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Effects of Artificial Beach Nourishment on Nearshore Sediment Distribution (Island of Norderney, Southern North Sea)

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ABSTRACT

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The continuous erosion of the western spit led to artificial beach nourishment of the affected parts with sand. The aim was to ensure the stability of the solid coastal protection structures. The beach nourishment has been repeatedly carried out at irregular intervals since 1951. This paper reviews some effects of the last beach restoration on the sediment distribution in spring 1989. The beach was partly refilled with well sorted fine sand. The mean grain size of the original beach sediments was much coarser.

Sediment samples were taken twice yearly to obtain an overall view of long-term changes of the sediment distribution. Samples taken at monthly intervals, mainly in the problematic zone of severe erosion, gave information on short-term changes. The grain size distribution, carbonate and heavy mineral contents were determined.

At first, after the beach nourishment, a strongly decreasing grain size was detected, but soon reversed. Despite a selective erosion of finer sediment particles and the relative enrichment of coarser grains, the grain size spectrum of the beach refilling as it was before the replenishment was observed in the spring of 1991. The natural grain size distribution which is in an equilibrium with the hydrodynamic forces was produced by erosion of the beach material. The fine grained sand used as the refill is a "foreign" material that does not correspond to the boundary conditions at this site.

The examination of heavy minerals provides information about transport directions of the beach and shoreface sediments. It shows that the cross-shore transport is dominant within the groin-fields. The grain size of the sediments of the refilled area does not differ very much from those of the shoreface sediments, and thus this parameter is unsuitable for an analysis of the along-shore transport of the sediment. Although, an eastward and southward along-shore transport could be revealed from the refilled beach section after the nourishment. A survey of the beach and shoreface morphology provides additional information on the sediment transport and temporal sediment volume development.

ADDITIONAL INDEX WORDS: *Coastal protection, beach sands, sediment distribution, coastal erosion, beach replenishment, beach, shoreface.*

INTRODUCTION

Norderney belongs to the East Frisian Islands which together with the Dutch West Frisian Islands form a classical system of protecting barrier-islands and back-barrier tidal flats. The tidal flats of the southern North Sea extend over 1,000 km from Den Helder in the Netherlands to Skallingen in Denmark. Covering almost 10,000 km^2 (including islands) they are one of the largest tidal flats on earth. The tidal range increases from 1.5 m in Den Helder to 4 m in the estuarine areas of the Elbe and Weser rivers because of the funnel-shaped German Bight.

Norderney can be characterized, with a mean tidal range of almost 2.4 m as mesotidal (Table 1). The island has a length of 14 km, a maximal width of 2 km, and an area of *ca.* 25 km^2 (Figures 1, 2).

A classification of the beach of Norderney Island can be revealed from hydro- and morphodynamic conditions (Figure 1): (1) the western beach is affected by influences of the tidal inlet "Norderneyer Seegat" between the islands of Juist and Norderney; (2) the divergence area between the groins C and A is characterized by a splitting of wave induced currents to the SW and NE (LUCK, 1970); (3) the northwestern beach is dominated by waves, and tidal currents are almost absent (NIEMEYER, 1987). This beach section has been largely eroded during the last decades; and (4) the northern beach has been less affected by erosion, since the effect of coastal protection structures is less dominant than on the western spit.

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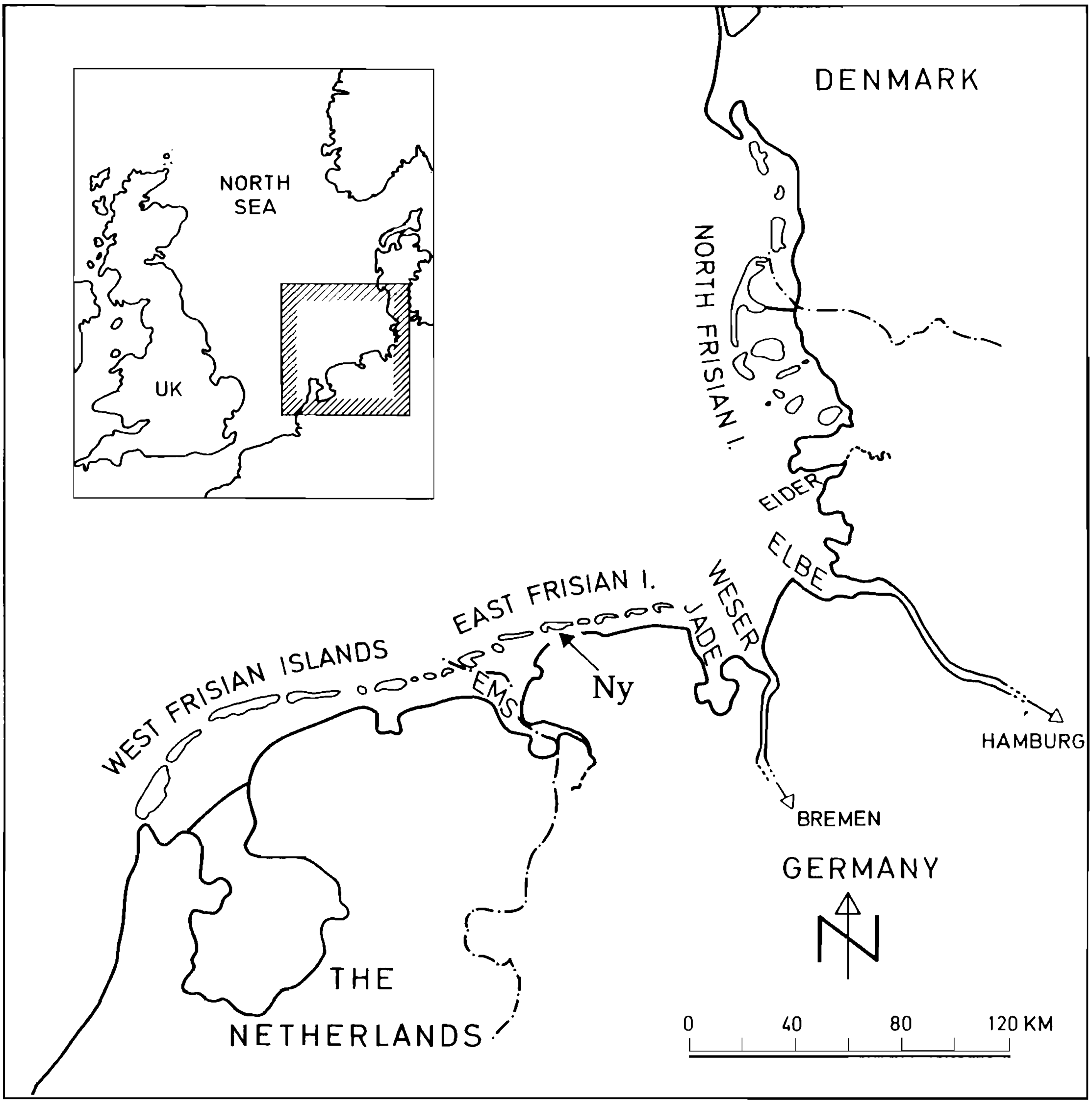

Figure 1. Location map of the East Frisian Islands (southern North Sea).

The entire beach which was studied is situated within the ebb delta of the tidal inlet of Norderney. Therefore, the incident wave energy is reduced by ebb delta shoals.

Sediment transport processes of the beach are closely connected with those of the ebb tidal delta. In the past, the transport processes within the ebb delta have often been studied (*e.g.*, KRAUSE, 1950; DECHEND and RICHTER, 1953; AKKERMANN, 1953; HOMEIER and KRAMER, 1957; NUMMEDAL and PENLAND, 1981). A recent detailed investigation of temporal changes of sediment distribution in the deeper channels of the ebb delta is due almost exclusively to tidal currents. Wave-induced currents appear increasingly as a transport medium on the shoals (Figure 3).

The influence of anthropogenic intervention in the natural dynamics can be seen as the many coastal protection measures on Norderney (Figure 3). The transport processes around the west-

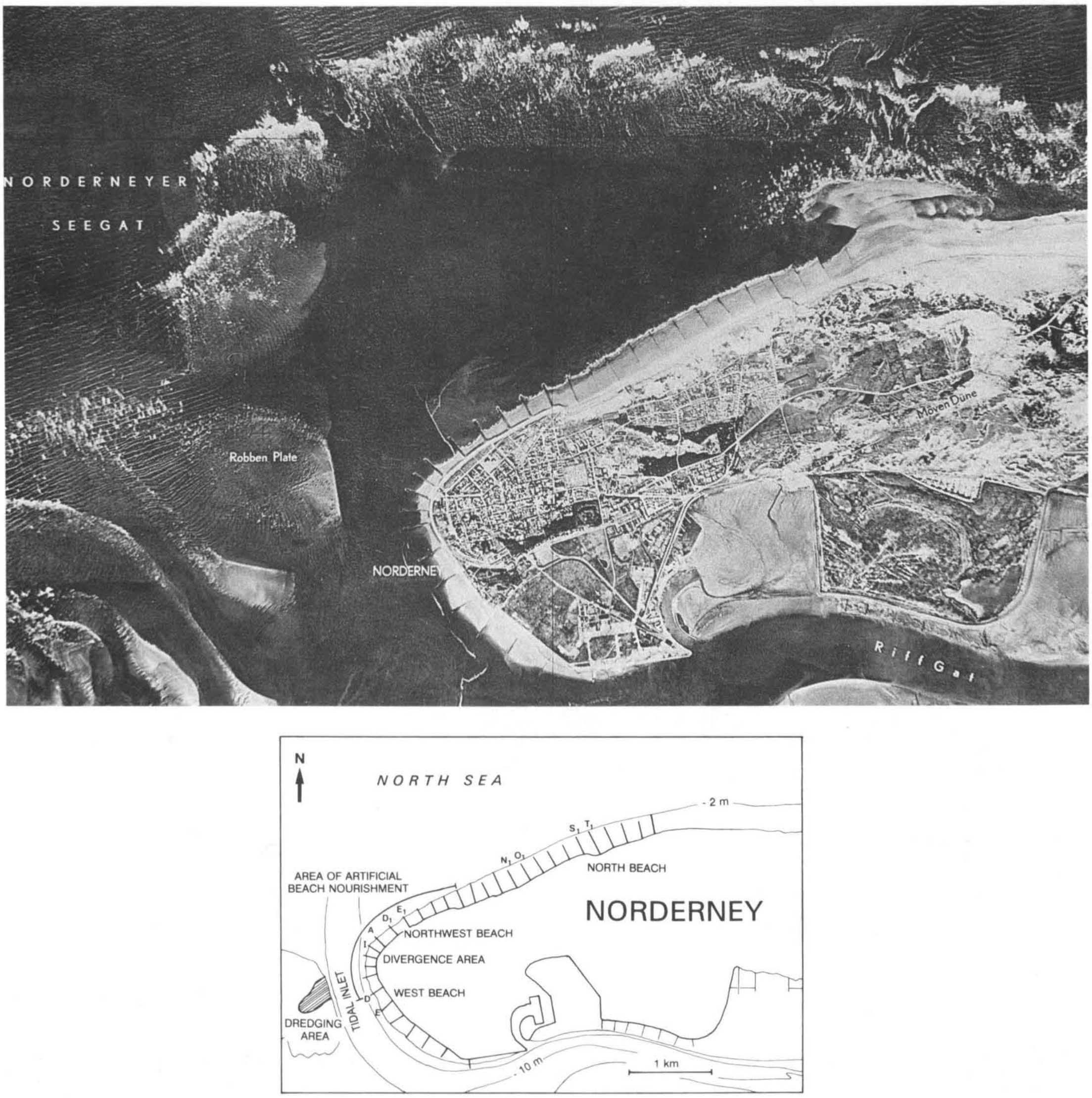

Figure 2. Aerial photo and location map of the island of Norderney; dredging area, range of the beach nourishment in 1989.

ern spit were changed by construction of groins, revetments and sea walls (KUNZ, 1987, 1991). The continuous erosion of the western spit of Norderney has led to necessary beach restoration by artificial nourishment of the affected parts with sand. The aim was to ensure the stability of the solid coastal protection structures. The beach nourishment has been carried out at irregular intervals since 1951 (Table 2). The western and northern beaches are secondarily nourished with

Table 1. *Hydrographic data for Norderney.*

MLW	−1,27 m	MTR	2,39 m
MHW	+1,12 m	HHW	+4,12 m
Velocities of tidal currents in the tidal inlet (m/sec)—mean (maximum):			
Ebb	0,70 (1,20)	to	0,95 (1,60)
Flood	0,60 (1,00)	to	0,80 (1,40)

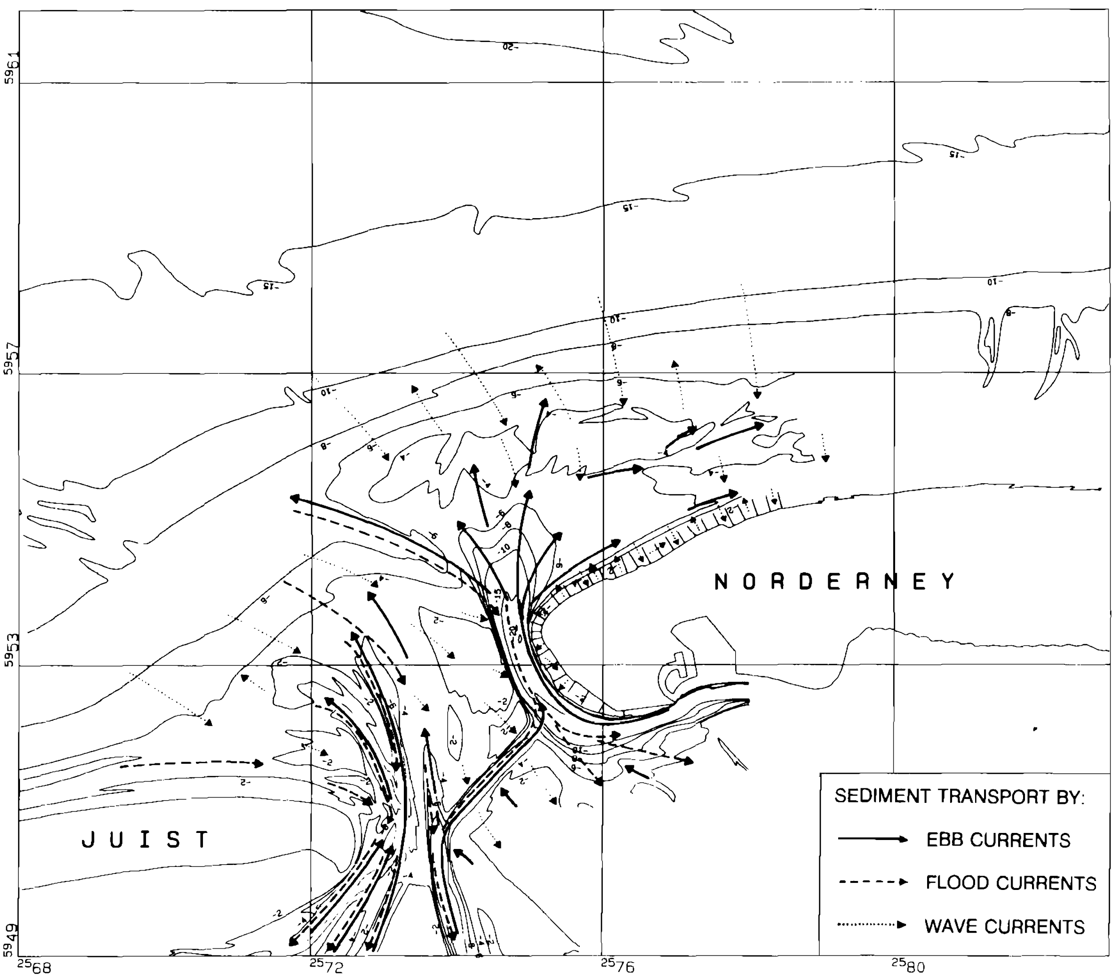

Figure 3. Sediment transport directions of the ebb delta of the tidal inlet of Norderney (after Westhoff, 1990).

sand from the refilled beach section. Therefore, they show a positive or at least a balanced sand budget.

In spring of 1989 the beach of Norderney was refilled between the groins D and J1 with *ca.* 450,000 m^3 of well sorted fine sand (mean grain size 0.17 ± 0.04 mm) dredged from an ebb shoal across the tidal inlet of Norderney (Figure 1). The mean grain size of the original beach sediments was much coarser (about 0.32–0.35 mm, medium sand).

METHODS

Sediment sampling of the beach and the shoreface was restricted to the areas of negative and balanced sediment budget because it was assumed that effects of the beach nourishment would be significantly noticed there only. Samples were taken along 34 shore perpendicular profiles of the beach and shoreface twice a year (autumn and spring) in an attempt to achieve an overall view of long-term changes of the sediment distribution. Samples taken at monthly intervals along seven profiles—mainly in the problematic zone of severe erosion—gave information about the short-term changes. Here only four representative profiles will be shown. The grain size distribution, carbonate and heavy mineral content of each sample were determined.

The samples were taken using 5 cm-cylinders

Table 2. *Volume and mean grain-size (d_{50}) of the artificial beach nourishments on Norderney from 1951 to 1990 (** dry nourishment) (KRAMER, 1960; LUCK, 1970; PÄTZOLD, 1982; ERCHINGER, 1986; KUNZ, 1991).*

Year	Volume (Mio. m^3)	d_{50} (mm)	Refilled Area Between the Groins	Dredging Area
1951–1952	1.245	0.10–0.13	O–V_1	back barrier flats
1967	0.240	0.15–0.30	E–K_1	front of groin G_1
1976	0.400	0.18–0.30	E–E_1	Robbenplate
1982	0.470	0.17–0.25	C–H_1	Robbenplate
1983**	0.064		J_1–N_1	E' Weiße Düne
1984	0.410	0.16–0.20	C–J_1	Robbenplate
1989	0.447	0.15–0.20	D–J_1	Robbenplate
1990**	0.045	0.15–0.22	J_1–N_1	E' Weiße Düne

without disturbing the sediment on low water line, mean water line, high water line, and in the backshore area, if the back shore area was apparent. The shoreface was sampled by a Van-Veen-grab from a boat, but these samples were disturbed.

Some transport processes could be determined by certain sediment parameters (*i.e.*, grain size, sorting, carbonate and heavy mineral content), although not all the parameters are equivalent. Fluorescent sand grains were quite helpful in studying smaller areas.

SEDIMENT DISTRIBUTION

The beach of Norderney is mainly characterized by wave influence. Tidal currents are only relevant on the western beach. Here, tidal currents of up to 30 cm/s can be measured (NIEMEYER, 1987). The sediments are mostly finer grained than

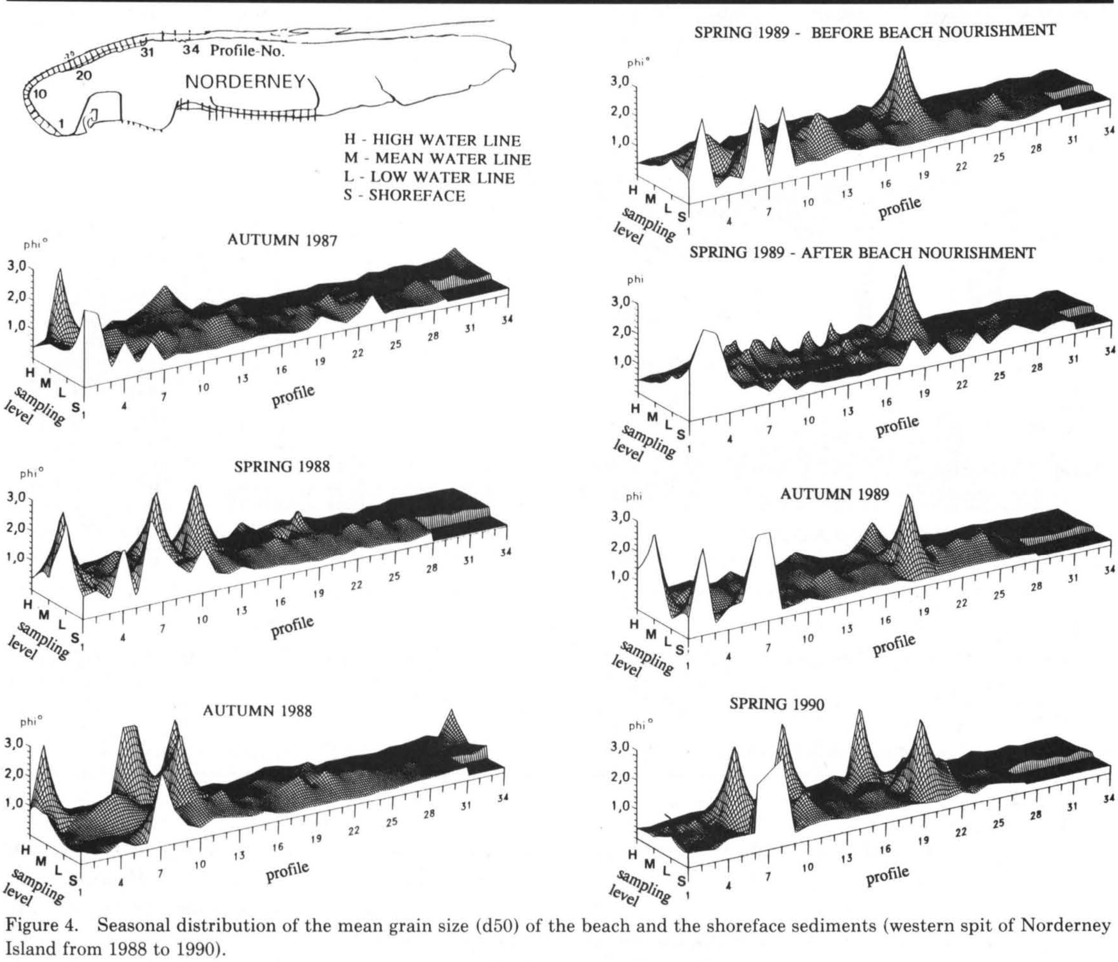

Figure 4. Seasonal distribution of the mean grain size (d50) of the beach and the shoreface sediments (western spit of Norderney Island from 1988 to 1990).

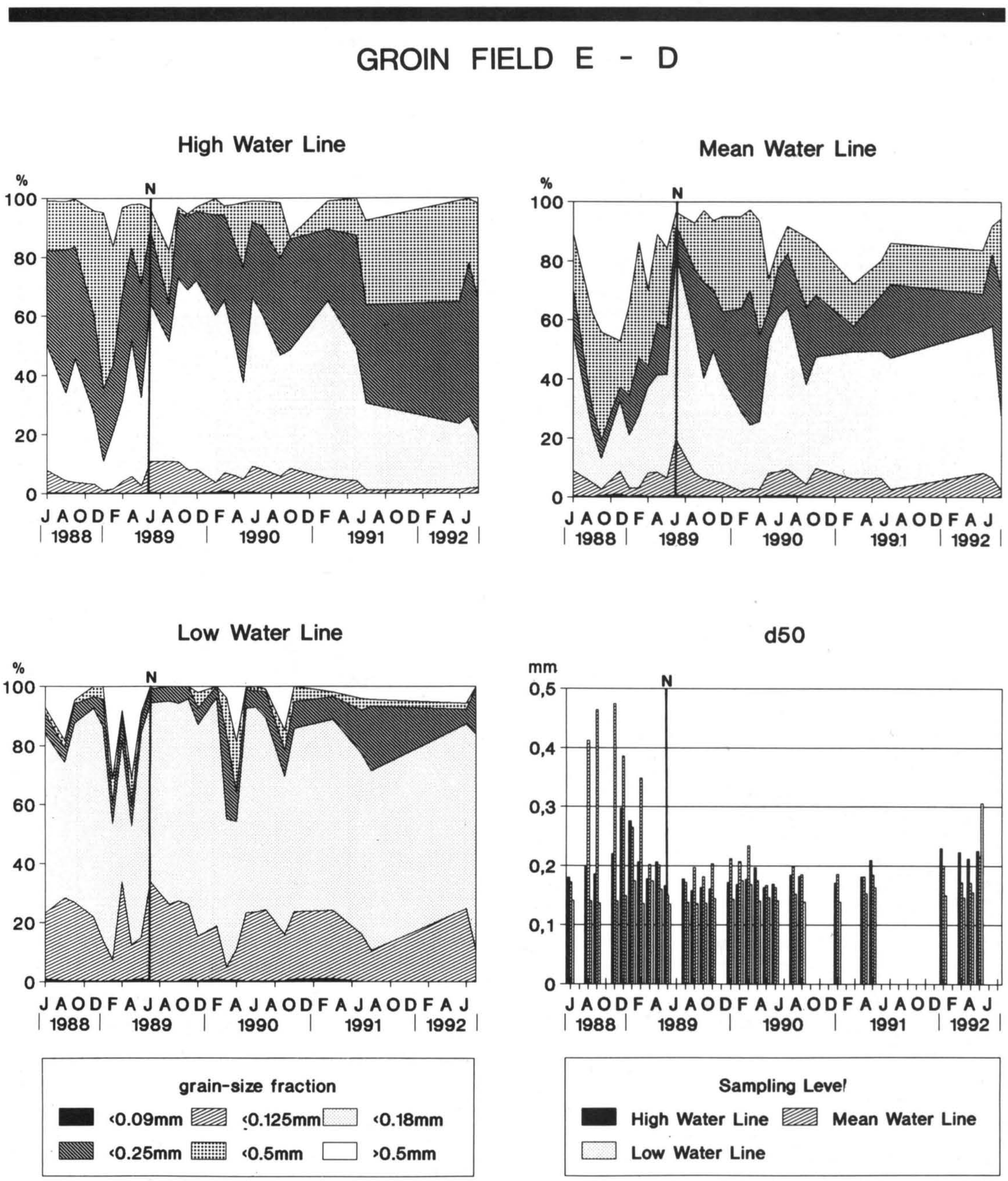

Figure 5. Grain size distribution over time in the groin field E–D before and after the artificial beach nourishment (N).

those of the groin fields further to the east. The high medians in the divergence area are due to the high percentage of broken shell. The northwestern beach sediments are also relatively coarser grained and poorly sorted. The grain size decreases on the northern beach. Generally, an increase in the grain size from the shoreface to the beach can be determined. On the beach, the coarsest sediments are along the mean water line. The sands of the high water line and the low water

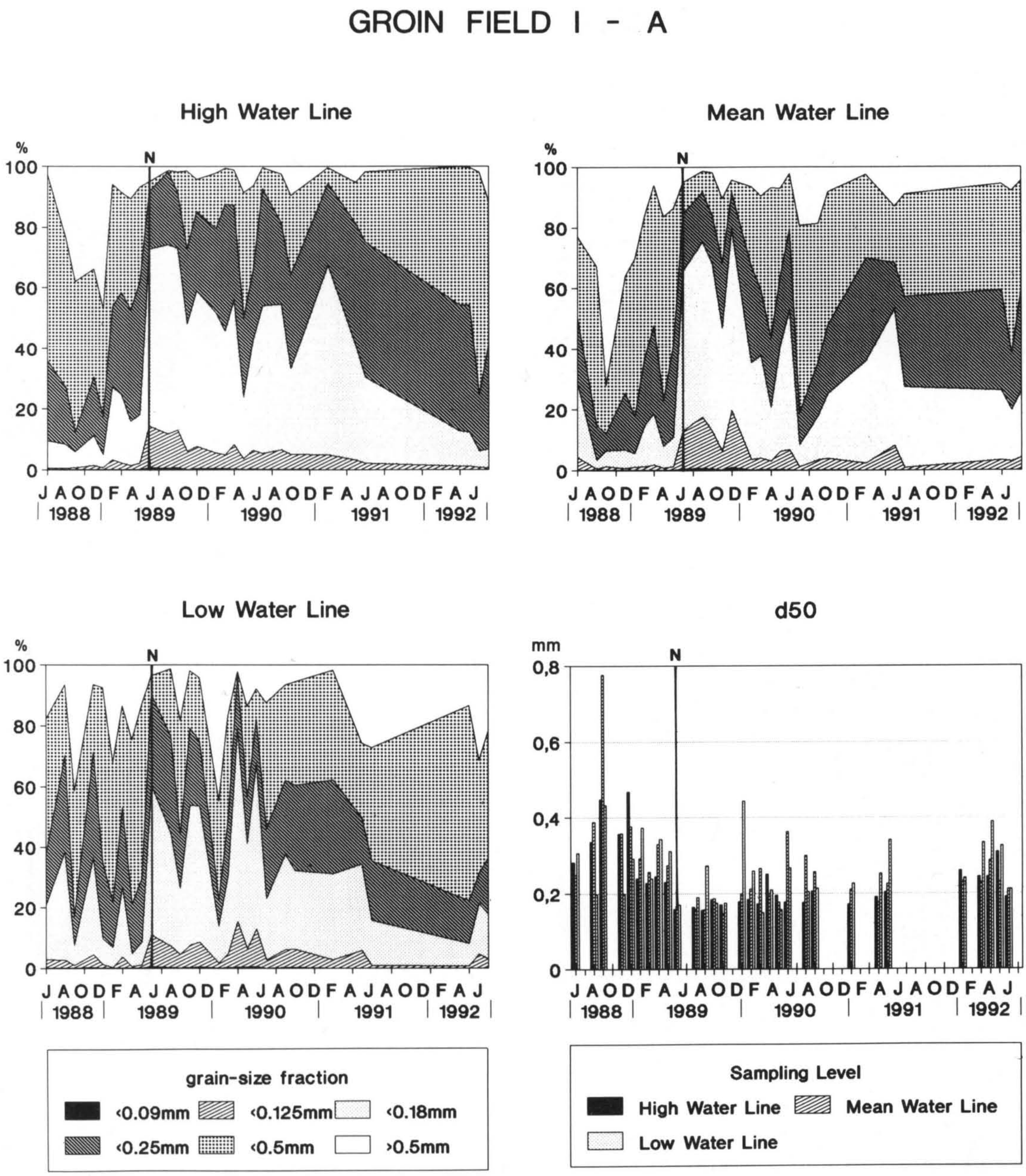

Figure 6. Grain size distribution over time in the groin field I–A before and after the artificial beach nourishment (N).

line are mostly fine grained. The sediments of the western beach have a particularity not seen on the other beach sections; *i.e.*, the sand of the low water line is much finer grained than the other sampling levels (Figure 4).

Effects of Artificial Beach Nourishment on Sediment Distribution

The effects of the beach restoration can be better recognized by the grain size distribution of

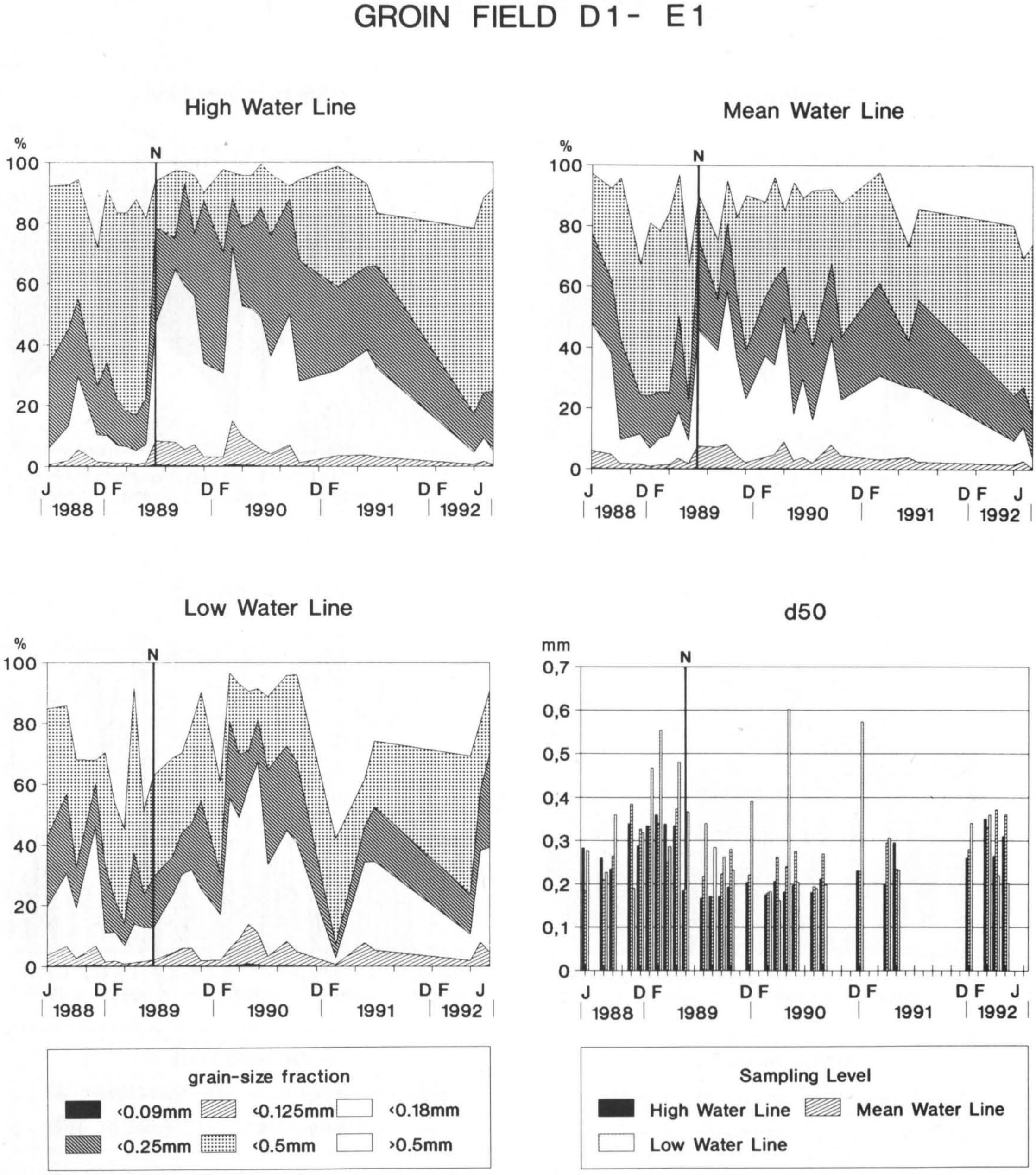

Figure 7. Grain size distribution over time in the groin field D1–E1 before and after the artificial beach nourishment (N).

certain groin fields. The temporal development of grain size distribution on different sampling levels is presented in Figures 5–8. After replenishment, when the beach was refilled by fine sands, a strongly decreasing grain size has been detected in the restored area as well as in the adjacent groin field E–D, although the refinement in the grain size spectrum is distinctive on different sampling levels. These changes can be clearly recognized along the high water line. East of the replenished

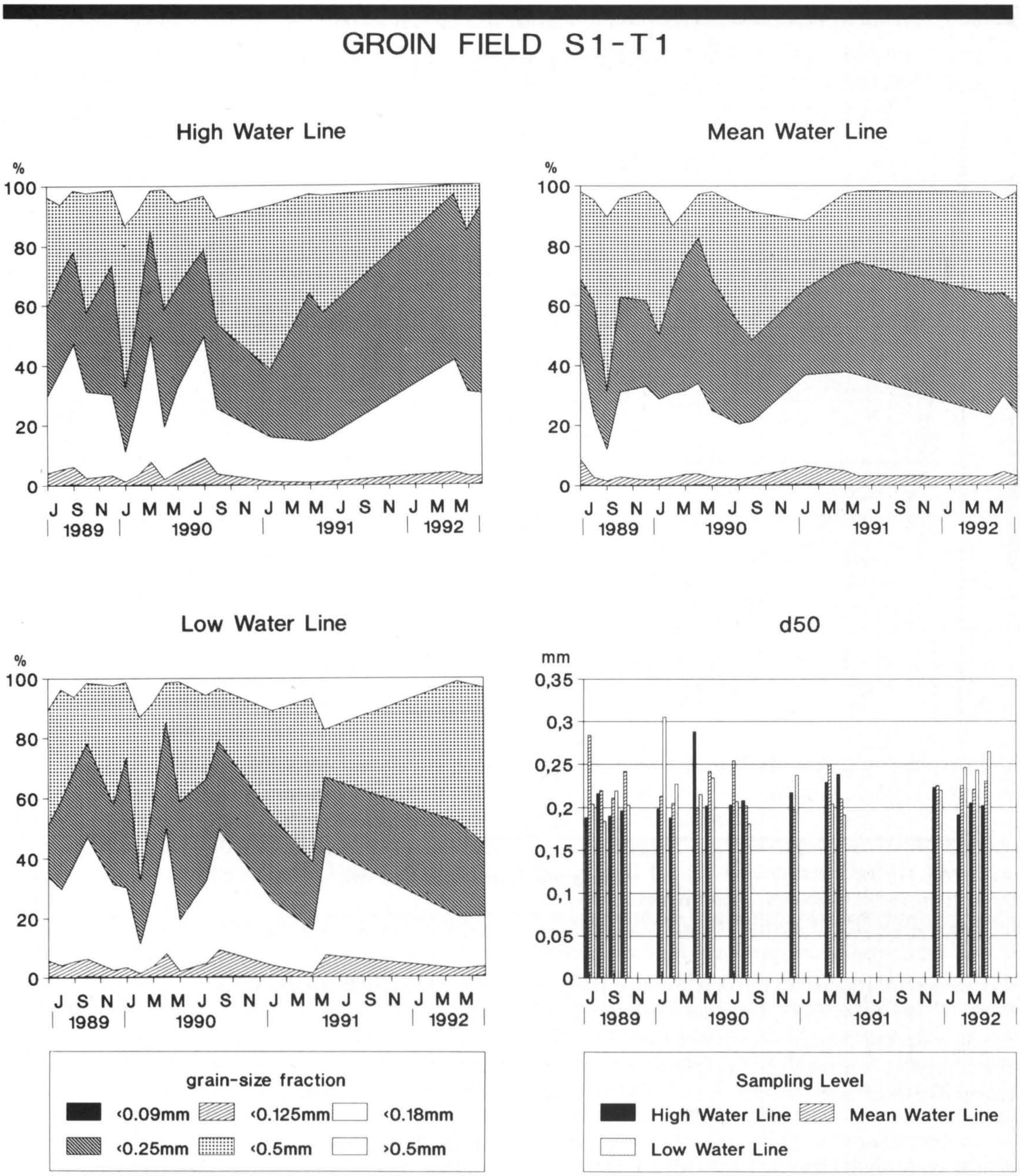

Figure 8. Grain size distribution over time in the groin field S1–T1 before and after the artificial beach nourishment (N).

area, these changes can be detected after a delay of almost two years. This fact is due to along-shore transport, which although postulated at times in the past, was not really proved until now. The transport directions are not known precisely. It can be assumed that the sediment was not directly transported eastwards because there is no dominating along-shore current. The sediment was probably carried by alternating cross-shore currents producing a zig-zag transport pattern which

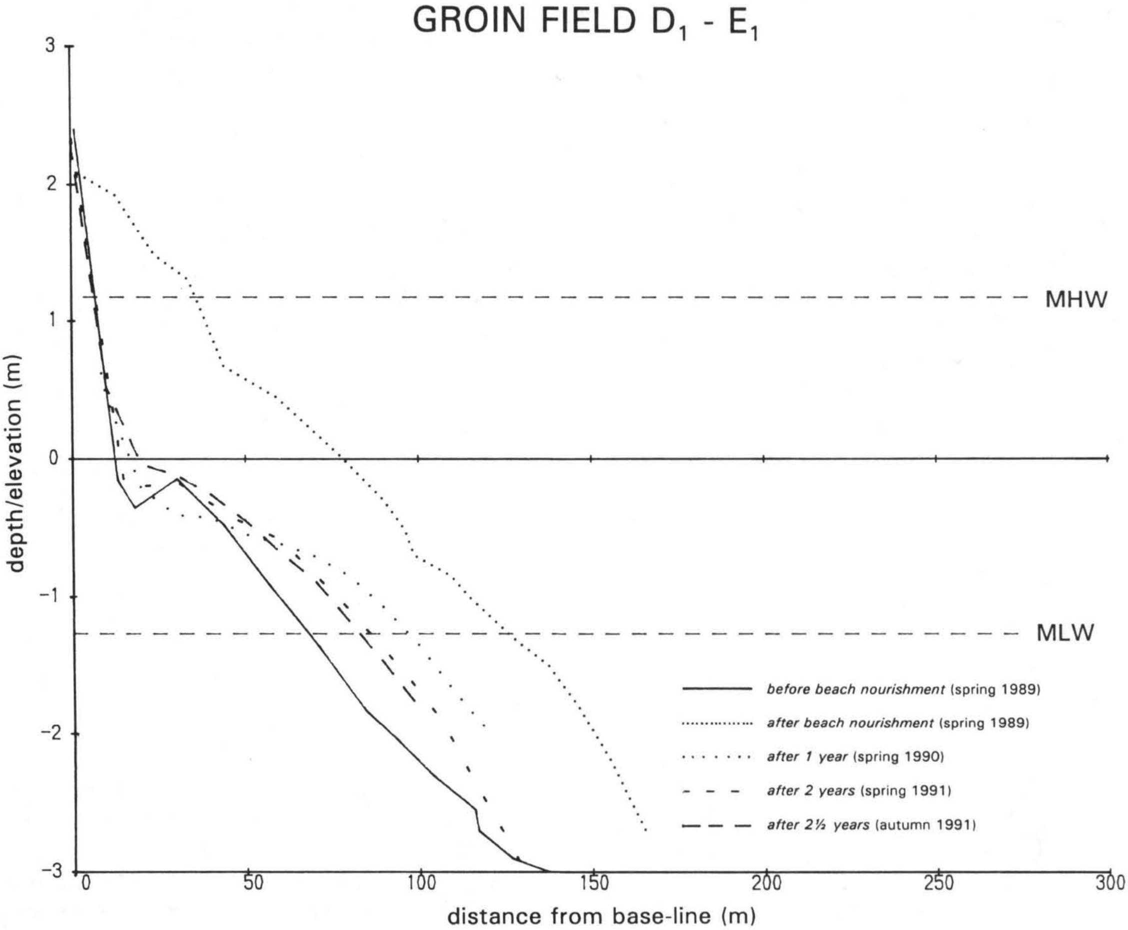

Figure 9. Beach profiles in groin field D1–E1 before and after the beach nourishment in 1989.

was shown by HANISCH (1981) to exist in the ebb delta of the tidal inlet between the islands of Spiekeroog and Wangerooge to the east. This zigzag transport is a result of vector differences between seaward and landward cross-shore currents.

Effects of Artificial Beach Nourishment on Morphology and Sediment Budget

During the investigations, the morphological development was also examined. The results of levelling and tachymetric surveys as well as soundings were used for sediment volume calculations. The morphological changes demonstrated by the example of groin filed D1–E1 (Figure 9).

Figure 10 demonstrates the temporal development of partial volumes between contour lines which have a distance of one meter each. It shows that initially after the beach nourishment in 1989, sand from the upper beach was mainly transported to the shoreface. The losses of the intertidal beach decreased after one year. Simultaneously, the sediment volume of the shoreface decreased as well.

SEDIMENT TRANSPORT

It is important to examine transport processes to get a better understanding of the causes of the losses of certain beach parts. Tracers are a suitable instrument for describing sediment transport paths.

Heavy minerals have different hydrodynamic properties due to their higher density relative to, for example, quartz grains and, therefore, can be

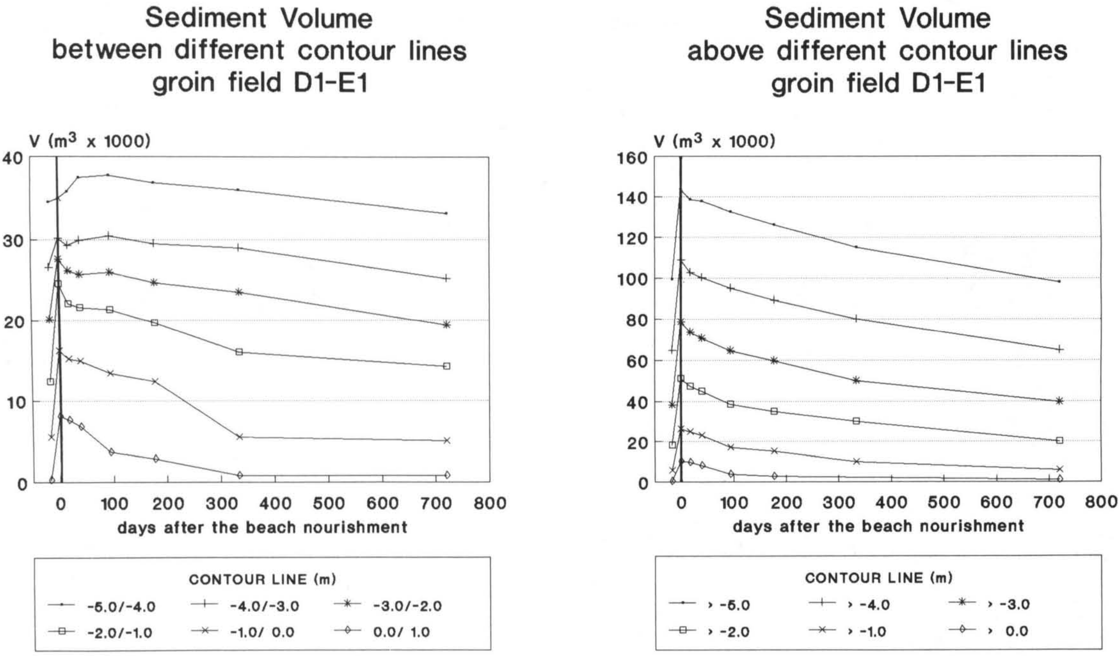

Figure 10. Temporal development of the sediment volume in groin field D1–E1 after the beach nourishment (N) in April, 1989.

used as natural tracers. Heavy minerals are concentrated mainly in the fine sieve fraction. According to VEENSTRA and WINKELMOLEN (1976), only the fraction 0.106–0.125 mm was analyzed for heavy minerals by using a Frantz Magnetic Separator.

Generally, there is an increase of heavy mineral content from the shoreface to the backshore. The heavy mineral content of the backshore can amount to up to 30% (Figure 11). There are significant seasonal differences as also seen in the grain size distribution. The heavy mineral content increases mainly in winter. In this season, the energy input due to storm surges, for instance, increases so that an intensified enrichment of heavy minerals can be recognized. The concentration of heavy minerals is due to selective entrainment and differential transport as agents of sorting because of density and size differences (*e.g.*, SLINGERLAND, 1977, 1984; KOMAR and WANG, 1984). The artificial beach nourishment has not changed the heavy mineral content of the surface sediments.

Besides natural tracers, artificial tracers can be used for clarification of transport processes. Sand marked with a fluorescent colour is well suited for this purpose (*e.g.*, AJUBLATOV, 1959; GRIESEIER, 1959; INGLE, 1966).

In spring of 1992, a transport model for the groin field D1–E1 was determined by investigations with two different coloured fluorescent sands (Figure 12). The limitation by the groins and the revetment lead to a complex transport pattern. A dextral circulation pattern can be recognized from the distribution of the orange fluorescent sand which was deposited in the eastern part of the groin field during low tide. There were no fluorescent grains seaward of the deposit site, so a dominating coastward transport can be predicted. The circulation transport is superposed by reflections, diffractions and refractions from coastal protection devices—the intensity of which differs in different areas of the groin field. This sediment transport pattern corresponds with hydrographic measurements (NIEMEYER, 1991, 1992).

CONCLUSIONS

The beach restoration led to a refinement of the beach sediments because of the finer grained borrow material. The grain size spectrum, before the

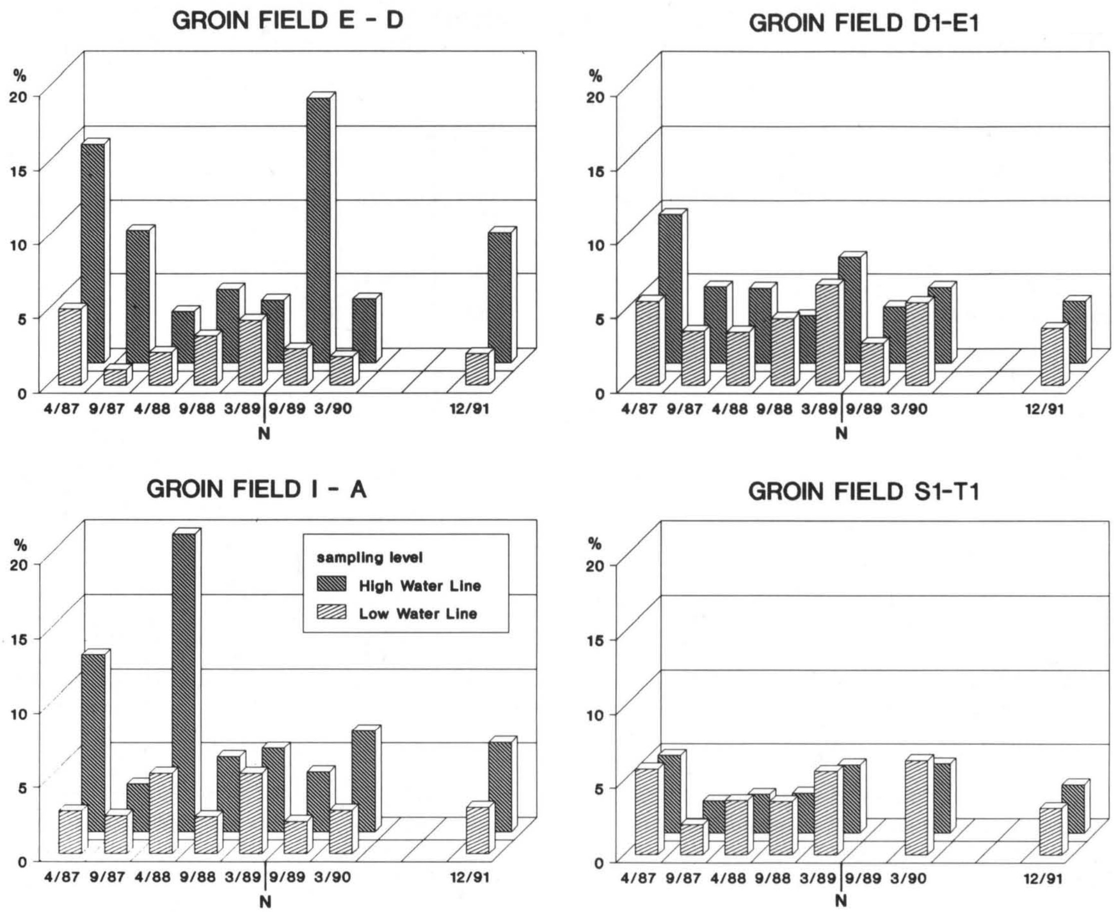

Figure 11. Seasonal variation of the heavy mineral content of the grain size fraction 0.106–0.125 mm in the groin fields E–D, D1–E1, N1–O1 and S1–T1.

beach nourishment, returned slowly. The original grain size distribution can be recognized in the replenished beach areas after almost two years. Already after a few months, there is a serious loss of beach material. A possible reason for this might be the fine grained nature (EITNER *et al.*, 1992). Hydrodynamic forces led to a selective removal of finer grain sizes and thus a selective enrichment of coarser grain fractions. This selection process is quite important, but it is not the only reason. The highest losses were in the first months after the replenishing in which the grain size did not change very much. It can be presumed that the hydrodynamic conditions work to bring the artificial beach profile back to the original, natural profile. The changes are larger the more the artificial profile differs from the natural one. The selection process comes to the foreground when the natural beach morphology has been reached again. In further investigations, this problem will be studied in detail.

ACKNOWLEDGEMENTS

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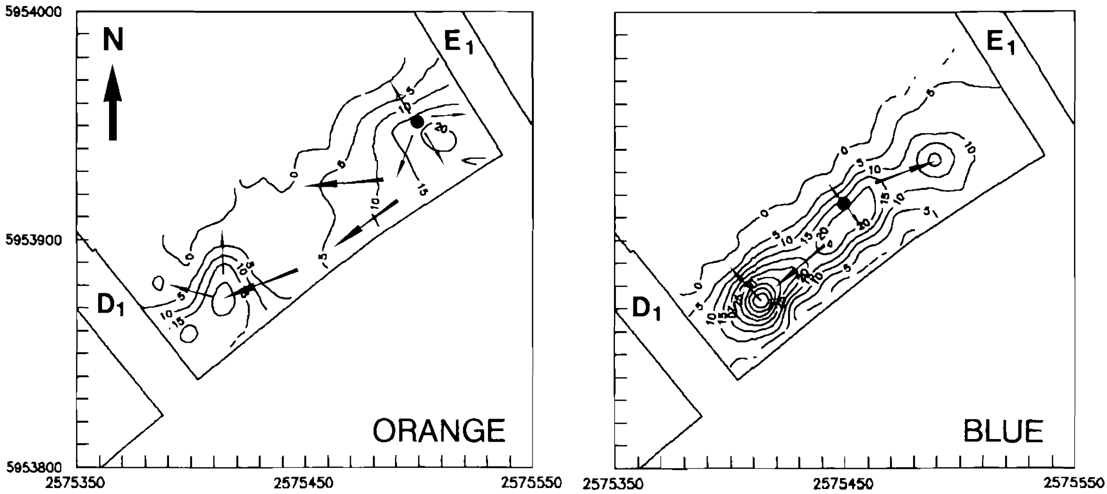

Figure 12. Model of the sediment transport with groin field D1–E1 in March, 1992.

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□ ZUSAMMENFASSUNG □

Die kontinuierlichen Strandhöhenabnahmen im Bereich des Norderneyer Westkopfes führte zu der künstlichen Auffüllung der betroffenen Strandabschnitte. Das Ziel war die Standsicherheit der massiven Küstenschutzwerke zu gewährleisten. Strandauffüllungen wurden seit 1951 wiederholt in unregelmäßigen Abständen durchgeführt. Hier werden einige Auswirkungen der Strandaufspülung vom Frühjahr 1989 auf die Sedimentverteilung dargestellt. Auf einen Teil des Strandes wurden gut sortierte Feinsande aufgebracht. Die mittlere Korngröße der ursprünglichen Strandsedimente war wesentlich gröber.

Sedimentproben wurden halbjährlich entnommen, um einen Überblick über die langfristigen Änderungen der Sedimentverteilungen zu erhalten. Um kurzfristige Änderungen zu erfassen, erfolgte monatlich die Probenentnahme vornehmlich im Bereich, der von den vergleichsweise stärksten Strandhöhenabnahmen betroffen war. Es wurden die Korngrößenverteilung, der Kalkgehalt und der Schwermineralanteil bestimmt.

Anfänglich konnte im Anschluß an die Strandauffüllung eine deutliche Korngrößenabnahme verzeichnet werden, die sich jedoch schon bald wieder umkehrte. Neben einer selektiven Erosion der feineren Sedimentbestandteile und der relativen Anreicherung der gröberen Partikel konnte eine Angleichung des Korngrößenspektrums an die ursprünglichen Sedimentverteilung im Frühjahr 1991 erkannt werden. Die natürliche Korngrößenverteilung, die im Gleichgewicht mit den hydrodynamischen Kräften steht, wird erzeugt durch den Abtrag von Strandmaterial. Der feinkörnige Sand, der als Auffüllmaterial verwendet wurde, wirkt als ein "Fremdkörper", der nicht zu den lokalen, äußeren Randbedingungen paßt.

Die Schwermineraluntersuchung erlaubet Aussagen über die Transportrichtungen der Strandund Vorstrandsedimente. Es zeigt sich, das der Küstenquertransport in den Buhnenfeldern vorherrscht. Die Korngröße der Sedimente im Auffüllbereich unterscheidet sich nur wenig von der der Vorstrandsedimente, so daß dieser Kennwert sich für eine Interpretation der Küstenlängstransport der Sedimente nicht eignet. Obwohl ein ost- und südwärts gerichteter Längstransport ausgehend vom Auffüllbereich im Anschluß an die Aufspülung festgestellt werden konnte. Die Untersuchung der Strand- und Vorstrandmorphologie bietet zusätzliche Informationen hinsichtlich des Sedimenttransportes und der zeitlichen Sedimentvolumenentwicklung.