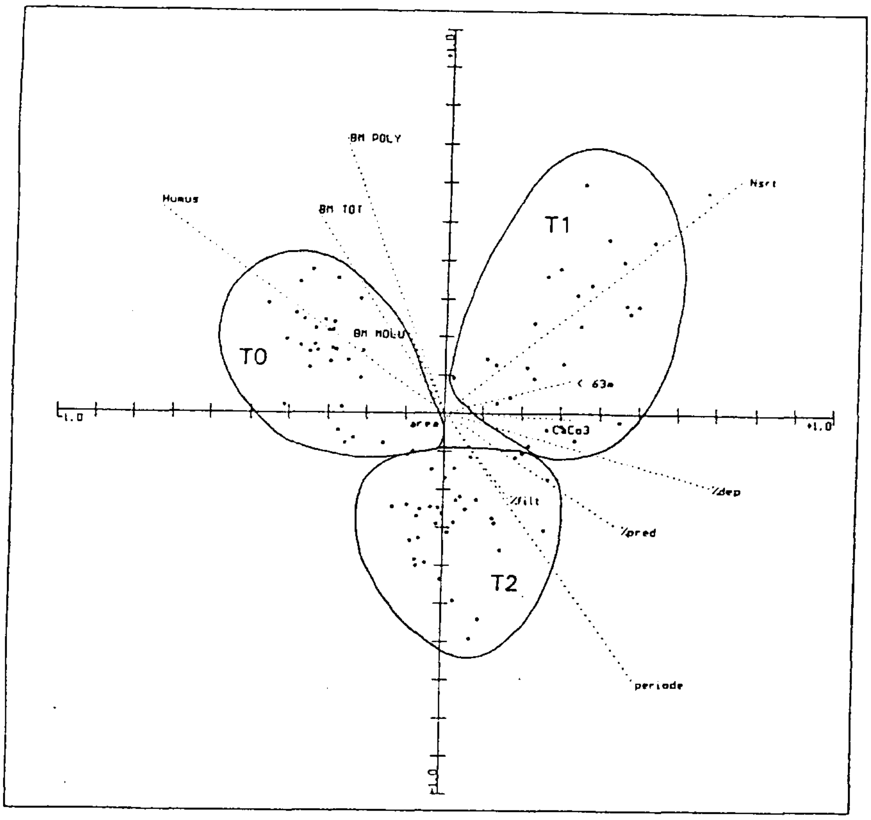


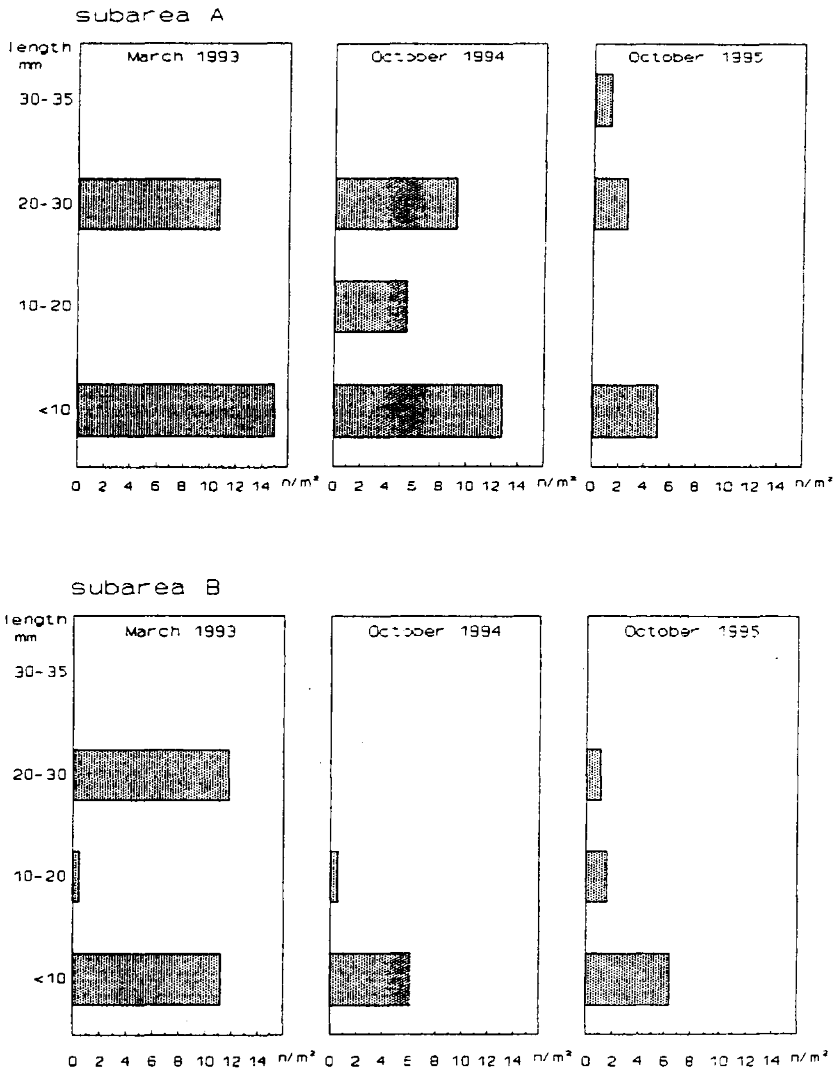
Figure B-16
RDA-ordination diagram of the stations of the three successive sampling surveys in the borrow area North off Terschelling. Numerical densities of species were log(N+1)-transformed. Explaining factors are: humus = % organic matter in the sediment, %<53 µm = mud content, $CaCO_3$ = % $CaCO_3$ in the sediment, periode = time of the survey, area = subarea A or B, Nsrt = number of species, BM TOT = Total biomass (g m^2), BM POLY = biomass of polychaetes, BM MOLL = biomass molluscs.

* *Age composition*

After the sand extraction, in the T1 survey a decline was observed in the biomass of molluscs, whereas at the same time no differences in numerical density were found between the T0 and T1 survey. Therefore, it was investigated whether sand extraction had resulted in selective disappearance of the larger (= older) specimens within each of the major mollusc species. This was performed by comparing the length composition of the population before and after the extraction (VAN ESSEN, 1996a).
In *Donax vittatus*, which was present only in low densities, the age composition in the 'disturbed' subarea B shifted from a population of larger adults and small juveniles to only juveniles. In subarea A no changes in length class composition were found (Fig. B-17).

Spisula subtruncata was very rare in the borrow area before sand was extracted. After sand extraction, *Spisula subtruncata* was present in the T1 survey (Oct. 1994) with considerable numbers of juveniles (2 - 15 mm length) in the 'disturbed' subarea B, whereas in subarea A only a few individuals were found (Fig. B-18). In October 1995 (T2-survey), this species had again largely disappeared in both subareas A and B.

Figure B-17
Abundance of different size classes (shell length) of *Donax vittatus* in subarea A (top panels) and subarea B (bottom panels) in March 1993 (T0), October 1994 (T1) and October 1995 (T2).



The bivalve *Tellina tenuis* was not found present in the T0-survey in March 1993. In the T1-survey, juveniles of *Tellina tenuis* showed up in both the subareas A and B, but reached the highest densities in subarea B. As in *Spisula subtruncata*, this species had disappeared almost completely in the T2-survey (Fig. B-19)

Figure B-18

Abundance of different size classes (shell length) of *Spisula subtruncata* in subarea A (top panels) and subarea B (bottom panels) in March 1993 (T0), October 1994 (T1) and October 1995 (T2).

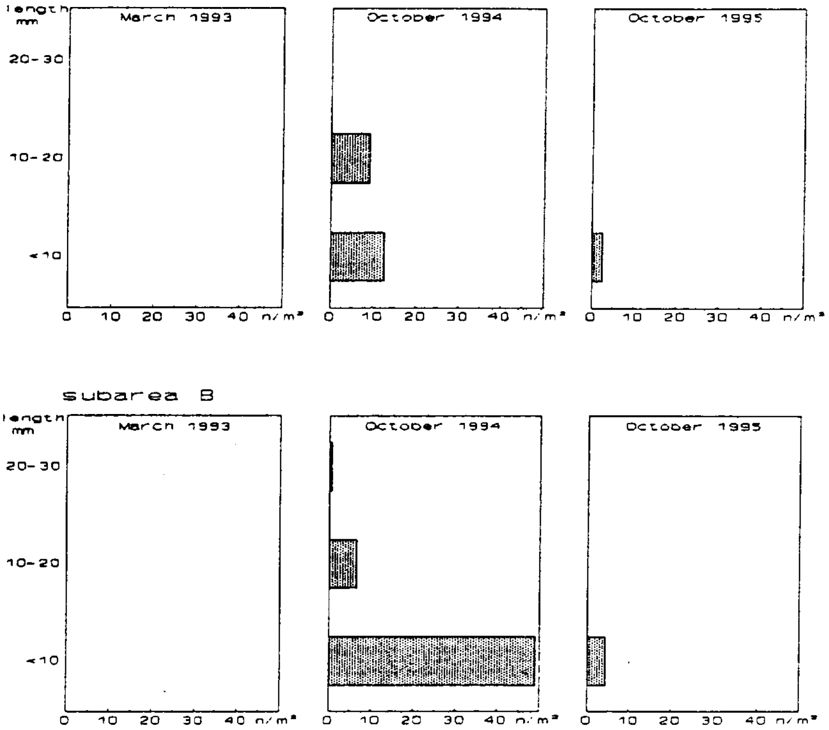
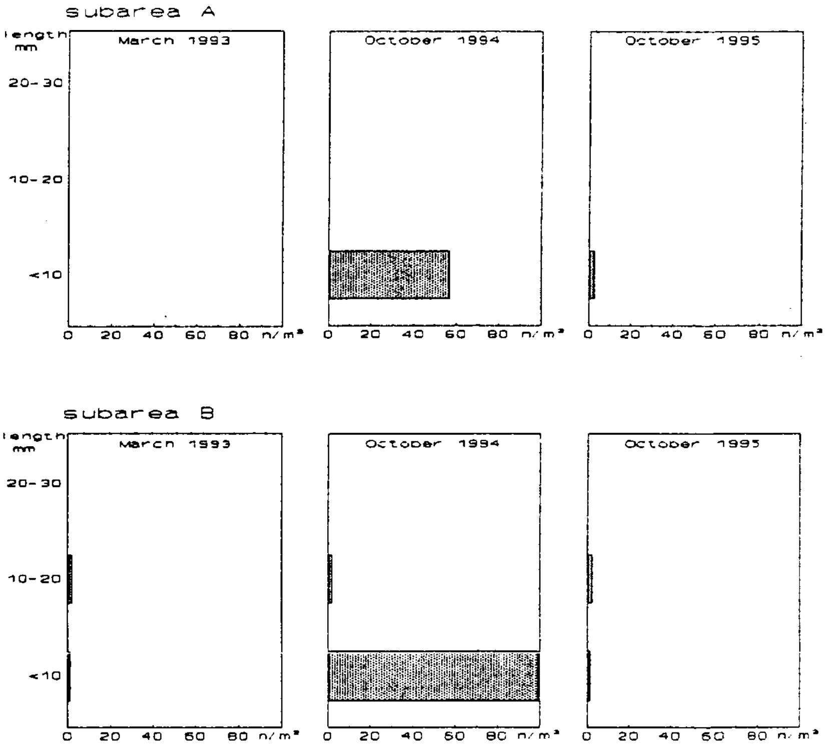


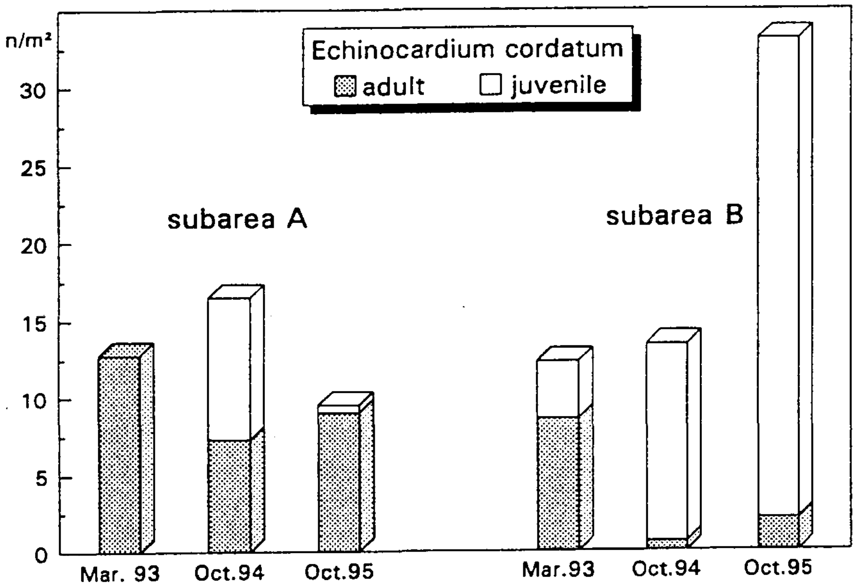
Figure B-19

Abundance of different size classes (shell length) of *Tellina tenuis* in subarea A (top panels) and subarea B (bottom panels) in March 1993 (T0), October 1994 (T1) and October 1995 (T2).



In *Echinocardium cordatum*, biomass had decreased in the T1 survey (Oct. 1994) as compared to the situation before sand extraction (T0 survey; March 1993) although numerical densities had increased. In fact, in the T0 survey mainly adult specimens (> *c.* 3.5 cm) were found. In the T1 survey, the population existed for more than 50% (subarea A) or almost completely (subarea B) of juveniles (<2 cm) (Fig. B-20). Especially in the 'disturbed' subarea B, the adult population of *Echinocardium cordatum* had strongly decreased, and juveniles had colonised the open space. In 1995 an even stronger colonisation by juveniles occurred in subarea B (Fig. B-20).

Figure B-20
Abundance of adults and juveniles of *Echinocardium cordatum* in subareas A and B in March 1993 (T0), October 1994 (T1) and October 1995 (T2).



*** *Functional groups***

The benthic fauna of the borrow area, with exception of the echinoderms, was classified into three groups according to feeding strategy: predators (mainly polychaetes), deposit feeders (polychaetes and crustaceana) and suspension feeders (mainly bivalve molluscs) (see Appendix B). From the 104 species encountered 21 were classified as predators, 20 species to be deposit feeders or grazers and 12 species as suspension feeders. The other 51 species had a mixed feeding type, or their feeding type was not known (VAN ESSEN, 1996b). An overview of the changes in average densities of predators, deposit feeders and suspension feeders in both subareas A and B is presented in Table B-3.

In the T1 survey, the density of predators had increased in comparison to the T0 survey. This increase was only significant in the 'disturbed' subarea B. In the T2 survey the density of predators had decreased to pre-extraction (= T0) values. The most obvious increase in subarea B was effectuated by two polychaete species, *viz. Anaitides subulifera* and *Eteone flava*. These two species did not increase in density in subarea A.

Table B-3
Average numerical densities of feeding types in three surveys at the borrow site off Terschelling. Significant differences with the March 1993 survey are indicated: *: $p<0.05$, **: $p<0.01$ (Wilcoxon).

		Mar-1993	Oct-1994	Oct-1995
Predators	subarea A	3.2	12.0	6.0
	subarea B	3.6	17.6**	7.6
Deposit feeders	subarea A	9.9	117.0*	54.6
-Polychaetes	subarea B	20.4	180.5**	81.2*
-Crustaceans	subarea A	112.1	26.9*	43.8*
	subarea B	89.4	18.9**	24.8**
Suspension feeders	subarea A	7.5	12.4	9.8
	subarea B	7.6	11.5	20.0

by two polychaete species, *viz. Anaitides subulifera* and *Eteone flava*. These two species did not increase in density in subarea A. For the other polychaete predator species no significant increase was found, neither in subarea A nor in subarea B.

In the group of the deposit feeders, a different response was observed in crustaceans and polychaetes. Densities of crustaceans (mainly amphipods) were severely reduced in the T1 survey (in both subareas), whereas in deposit feeding polychaetes a strong increase was found. In the T2 survey, densities were still below those of the T0 survey.

Suspension feeders (all bivalve molluscs) showed an overall abundance that was similar in all surveys. As shown above (under 'Age composition') similar abundances do not necessarily imply a similar age composition.

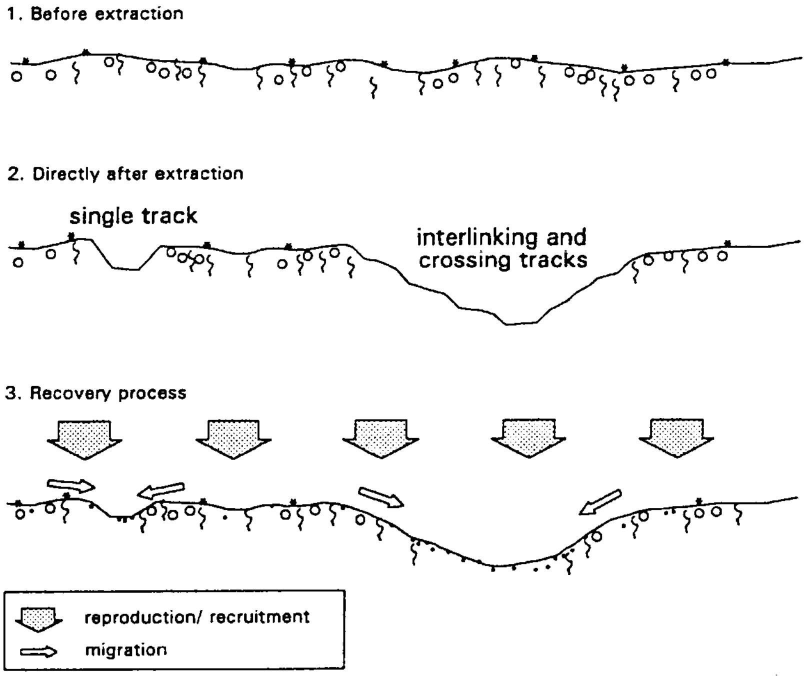
4 Discussion

4.1 Methodology

The three surveys in the borrow area were not held in the same time of the year. The pre-extraction survey (T0) was conducted in early spring when biomass was low and in most benthic species reproduction has not yet resulted in recruitment of juveniles. Both post-extraction surveys, however, were held in autumn, at the end of the growing and reproductive season. Therefore, in autumn both abundance and biomass of species are likely to be higher than in early spring. Due to increased species abundance the number of species per station may also be higher in autumn than in spring (see VAN DALFSEN & OOSTERBAAN, 1995b).
Indeed, in the T1 survey the mean number of species per stations was higher than in the T0 survey (*cf.* Fig. B-7). Abundance and biomass, however, decreased (in subarea B; *cf.* Fig. B-9) or stayed at the same level (in subarea A; *cf.* Fig. B-11). In the T2 survey, the mean number of species was lower than that in the T1 survey, and similar to that in the T0 survey (*cf.* Fig. B-7). Therefore, it may be concluded that having sampled in different seasons of the year has not been a major factor influencing the results of this study.

*** *Area affected by sand extraction***
Not all tracks sailed by the hopper dredgers were recorded and saved. Therefore, no accurate information is available to confirm or falsify the assumption regarding a different degree of impact on the seabed between the subareas A and B. Subarea A was distinguished as having undergone minimal changes of seabed morphology (sedimentation/erosion between 0.1m and -0.1m). If sand has been extracted in this subarea, disturbance of the seabed may have been less than in subarea B, possibly with a relatively low density of single, non interlinking, dredging tracks (see Fig. B-21). This would still mean that a substantial part of the fauna may have been removed due to sand extraction without any clue on the sedimentation-erosion map (*cf.* Fig. B-5/1). In subarea B, disturbance of the seabed due to sand extraction must have been much greater as depth increased with 0.25 - 1.5 m (see Fig. B-21).
There are additional arguments for not considering the subareas A and B as reference and disturbed areas, respectively. Firstly, in both subareas a strong decrease was found in the amount of organic material (see Fig. B-6a). This may point to dredging activities in both subareas causing the finer sediment fraction and organic matter to be washed out. Such a change in sediment characteristics, however, may also be the result of a natural disturbance, such as storm induced waves (*cf.* WINKELMOLEN & VEENSTRA, 1980).

Figure B-21
Conceptual model of different degree of impact of sand dredging in subareas A (single track) and B (interlinking and crossing tracks) of the borrow area, and processes (reproduction, recruitment, migration) leading to recolonisation of the affected benthic community.



Dredging of sand in the borrow area may have resulted in a silt cloud originating from sediment returned to sea via the spillways on the dredger. This cloud of silt may have deposited in subarea B as well as in subarea A as dredging for sand was done irrespective of the tide. Tidal currents in this area are SW-NE oriented. Such an effect, however, is expected to have been minimal as according to Ballast Nedam dredging company overflow at the dredgers was minimal.

The consequence of the above considerations is that subarea A cannot without any restriction be considered as a reference area; it is a relative reference at the most. Therefore, the use of subarea A as a (relative) reference will be further evaluated in the following parts of the discussion.

*** *Animal-sediment relationships***
The relationship between macrofauna distribution and sediment composition has been the subject of several papers (*e.g.* DANKERS & BEUKEMA, 1981; SALZWEDEL *et al.*, 1985; KÜNITZER *et al.*, 1992; MACKIE *et al.*, 1995). Often a high correlations of community structure and species distribution with the sediment composition were found. Gross differences in sediment type (gravel, sand, silt) are mostly related to different communities, whereas within a certain sediment type, distributional ranges of macrofauna may be rather large (*cf.* WOLFF, 1973; DANKERS & BEUKEMA, 1981).
In this study the sediment was characterised using $CaCO_3$, organic matter and silt (fraction <53 μm) as parameters. Of these parameters, only the amount of organic matter decreased significantly due to the extraction of

sand. For this reason no significant response of the benthic fauna can be expected.
The major response of the benthic fauna will be related to the actual removal of sand, and of benthic animals living herein, and to the mechanisms of recolonisation of the open spaces. As no permanent major changes occurred in sediment characteristics or hydrographic conditions, a full recovery of the benthic fauna can be expected. This recovery will be dependent on mobility and life strategies of the different benthic species.

4.2 Short-term effects

With the extraction of sand most of the benthic fauna will be removed from the dredged track, except for the mobile epifauna organisms. Part of the original fauna may be retained ('relic' fauna; *cf.* WOODIN, 1981), of which only that part will be able to survive that is not damaged by the operation of the sand suction pipe.
Immediately, the new sediment layer is open for colonisation. Colonisation may be mediated by active movements of infaunal species (SANTOS & SIMON, 1980) and/or passive transport via the water column (*cf.* ECKMAN, 1983). This will be dependent on the availability of organisms in and on the neighbouring sea floor. Additionally, depending on the reproductive season of the different benthic species, larvae may settle in the new sediment layer. Especially opportunistic species can be expected to be the first to invade the open spaces (GRASSLE & SANDERS, 1973), although such an expectation does not always appear to be correct (McGRORTY & READING, 1984). Other species that are better resource competitors will follow afterwards to replace the opportunists (GRASSLE & SANDERS, 1973).

The TWINSPAN analysis clearly demonstrated the disturbing effect of the sand extraction. Well known opportunistic species, such as *Capitella capitata*, *Spio filicornis*, and *Spiophanes bombyx* showed up in the T1 survey, *i.e.* after the sand extraction, and attained high densities. Also, a number of other species among which the polychaetes *Poecilochaetus serpens*, *Anaitides mucosa* and *Nereis longissima* and the molluscs *Tellina tenuis* and *Spisula subtruncata* appeared in the T1 survey to disappear again in the T2 survey. Only *Spiophanes bombyx* was still abundant at the T2 survey. Species that were most abundant before the actual sand extraction (T0 survey), *viz.* *Magelona papillicornis*, *Nephtys hombergii* and *Urothoe poseidonis*, showed a strong reduction in their density in the post-extraction surveys.

The process of recolonisation is also clearly demonstrated by the increase of abundance in the T1 survey of *Spisula subtruncata*, *Tellina tenuis* and *Tellina fabula* due to settlement of recruits. For *Tellina tenuis* and *Spisula subtruncata*, which were rare before the extraction, the 'disturbed' subarea B seemed to have better conditions for settlement of juveniles. In 1994, recruitment occurred in both subareas. Survival, however, of both these species till the T2 survey was very poor. This may indicate that life conditions in this part of the coastal zone are not favourable to sustain healthy populations of these species. In fact, *Tellina tenuis* is more or less confined to shallower coastal areas, probably as a result of better food conditions (WOLFF, 1973). The distribution pattern of *Spisula subtruncata* is more or less delimited by the 22 m depth contour (*cf.* HOLTMANN *et al.*, 1996).

The impact of the sand extraction on the populations of bivalves is well illustrated by *Donax vittatus* where the large adult specimens disappeared in the 'disturbed' subarea B but persisted in the 'reference' subarea A (Fig. B-17). The population in subarea B area recovered by settlement of juveniles in 1994 and 1995. Such an annual recruitment also occurred in subarea A.

The population of *Echinocardium cordatum* at the borrow area showed similar changes as in *Donax vittatus.* In subarea B, large specimens were strongly reduced in abundance, whereas such a reduction in adult numbers was less extreme in subarea A (see Fig. B-20).

The data on *Donax vittatus* and *Echinocardium cordatum* suggest a clear negative effect of sand extraction in subarea B, at the same time indicating that subarea A was relatively little affected by the sand extraction. As to the decrease of *Echinocardium cordatum* it is most likely that this was caused by this fragile species being susceptible to mechanical damage at dredging of sand. In the more robust bivalve *Donax vittatus* removal together with the extracted sand may have been the main cause of the decrease in numbers.

As a consequence of the mechanical disturbance organisms may be killed or weakened, thereby making them susceptible to predators or scavengers. This would imply a short term increase of predating and/or scavenging species. This effect of the extraction could not be detected as the first post-extraction survey was made almost one year after the cessation of the activities.

4.3 Longer term effects and recovery

4.3.1 Abiotic changes

The sounding charts of the borrow area as obtained before (February 1993) and after (June 1994) reveal no significant changes in depth in subarea A. In subarea B, however, a significant increase of depth had occurred, which, taking into account the sailing tracks of hopper dredgers (Fig. B-3), must be considered the result of the extraction of sand. After June 1994, a continued erosion was observed in subarea B, not in subarea A. This continued erosion in subarea B is not what would be expected. The normal process after creating a kind of pit in the seafloor would be filling in by natural sedimentation processes. This was shown to happen at various intertidal and subtidal sedimentary (McGRORTY & READING, 1984; VAN DE VEER *et al.*, 1985) as well as gravel bottoms (KENNY & REES, 1994; VAN MOORSEL, 1994). The observed ongoing erosion may be explained as a phenomenon of natural sea floor dynamics in the area.

Detailed larger scale depth soundings, however, to corroborate this assumption are not available.
It was already pointed out in section B.4.1. that the percentage of organic matter in the sediment of the borrow area had strongly decreased, both in subarea A and B. A possible explanation would be washing out of the finer and lighter particles during the sand dredging operation. This would result in a greater decrease in subarea B than in subarea A, which was not observed. An other explanation would be the washing out of a fine fraction due to an episodic event such as a storm (*cf.* WINKELMOLEN & VEENSTRA, 1980). In favour of the latter explanation is the fact that in both subareas A and B a decrease in organic matter content of the sediment was observed.

4.3.2 Changes in biota

After the completion of the sand extraction, the structure of the benthic community in the borrow area deviated from the one that was present before the extraction was started. This is illustrated by the results of the cluster analysis and both ordination analyses. All these three methods were found to complement each other well, *i.e.* grouping the stations of each of the three surveys separately.
The TWINSPAN clustering showed the stations of the T1 survey to be separated from the stations of the T0 and T2 surveys, the latter two surveys being more similar in structure of the benthic fauna community. This is caused by the rise and fall of a number of mainly opportunistic species. In the MDS plot (Fig. B-15) the same development of the community can be clearly observed as the greater distance of the cluster of T1 survey stations to that of the T0 survey, and the shift of the T2 group of stations towards the position of the station cluster of the T0. The DCA ordination revealed that decrease of organic matter content of the sediment is the abiotic factor most strongly correlated with the observed changes in the community structure. This ordination also shows that changes in the number of species and number of predator species per station are a clear component of this change in community structure.

With respect to the structure of the benthic community, all three methods show that in the October 1994 (T1) survey a deviation from the original (= pre-extraction) structure had occurred. By October 1995 (T2 survey), the benthic community had to a great extent returned to a structure as was present before the sand extraction was carried out (T0 survey). Recovery, however, is not considered to be complete in October 1995. Especially in the long-living mollusc species, the age structure of the populations is still unbalanced due to the disappearance of older specimens. In this group of benthic animals, recovery has proceeded primarily through reproduction. Immigrations of specimens from neighbouring areas is not likely to have contributed much, if any. Recolonization of the borrow area by short-living and more motile species, such as polychaetes and crustaceans, has most likely proceeded through both reproduction and immigration from the surrounding area.
Natural development of benthic communities does not always show a more or less stable community structure over time. In the course of the

years a benthic community may very well depart from its initial structure and composition to evolve into a community rather similar but not identical to the one that was found in the first year of observation (*e.g.* SOUPRAYEN *et al.*, 1992). So, a major part of the differences between the benthic communities as found in the T0 and T2-survey may refer to natural fluctuations.

4.4 Effects for consumers of benthos

Generally speaking, the importance of benthos as food for fishes and birds depends on their abundance (and dominance) in the benthic community and size (*e.g.* DE GROOT, 1971).
The coastal zone down to ca. 30 m depth is important as nursery for various demersal fish species. Measured by numbers, the most important of these species are plaice (*Pleuronectes platessa*), common goby (*Pomatoschistus minutus*), dab (*Limanda limanda*), five-bearded rockling (*Ciliata mustela*), sole (*Solea solea*) and flounder (*Platichthys flesus*). Dragonet (*Callionymus lyra*) and solenette (*Buglossidium luteum*) are important resident species (BERGMAN & LEOPOLD, 1992). Different fish species and different life stages of fish (young *vs.* adult) generally use different size prey. Young Dab (*Limanda limanda*) start feeding on *Diastylis* sp. as soon as it becomes abundant. Young cod (*Gadus morhua*), on the other hand, only consumes the crustaceans *Diastylis* sp. and *Gastrosaccus spinifer* that have reached a certain minimal individual weight (ARNTZ & BRUNSWIG, 1976). In general terms, most benthic crustaceans, polychaetes will be suitable as food for these fish. Also molluscs are being eaten, *e.g.* by juvenile turbot, dab and sole (DE GROOT, 1971).
If we do consider only subarea B as directly affected by the extraction of sand then in only 1.4 km² a decrease in biomass occurred, mainly due to the disappearance of larger bivalves and larger sea urchins. These larger specimens have relatively little relevance as prey for the by large juvenile demersal fish populations. Therefore, although polychaete biomass was reduced in subarea B (see Fig. B-12b), the risk of subaqueous sand extraction to consumers of benthos among the coastal fish populations is considered almost negligable, mainly due to the relatively small spatial scale of the disturbance.
The most important food source for eiders (*Somateria mollissima*) and common scoters (*Melanitta nigra*) in the Netherlands are the molluscs *Spisula subtruncata*, *Donax vittatus* and *Cerastoderma edule* (LEOPOLD, 1996). *Cerastoderma edule* is primarily found in the Dutch Wadden Sea and is rare on the North Sea coast. Of *Spisula subtruncata* large banks are found along the Dutch coast with densities over 5000 individuals per m². Common scoters concentrate on these banks (OFFRINGA, 1991; LEOPOLD *et al.*, 1995). In the borrow area, however, densities of *Spisula subtruncata* were very low and density of *Donax vittatus* was moderate. Therefore, the borrow area cannot be considered as an important feeding ground for diving ducks, although common scoters are known to be able to dive to depths of 30 m.

5 Conclusions

5.1 Short-term effects

The short-term effects of the extraction of sand on the benthic fauna of the borrow site are most evident for long-living species, such as bivalve molluscs and echinoderms. Here, especially the adults are affected, causing a significant reduction in numbers and biomass of these species. Within the group of polychaetes, an opportunistic response was observed of species colonizing the area after sand extraction. This response caused a significant change in the benthic community structure.

5.2 Longer term effects and recovery

On the longer term, numbers of bivalve molluscs and echinoderms recovered, mainly by recruitment. Adult specimens, however, had remained rare. Recovery of their numbers is expected to take a couple of years or more. The short-term opportunistic response of polychaetes was followed by a replacement by species that probably are more competitive. Two years after the sand extraction the structure of the the benthic community had largely returned to the one present before the extraction was carried out. Still existing differences largely relate to differences in the abundance of the longer living species (i.e. bivalves and sea urchins). The observed overall decline in abundance of benthos may to a large extent be considered as a natural fluctuation because this decrease occurred in subarea B as well as in subarea A.

5.3 Risk to fish and birds

In principle, the short-term effect of sand extraction (reduction of biomass and abundance of benthic species) is a reduction of food supply for demersal fish. As the reduction in benthic species mainly relates to disappearance of larger specimens (sea urchins, bivalves), food supply of juvenile flatfish, having a preference for the smaller food items, is not expected to be seriously affected. For the supposedly affected subarea B (1.4 km^2) a loss of polychaete biomass of around 9000 kg ash-free dry weight (or 6.4 g AFDW/m^2) was calculated by comparison of the T0- and T1-survey results. For crustaceans this loss was estimated to amount to only 270 kg AFDW (or 0.2 g AFDW/m^2).
The strong reduction of abundance of *Echinocardium cordatum* does not have much effect as this species does not play a significant role in the diet of juvenile flatfish and birds.

Although the local population of *Donax vittatus* was seriously affected by the sand extraction (disappearance of adult specimens), this did not lead to a significant reduction of food supply for common scoter. Although this duck is able to collect molluscs at 30 m water depth, the abundance of *Donax vittatus* in the borrow area before sand extraction took place was too low to be attractive for exploitation by these birds, given the occurrence of much denser banks of *Spisula subtruncata* closer to coast. Current Dutch policy does not allow sand extraction landward of the 20 m depth contour (ANONYMOUS, 1993b). Therefore, subaqueous sand extraction at a limited scale as in this project around or seaward of the 20 m depth contour is not very likely to interfere significantly with local benthos and their consumers.

Appendix B.

List of macrobenthos species collected during the RIACON project in the sand extraction/borrow area off the island of Terschelling between March 1993 and April 1995, and the number of stations were the species were found for each of the surveys.

Species indicated with an asterisk (*) were excluded from the data analyses (see 2.6).

Phylum codes:

1	Mollusca
2	Crustacea
3	Annelida
4	Echinodermata
5	Nemertinae
6	Acrania

Taxon codes:

A	Amphipoda	M	Mysidacea
B	Bivalva	N	Nemertinea
D	Decapoda	O	Ophiuroidea
E	Echinoidea	P	Polychaeta
G	Gastropoda	S	Asteroidea
I	Isopoda	U	Cumacea
Ac	Acrania		

Feeding type codes:

1	scavenger & omnivore
2	omnivore & predator
3	filter feeder
4	filter feeder and selective deposit feeder
5	non-selective deposit feeder
6	non-selective deposit feeder & predator
7	predator
8	predator & omnivore
9	selective deposit feeder or grazer
10	selective deposit feeder or grazer & filter feeder
11	(non)-selective deposit feeder or grazer
12	predator & filter feeder
13	predator & grazer

Assignment of species to feeding type was done according to: FAUCHALD & JUMARS (1979); HARTMANN-SCHRÖDER (1969); HOLTMANN *et al.* (1996); MULDER *et al.* (1988); NAYLOR (1972); PLEIJEL & DALES (1991); RUPPERT & BARNES (1994); SEIP & BRAND (1979) and STECHER & DÖRJES (1993).

					present in n stations (total nr. of stations)		
Species	Abreviation	Phylum	Taxon	Feeding type	T1 1993 (30)	T2 1994 (30)	T3 1995 (34)
Abra alba	ABRAALBA	1	B	9	2	1	
Abra tenuis	ABRATENU	1	B			1	
Donax vittatus	DONAVITT	1	B	3	26	15	15
Ensis directus	ENSIDIRE	1	B	3	3	10	5
Ensis siliqua	ENSISILI	1	B	3	3	1	
Lunatia catena	LUNACATE	1	G	7	2	3	1
Lunatia poliana	LUNAPOLI	1	G	7	1	5	11
Macoma balthica	MACOBALT	1	B	10		1	
Mactra corallina	MACTCORA	1	B	3	1	2	3
Montacuta ferruginosa	MONTFERR	1	B	3	15	6	15
Mysella bidentata	MYSEBIDE	1	B	3	4	12	15
Spisula elliptica	SPISELLI	1	B	3	1	8	2
Spisula subtruncata	SPISSUBT	1	B	3		22	7
Tellina fabula	TELLFABU	1	B	10	28	23	15
Tellina tenuis	TELLTENU	1	B	4	2	23	4
Venus striatula	VENUSTRI	1	B	3	3	2	1
Ampelisca brevicornis	AMPEBREV	2	A		1	1	
Anapagurus laevis	ANAPLAEV	2	D			1	
Apherusa ovalipes	APHEOVAL	2	A				1
Argissa hamatipes	ARGIHAMA	2	A	8	2		1
Atylus falcatus	ATYLFALC	2	A	9	5	1	
Atylus swammerdami	TYLSWAM	2	A		3	4	2
Bathyporeia elegans	BATHELEG	2	A	9	29	24	32
Bathyporeia guilliamsoniana	BATHGUIL	2	A	9	26	9	17
Callianassa subterranea	CALLSUBT	2	D	9	1	6	1
Caprellidae species	CAPRSPEC	2	A				
Crangon allmanni*	CRANALLM	2	D				1
Crangon crangon*	CRANCRAN	2	D	8	1	7	
Diastylis bradyi	DIASBRAD	2	U	9	1	3	6
Diastylis lucifera	DIASLUCI	2	U	9	2	11	3
Diastylis rathkei	DIASRATH	2	U	11	1	1	4
Diastylis rugosa	DIASRUGO	2	U		1		
Diastylis tumida	DIASTUMI	2	U			1	
Eualus pusiolus*	EUALPUSI	2	D			1	
Gastrosaccus spinifer*	GESTSPIN	2	M	8	2	11	16
Idothea linearis	IDOTLINE	2	I	9		7	
Iphinoe trispinosa	IPHITRIS	2	U	9	2	16	
Jassa falcata	JASSFALC	2	A			1	
Leucothoe incisa	LEUCINCI	2	A			2	
Liocarcinus pusillus*	LIOCPUSI	2	D			1	
Megaluropus agilis	MEGAAGIL	2	A		2	20	5
Melita obtusata	MELIOBTU	2	A			1	
Microprotopus maculatus	MICRMACU	2	A			1	
Neomysis integer*	NEOMINTE	2	M			6	

Orchomene nana	ORCHNANA	2	A		2	3	3
Pagurus bernhardus	PAGUBERN	2	D	2		1	
Pinnotheres pisum	PINNPISU	2	D		1		2
Pontocrates altamarinus	PONTALTA	2	A	9	28	10	8
Pontocrates arenarius	PONTAREN	2	A	9		1	
Pontophilus trispinosus*	PONTTRIS	2	D			20	22
Pseudocuma gilsoni	PSEUGILS	2	U			1	
Pseudocuma longicornis	PSEULONG	2	U	9	9	2	1
Pseudocuma similis	PSEUSIMI	2	U			1	
Thia scutellata	THIASCUT	2	D		1		
Urothoe poseidonis	UROTPOSE	2	A	9	3	25	30
Anaitides groenlandica	ANAIGROE	3	P	7	1	2	
Anaitides maculata	ANAIMACU	3	P	7			
Anaitides mucosa	ANAIMUCO	3	P	7	3	27	3
Anaitides subulifera	ANAISUBU	3	P	7		15	8
Aonides paucibranchiata	AONIPAUC	3	P			1	
Autolytus langerhansi	AUTOLANG	3	P	7		1	
Autolytus prolifer	AUTOPROL	3	P	7		2	2
Capitella capitata	CAPICAPI	3	P	5/7	2	25	6
Chaetozone setosa	CHEASETO	3	P	9	8	21	28
Eteone barbata	ETEOBARB	3	P			2	
Eteone flava	ETEOFLAV	3	P	7	1	5	
Eteone foliosa	ETEOFOLI	3	P			1	
Eteone lactea	ETEOLACT	3	P			1	
Eteone longa	ETEOLONG	3	P	7	19	18	8
Eumida sanguinea	EUMISANG	3	P	7		14	7
Glycinde nordmanni	GLYCNORM	3	P	7	3		
Harmothoe longisetis	HARMLONG	3	P	7	2		
Harmothoe lunulata	HARMLUNU	3	P	7	1	11	
Harmothoe species	HARMSPEC	3	P	7		1	
Lanice conchilega	LANICONC	3	P	10	4	20	6
Magelona papillicornis	MAGEPAPI	3	P	4	30	29	34
Microphthalmus similis	MICRSIMI	3	P			2	
Nephtys caeca	NEPHCAEC	3	P	2	2	5	3
Nephtys cirrosa	NEPHCIRR	3	P	7		1	21
Nephtys hombergii	NEPHHOMB	3	P	2	29	29	12
Nephtys longosetosa	NEPHLONG	3	P	7		5	7
Nereis diversicolor	NEREDIVE	3	P	6	2		
Nereimyra punctata	NEREPUNC	3	P			1	
Nereis virens	NEREVIRE	3	P	2	1		
Nereis longissima	NERELONG	3	P	5	1	22	7
Ophelia limacina	OPHELIMA	3	P	5	2	1	1
Owenia fusiformis	OWENFISI	3	P	4		2	
Pectinaria koreni	PECTKORE	3	P	9	1	9	
Pholoe minuta	PHOLMINU	3	P	7		1	
Poecilochaetus serpens	POECSERP	3	P	4	1	23	3
Pygospio elegans	PYGOELEG	3	P	9		3	
Scoloplos armiger	SCOLARMI	3	P	5	19	14	2
Scolelepis bonnieri	SCOLBONN	3	P	7	25	24	22

Scolelepis squamata	SCOLSQUA	3	P	10	1	3	1
Sigalion mathildae	SIGAMATH	3	P	7	4	5	5
Spiophanes bombyx	SPIOBOMB	3	P	9	1	30	34
Spio filicornis	SPIOFILI	3	P	4	2	29	3
Stenelais limicola	STENLIMI	3	P	7	10		
Syllidia armata	SYLLARMA	3	P	7	7	2	3
Acrocnida brachiata	ACROBRAC	4	O				5
Asterias rubens	ASTERUBE	4	S	2		1	
Echinocardium cordatum	ECHICORD	4	E	5	13	14	27
Ophiura texturata	OPHITEXT	4	O	2		4	1
Nemertinae species	NEMERTIN	5	N	7	29	30	34
Branchiostoma lanceolatum*	BRANLANC	6	Ac	0	1	2	3

PART C

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