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Process-Response Analysis for the North Frisian Supratidal Sands (Germany)

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ABSTRACT

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The North Frisian supratidal sands are located at the seaward border of the German Wadden Sea. They occupy a total area of about 28 km^2 and have neither dunes nor a vegetation cover. Previous investigations have documented that the sands have been migrating landward at least since 1947. These sands have great ecological as well as coastal defense significance and as a result, were subjected to a process-response analysis. From 1947 to 1991, the sands moved in an eastward direction over a distance ranging from 250 m in the south to 1,600 m in the north. It is suggested that this movement occurred in response to a 0.49 cm/yr rise of mean high water (MHW). Consequently, 36 to 42 million m^3 of sediment was released from the upper beaches of the sands. During the same period, 32 million m^3 of sediment was deposited at the surface and the spits of the sands. The increase in elevation was sufficient to balance the observed MHW-rise. Thus, most of the sediment eroded from the western side raised and lengthened the sands. The actual sediment redistribution (morphodynamics) is probably controlled by overwash and spit forming processes, operating within a framework of a rising sea level and increasing storminess.

ADDITIONAL INDEX WORDS: *Coastal sediments, morphodynamics, storms, Wadden Sea.*

INTRODUCTION

The supratidal sands Japsand, Norderoogsand and Süderoogsand are located at the seaward border of the North Frisian Wadden Sea (Figure 1). Most of the energy of the incoming deep-water waves from the North Sea dissipates along the seaward slopes. Therefore, these sands are important for the long term stability of the southern part of the North Frisian Wadden Sea. Furthermore, they also have a high ecological significance, *i.e.,* resting places for seals during high tide.

The coastal authorities of the German Federal State of Schleswig-Holstein initiated a research program in order to gain more detailed information about the stability of the sands under changing hydrographic conditions. The specific objectives of this study are to: (1) determine the hydrographic changes in the area; (2) quantify the morphological changes of the sands since 1947; and (3) correlate the observed morphologic and hydrographic changes.

REGIONAL SETTING AND STUDY AREA

The German North Sea coast is part of the Wadden Sea. Its shape is highly irregular with extensive tidal flats, inlets and islands (Figure 1). The morphology of the Wadden Sea was described by EHLERS and KUNZ (1993), the morphodynamics by EHLERS (1988) and the hydrological conditions and long term variations by SIEFERT (1984) and JENSEN *et al.* (1993).

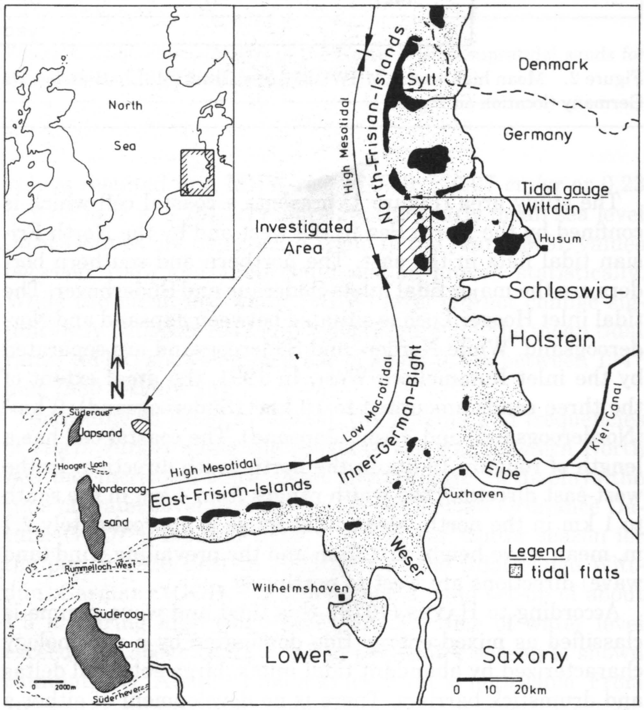

Figure 1. The study area within the German Bight.

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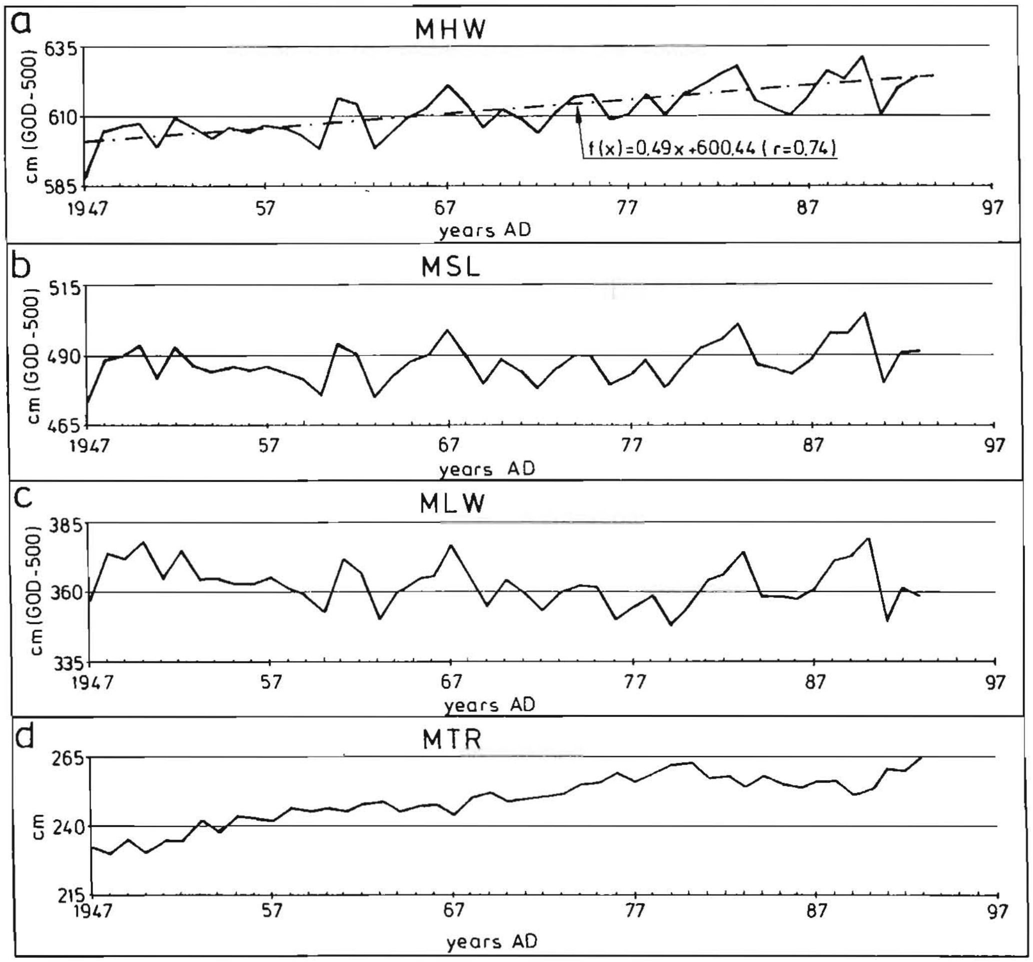

Figure 2. Mean high water (MHW), mean sea level (MSL), mean low water (MLW) and mean tidal range (MTR) development at the tidal gauge Wittdün, Germany (location on Figure 1).

The study area (Figure 1) presents a coastal cell which is confined by the North Sea in the west and by the North Frisian tidal flats in the east. The northern and southern borders are the major tidal inlets Süderaue and Süderhever. The tidal inlet Hooger Loch is situated between Japsand and Norderoogsand. While Norder- and Süderoogsand are separated by the inlet Rummelloch-West. In 1991, the areal extent of the three sands amounted to 16 km² (Süderoogsand), 9 km² (Norderoogsand) and 3 km² (Japsand). The coastal cell has a length of roughly 19 km in the north-south direction. In the west-east direction, the width ranges from 4 km in the south to 1 km in the north. Mean tidal range is approximately 2.7 m, mean wave height is 0.75 m and the prevailing wind (and wave) directions are west to northwest.

According to HAYES (1979), this tidal and wave regime is classified as mixed energy tide dominated by a morphology characterized by abundant tidal inlets, large ebb-tidal deltas and drumstick barriers. There is no development of either a mature dune ridge or any kind of vegetation cover on the sands. During long periods of calm weather, small primary dunes tend to develop on Süderoogsand. However, these dunes are leveled after each major storm surge.

The Hooger Loch and Rummelloch-West are mixed energy, high tide range inlets according to the tidal inlet classification of NUMMEDAL and FISCHER (1978). The inlets are characterized by small flood-tidal deltas, wide inlet throats, and (relatively) large ebb-tidal deltas.

METHODS

The morphological analysis was carried out with the software package "MORAN", developed by the German Coastal Engineering Board (SIEFERT and BARTHEL, 1981). The area of investigation was divided into units of 1 km² size. These units were subdivided into 100 sections of 1 ha size. For each section, the mean height was determined manually and fed in MORAN. A comparison of two surveys with MORAN gives the height changes for each section as well as the mean height changes per unit. The method of morphological analysis with "MORAN" is described in detail by SIEFERT (1989).

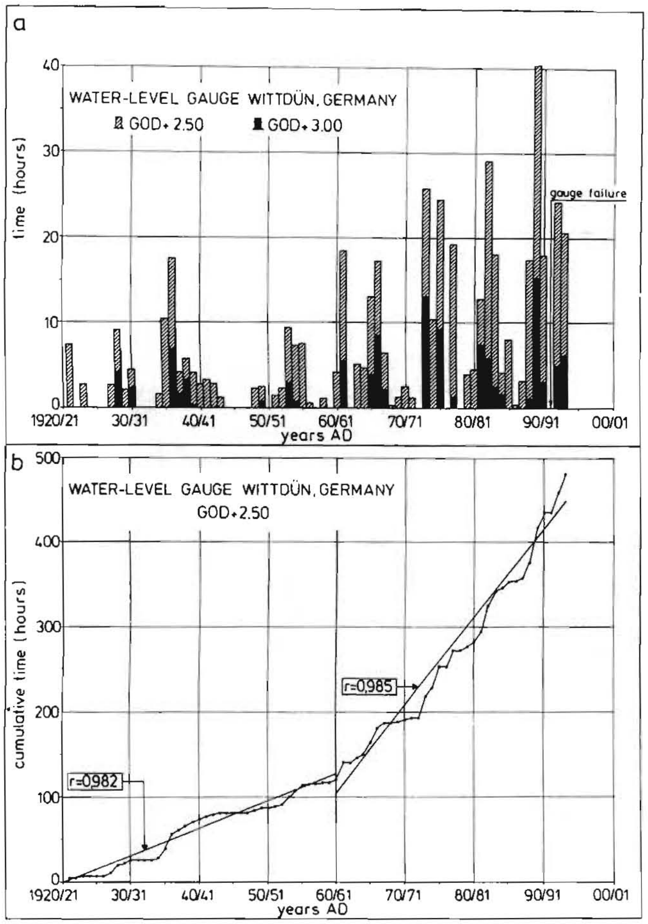

Figure 3. a) Time of water level exceedance above GOD + 2.50 and GOD + 3.00 m per winter season for the period 1920/1921 to 1993/1994. b) Cumulative time of water level exceedance above GOD + 2.50 m for the period 1920/1921 to 1993/1994.

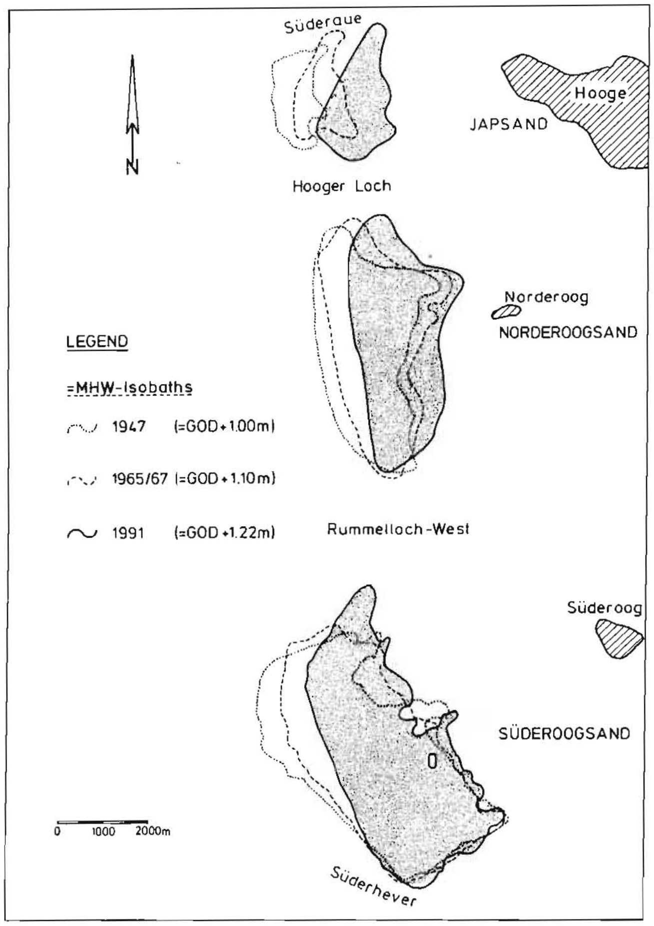

Figure 4. Shorelines (MHW) of the North Frisian supratidal sands for the years 1947, 1965/1967 and 1991.

In total, four map comparisons were carried out for Süderoogsand and three for Japsand and Norderoogsand. Furthermore, profile and shoreline comparisons were investigated. The maps (scale 1:10,000), used for the morphological analysis are based on terrestrial surveys carried out by the state coastal authorities in the years 1947, 1965/1967, 1976 (Süderoogsand), 1980 and 1991. These surveys have an accuracy of about ± 3 cm in the vertical and 1 m in shoreline position.

The analysis of sea level changes since 1947 and variations in storminess since 1920 in the investigated area are based on tidal records of gauge Wittdün on the island Amrum, Germany. This tidal gauge is situated about five km to the north of the sands (Figure 1).

Hydrographic Development

As shown by Figure 2a, the yearly mean high water (MHW) values at the Wittdün tidal gauge, show a rising trend. For the period 1947–1993, a linear regression through the yearly values resulted in a MHW-rise of 0.49 ± 0.07 cm/yr or 0.23 ± 0.03 m (r = 0.76). In Figure 2b, the yearly mean sea level (MSL) values are depicted. A trend in the yearly MSL values between 1947 and 1993 could not be proven statistically. While the mean low water (MLW) level did not change significantly between 1947 and 1993 (Figure 2c), the mean tidal range (MTR) shows an increase of about 0.3 m between 1947 and 1980 (Figure 2d).

According to SIEFERT (1984), the heights and frequencies of storm surges along the coasts of the southeastern North Sea has increased since about 1960. Figure 3a displays the time of water level exceedance above German Ordnance Datum (GOD) + 2.5 and GOD + 3.0 m per winter season for the period 1920/1921 to 1993/1994 at the tidal gauge Wittdün, Germany (GOD + 2.5 m means a wind set-up of about 1.5 m during high tide). In Figure 3b, time of water level exceedance above GOD + 2.5 m per winter season is shown cumulatively. Around 1960 a knick-point is noticeable. From 1920/1921 to 1960/1961, the mean time of water level exceedance above GOD + 2.5 m per winter season amounted to three hours and five minutes; and between 1960/1961 and

Table 1. *MHW-level, island area above MHW, average elevation above MHW and volume of sediment stored above MHW for the North Frisian supratidal sands for the years 1947, 1965/67, 1976 (Süderoogsand), 1980 and 1991.*

Years	MHW-level (GOD + m)	Island Area above MHW ($m^2 \times 10^6$)	Average Elevation above MHW (m)	Volume above MHW ($m^3 \times 10^6$)
		Japsand		
1947	1.00	1.99	0.06	0.12
1965	1.10	1.90	0.13	0.25
1980	1.16	2.90	0.14	0.41
1991	1.22	2.97	0.26	0.77
		Norderoogsand		
1947	1.00	8.29	0.20	1.66
1965	1.10	9.04	0.22	1.99
1980	1.16	9.08	0.25	2.27
1991	1.22	8.97	0.23	2.06
		Süderoogsand		
1947	1.00	14.62	0.29	4.24
1967	1.10	16.29	0.33	5.38
1976	1.14	17.18	0.32	5.50
1980	1.16	16.03	0.30	4.81
1991	1.22	15.37	0.32	4.92

1993/1994, it amounted to 10 hours and 35 minutes. Furthermore, 21 of the 25 most severe storm surges in the study area since 1920 occurred after 1960. Thus, storm frequency and heights apparently have increased significantly in the study area over the last three decades.

As a result, it is concluded that energy impacts of both storm surges and tides have increased over the last three decades. Furthermore, the level at which these components operate is steadily increasing in response to observed MHW-rise.

Morphology

In this section, the morphological development between 1947 and 1991 is described for Japsand, Norderoogsand and Süderoogsand successively.

Over the period 1947–1991 Japsand retreated 1,400 m at a rate of approximately 32 m/yr (Figure 4). Consequently, the migrating sand body was completely reworked in this 44 year time period.

In Table 1, the areal extent above MHW, the average elevation (mean height) above MHW and the volume of sediment stored above MHW of the three sands for each of the successive surveys are listed. It should be stressed here that MHW is not a fixed geodetic level. Between 1947 and 1991, MHW rose by about 0.22 m (Figure 2a). The supratidal areal extent of Japsand increased from 1.99 km^2 in 1947 to 2.97 km^2 in 1991. Simultaneously, the elevation of the sand increased from 0.06 to 0.26 m above MHW. Hence, the volume of sediment stored above MHW increased from 0.12 to 0.77 million m^3 between 1947 and 1991.

In Figure 5, profiles over the three sands for the years 1947, 1965/67 and 1991 are displayed. This figure shows that the upper beach of Japsand retreated for the entire period of study. Less accurate bathymetric surveys suggest that the western side of Japsand was eroded to a depth of 3 to 4 m below GOD. Hence, about 10 to 12 million m^3 of sand eroded from the upper beach. Although Japsand constantly increased in height, sediment was concentrated immediately behind the beach zone, at the spits, and in lee of the sand. The total volume of sediment deposited on Japsand amounted to 8.7 million m^3.

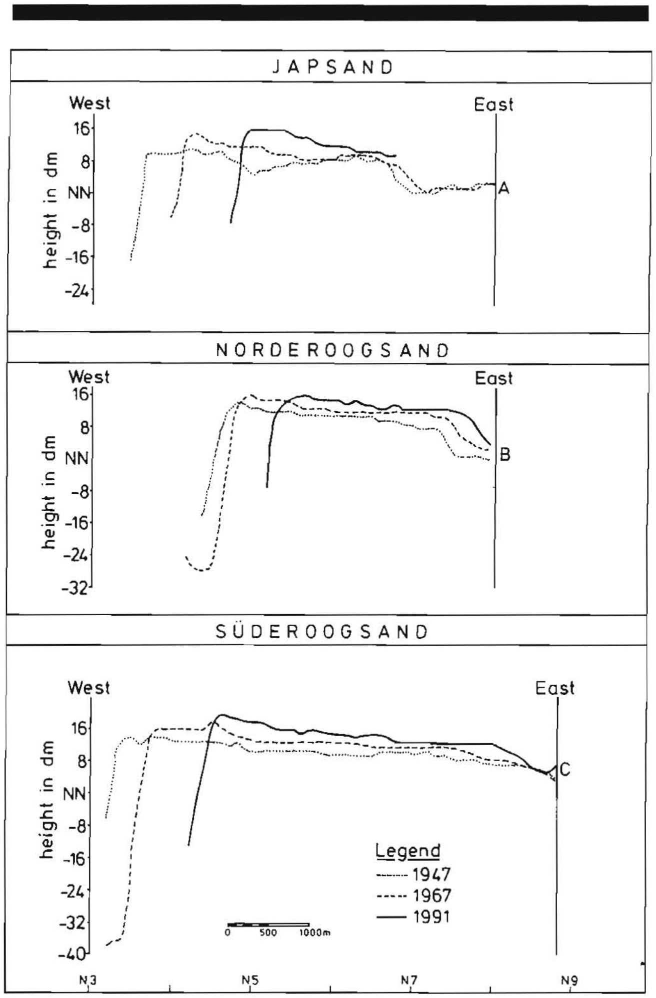

Figure 5. Profiles over the North Frisian supratidal sands for the years 1947, 1965/1967 and 1991.

Between 1947 and 1991, Norderoogsand retreated about 700 m in a landward direction. After 1967, the rate was two times higher than the previous 20 years (20 and 10 m/yr, respectively). All three morphologic parameters displayed in Table 1 remained relatively constant on Norderoogsand for each of the successive surveys. Similar to Japsand, erosion concentrated in the upper beach zone to a depth of about 3 m below GOD (Figure 5). During the period of investigation, change along the western side of Norderoogsand amounted to a decrease of 12 to 14 million m^3. The sedimentation pattern resembled that on Japsand with a maximum behind the beach zone, at the spits, and in the lee. Altogether, 9.9 million m^3 of sand was deposited on Norderoogsand.

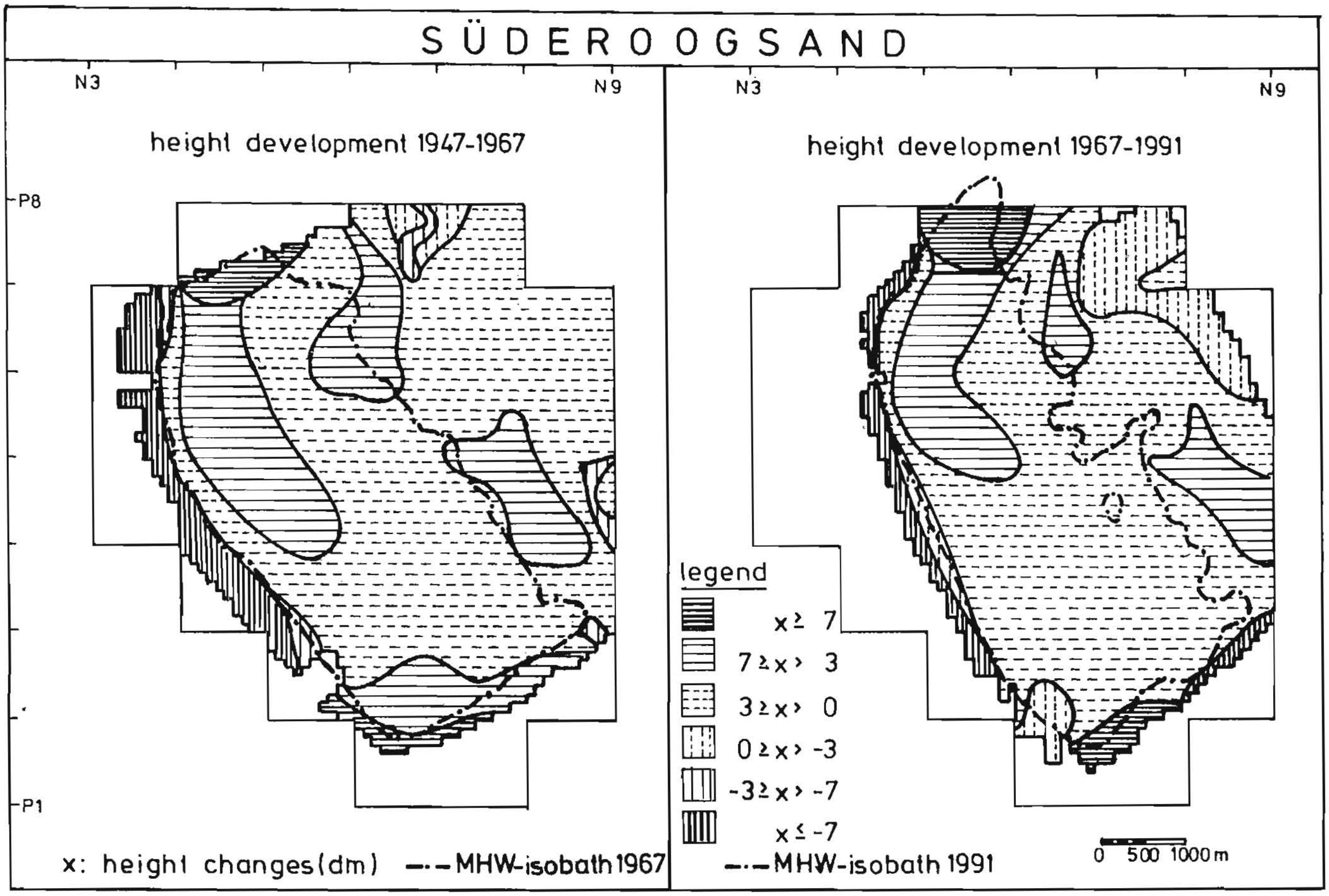

Figure 6. Height development at Süderoogsand over the time intervals 1947–1967 and 1967–1991.

In contrast to the other sands, Süderoogsand did not retreat at the same rate over its entire length. The northern part migrated about 1,000 m to the east, whereas the southern part retreated only 250 m (Figure 4). As at Norderoogsand, the migration rate of Süderoogsand over the period 1965/1967–1991 was about twice as high as before 1965/1967 (Figure 5). All three morphological parameters listed in Table 1 were relatively constant on Süderoogsand for each of the successive surveys. Finally, the sediment redistribution pattern (Figure 6) was similar to those of Japsand and Norderoogsand. The erosion in the upper beach amounted to 14 to 16 million m^3; whereas, 13.8 million m^3 of sediment was deposited on the surface and at the spits of Süderoogsand.

From this data set, it appears that Süder- and Norderoogsand were more or less in a morphologic steady state between 1947 and 1991. Although the absolute elevation of these two sands increased by about 0.22 m, their relative height to MHW did not change significantly over the investigated time period. In contrast, Japsand probably was a young structure in 1947 which emerged above MHW only a few years ago. This hypothesis is supported by older maps on which no supratidal form is found in the position of Japsand. Perhaps on Japsand the steady state was reached in 1991 as the elevation above MHW (and therewith the inundation frequency) became similar to those on the other sands.

DISCUSSION

According to BRUUN (1962), a rise in sea level will be followed by a shoreward displacement of the beach profile as the upper beach is eroded. The two-dimensional Bruun Rule is based on the assumption of a closed material balance system between (1) beach and nearshore and (2) the offshore bottom profile. Under this assumption, the eroded material from the upper beach will be deposited on the near offshore bottom, thereby raising it's height enough to balance the observed sea-level rise (BRUUN, 1988). However in the case of the North Frisian supratidal sands, the material balance system is open to three sides. Material, eroded from the upper beach can be transported (1) seaward to the near offshore bottom, (2) parallel to the shoreline to the spits of the sands and to the tidal inlets and (3) landward to the surface of the sands. The results from the sediment budget analysis in the study area indicate that most of the sediment that was erod-

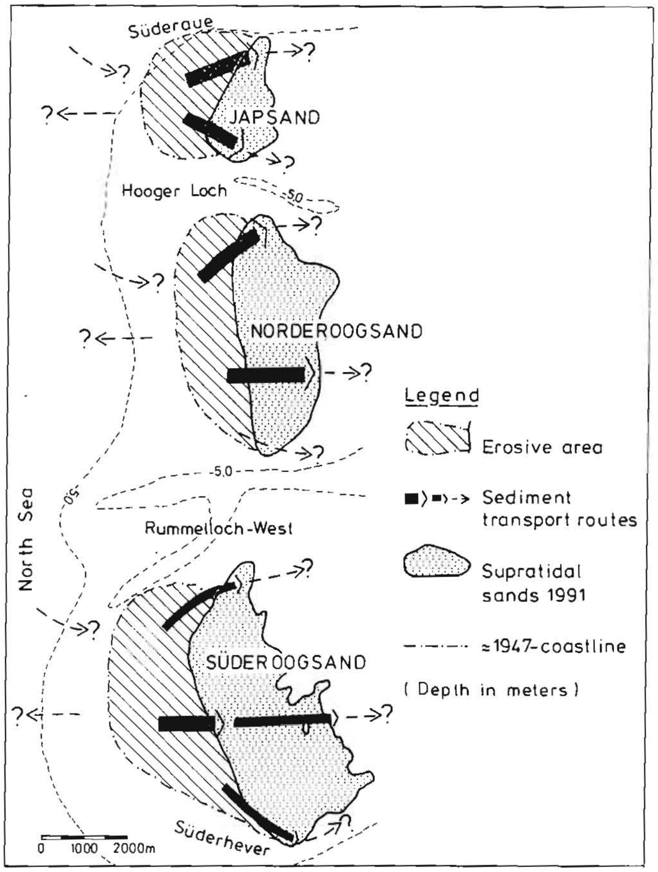

Figure 7. Sediment transport routes in the coastal cell of the North Frisian supratidal sands (schematized).

ed from the upper beach was deposited at the surface and at the spits of the sands.

Furthermore, the Bruun Rule generally relates beach profile position to MSL. Figure 2b shows that no significant MSL-rise occurred in the study area between 1947 and 1993. Hence, the observed shoreline displacement cannot be the result of a MSL-rise. In a tidal coastal environment, the water level normally remains for a much longer period of time around MHW than around MSL. Therefore, it is suggested that MHW could have a greater morphological significance in meso- and macrotidal environments than the statistically established MSL. Following this hypothesis, the landward movement of the North Frisian supratidal sands could represent adjustments to the observed MHW-rise.

In all, 36 to 42 million m^3 of sediment was eroded from the upper beach. Most of this sediment was apparently deposited on top and in the lee of the sands, enough to maintain their form and elevation (in relation to MHW) in a more eastward position. This follows the classic process of landward rollover. Another part of the sediment was deposited at the spits of the sands (Figure 4). This spit formation as well as the observed increase in migration rates of Norderoogsand and Süderoogsand since 1965/1967 may be the result of increasing storminess since about 1960. It appears that the megascale morphological development of the sands was governed by MHW-rise and increasing storminess since 1960.

LEATHERMAN (1989) stated: "Sea level sets the stage for profile adjustment by coastal storms". According to this statement, the actual morphodynamics of the study area are governed by storm processes, *i.e.,* overwash and spit forming processes (Figure 7). As no dunes exist on the sands, no single deep overwash channel is scoured. Instead, large parts of the beach crest are overtopped simultaneously and the deposition takes place in the form of extensive washover flats.

CONCLUSIONS

(1) The megascale morphological development of the North Frisian supratidal sands between 1947 and 1991 is governed by the long term MHW-rise of about 0.49 cm/yr and the increase in storminess since approximately 1960. In response, the sands retreated between 250 m in the south and 1,600 m in the north in a landward direction (landward rollover). In addition, shoreline changes indicate a lengthening of the sands and a narrowing of the inlets Hooger Loch and Rummelloch-West.

(2) The morphodynamics of the sands appears to be governed by overwash and spit forming processes. From 1947 until 1991, these processes deposited about 32 million m^3 of sediment on the sands. As a result of the overwash processes, Norderoogsand and Süderoogsand maintained their relative extension, elevation and volume above MHW, while Japsand increased in size. Spit forming processes which intensified after 1960 caused the inlets to narrow.

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