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Sand Budget Trends and Changes Along the Holland Coast

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ABSTRACT

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The Dutch coast primarily consists of sandy dunes, beaches and shoreface. From 1963 onwards, the morphology of this system was regularly monitored, providing a very valuable morphological data set. Based on information from this data set, a sand budget study was undertaken for the central part of the Dutch coast, the 120 km long Holland coast. The studied coastal zone extends from the landward side of the sandy dunes to about three kilometers seaward of the dunefoot. This paper aims at the description of large-scale morphological developments, both in time and in space. Therefore areas with a morphologically distinct character were identified and trends in sand volume for these areas were calculated.

ADDITIONAL INDEX WORDS: *Dunes, breaker zone, shoreface, sand budget, coastal management, Holland coast.*

INTRODUCTION

The Dutch coast is sandy, and at some places enforced with massive sea defence structures. It is composed of three major geomorphological units: in the south, the 'Delta' coast, consisting of (former) delta's and islands; between Hoek van Holland and Den Helder, a stretch of coast not interrupted by tidal inlets (the Holland coast); and in the north, the Wadden-islands, a series of barrier islands, separated by tidal inlets (Figure 1). The differences in coastal geomorphology are extensively described by VAN ALPHEN and DAMOISEAUX (1989).

Although considerably influenced by man, the Dutch coast still possesses a dynamic character: continuous displacement of sand from one place to another results in erosion at one place and accretion at another. Because erosion is often associated with landward displacement of the shoreline, there is a threat of weakening of the sea defences at an increasing number of places. This requires continuous attention in order to assure protection against inundation of the low lying country behind the dunes.

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Apart from this, there is a need for a better understanding of the processes that lead to coastal erosion. The 'Coastal Genesis' project aims at clarifying unknown large-scale phenomena in coastal morphology and at providing information for predictions of shoreline development and for taking measures for coastal management [see ZITMAN (1988) and ZITMAN et al. (1990)]. The project, a combined effort of several Dutch institutes and universities, started in 1985 and the first phase is presently concluded. This phase focussed on analysing data of the Holland coast. Geological and historical investigations led to knowledge of the development of the coast at time-scales of thousands to hundreds of years. The present-day position of the shoreline of the Holland coast is a result of an evolution of about 5000 years, in which progradation took place during the first millennia and regression and erosion from about 2300 BP onwards. Especially the period of 1000 to 1200 AD, when the younger dunes were formed, was attended with considerable adaption (especially steepening) of the coastal profile (ROEP,

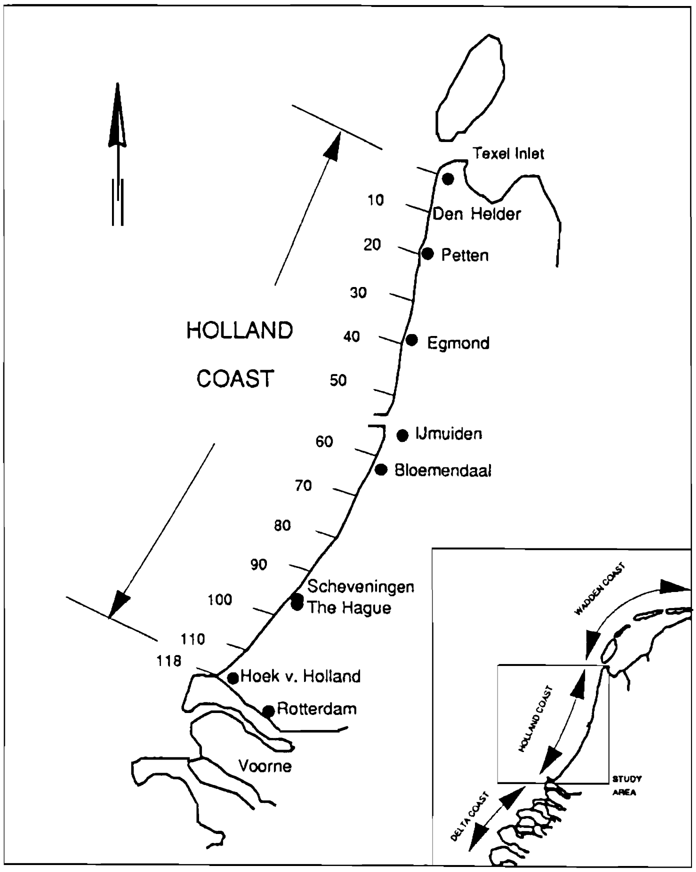

Figure 1. Location of the study area in The Netherlands. The numbers indicate the coordinates of the reference system (kilometers).

1984). During the last two centuries a more gradual and less pronounced displacement of the shoreline is observed. This period coincides with more intense human interference with the coast (LIGTENDAG, 1990).

More recent data of the Holland coast were also analysed. In earlier studies EDELMAN and EGGINK (1963), as well as BAKKER and JOUSTRA (1970) showed that the Holland coast could be subdivided in three major regions of different behaviour: a retrograding southern part (Hoek van Holland to Scheveningen), a prograding central part (Scheveningen to Egmond) and again a retrograding northern part (Egmond to Den Helder). Time-series of 150 years of data concerning shoreline positions (low water-, high water- and dune foot-line) served for determination of large-scale patterns in shoreline behaviour of the Holland coast (VERHAGEN, 1989). Large spatial and relatively small temporal variations were also described by WIERSMA (1989). Profile measurements along the entire coast, available from 1963 onwards, were used to study the behaviour of longshore bars (VROEG *et al.*, 1988).

Both data on shoreline position and depth profiles need further elaboration to obtain a more comprehensive description of the morphology of the Dutch coast. This paper especially deals with the profile measurements and is aimed at describing the sand budget of the Holland coast.

This sand budget study is conducted to gain insight into quantitative changes in the large-scale sand budget of the coastal zone of the Holland coast, as defined by BOWEN and INMAN (1966) and KOMAR (1983). Both a description on the scale of the entire area (resulting erosion or accretion) and on a more detailed scale are pursued. Apart from insight into coastal changes, sand budget data can serve (and have already served (STIVE *et al.*, 1990) for verification of (large-scale) coastal models.

MEASUREMENTS

Since 1963, profile measurements of the entire Dutch coast have been performed on a regular basis. They include yearly coastal measurements in a rather dense network of relatively short profiles (about 1000 m) and five-yearly measurements with larger spacing and greater length (2500 to 3000 m). The data of the measurements are stored in a computer data set and are available for coastal managers, advisers and researchers. Both types of measurements are oriented within the same reference system, the so-called RSP-line, being an imaginary line along the coast, originally situated on the beach. At each kilometer of this line a beach pole was placed, marking the zero horizontal coordinate of the transect (Figure 2). Along the Holland coast, the beach poles are numbered from 1 (Den Helder) to 118 (Hoek van Holland; Figure 1). The profiles are orientated approximately perpendicular to the reference-line. The five-yearly measurements take place in transects through these main beach poles. The yearly measurements are taken along these lines as well. In addition, yearly profile measurements are collected at locations with mutual distances of 200 to 250 m in between each of the beach poles.

The profile measurements consist of two different types of data, which are brought together into one profile. The dry part of the coastal profile (beach and dune) was originally measured by levelling; from 1976 onwards photogrammetry has been used. The underwater part of the profile is measured with echosoundings from ships with automatic position-finding systems. The heights and depths are uniquely related to the fixed Dutch Ordnance Datum ('N.A.P.', about mean sea level). Tidal corrections take place afterwards. The mean overall standard deviation of a single measured depth is about 20 cm (NANNINGA, 1985).

The yearly and five-yearly data sets of the measurements are not exactly equidistant in time: measurements are performed in periods with suitable weather conditions between April and October.

PROCEDURE

Insight into quantitative changes in the large-scale budget of sand is gained by calculating trends in the yearly volumes of sand stored within the defined areas. An advantage of this method is that yearly fluctuations and small accidental errors are smoothed out.

The trend in the sand volume of any arbitrary chosen area can be considered as the result of the equation of mass conservation (Figure 3):

$$A + B + C + D = \delta S$$

in which 'δS' is the calculated change in volume. It is equal to the net amount of sand entering or leaving the area within a specified period. The characters 'A' to 'D' indicate the volumes of sand transported across the boundaries of the observed area (either input or output) during the observed time interval.

For the benefit of sand volume calculations, profile measurements are coupled to a data set of a geometrically sound area network. Every year yields a value of the sand volume within the defined area.

Variations in sand volume over the years are generally small for the area as a whole. As a consequence, measurement errors can cause considerable deviations in the trends of the sand volumes, especially when the number of measurements is small, as, for instance, in the case of the five-yearly soundings. Therefore demands on the quality of the survey data are very high. A strong effort was made to remove significant accidental and systematic errors from the data set.

Another problem is the existence of gaps in the data set. These are either accidental or more or less structural. Accidental gaps are fairly easily discovered and rectified. Important structural gaps were found in the survey data of the dunes (1963–1976). The dunes landward of the foredune were not monitored during that period. Since analysis was aimed at the entire profile from dune to shoreface over the whole period, special attention had to be paid to complete the measurements of the landward side of

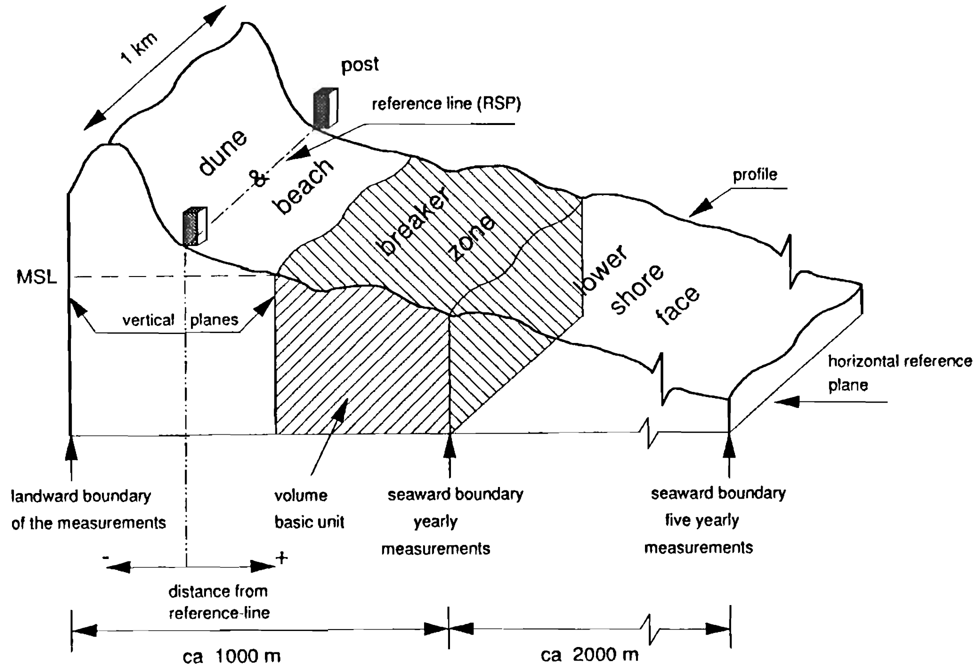

Figure 2. Schematic cross-section of the Holland coast. The three morphologic zones are separated by vertical planes. The basic unit for sand volume calculations is indicated for the breaker zone (vertical plane concept).

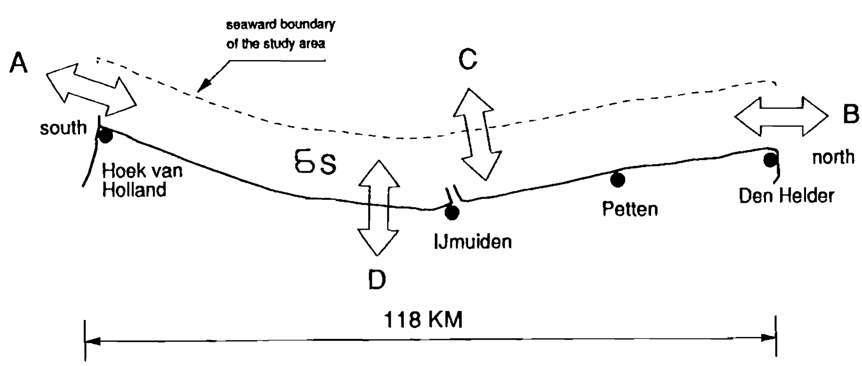

Figure 3. The sand budget (principle of mass conservation): A + B + C + D = δS.

these dune profiles. This was done with special contour maps (scale 1:2000) of the dune area of this period.

Sand volume calculations were carried out using the vertical plane concept. With this concept the coast is subdivided alongshore in units of practical length. Sand volumes within these units are calculated with respect to a horizontal reference plane at a depth of 30 meters. As long as the plane lies deeper than the deepest section within the profile, the exact depth of it is of no importance, because only volume changes are considered.

Calculations are made either for the whole unit (from dune to shoreface) or for a part of it (in shore-normal direction). In both cases vertical planes, parallel to the reference line, indicate the boundaries of the sub-area (Figure 2). Hence this method enables calculation of sand volumes up to the outward ends of the measured profiles. The depths reached at the seaward boundary of the profiles are indicated in Figure 4.

A major objective of the study was identification of characteristic features of morphologic zones (dunes, beach, breaker zone and lower shoreface) along the Holland coast by volumetric analyses. Morphologic zones vary largely in width along the coast. Therefore it was not possible to use a uniform measure for the width of these zones. To meet this problem, the coast was subdivided in small units of 1 km in longshore direction. This enabled selection of the vertical plane position to match with the local morphologic zones. However, in most units the lowermost past of the lower shoreface was not covered by the measurements.

In summary, the coastal zone of the Holland coast was subdivided into units with a length of 1 kilometer and widths, encompassing either dune and beach, breaker zone or lower shoreface. The depths of the transitions between these zones are approximately MSL for the transition dune and beach to breaker zone, and −6 m for the transition from breakerzone to lower shoreface.

A linear regression of the calculated sand volumes of each unit determines the magnitude of the erosional or accretional trends in m^3/km per zone per year. Information about trends for larger areas is obtained by adding up the trends of all units in the area of concern.

Confidence intervals or correlation factors around the regression values are not given in this article. This would have little value, because the presented trends are composed trends as mentioned above. Further, the underlying trends of units (1 km width) are the result of several thousands of individual measuring points with varying standard deviations. In general, the low monitoring frequency on the lower shoreface (measurements once every five years and with larger spacing) induces less accurate trends.

Coherent areas are selected, both along the coast and in shore-normal direction. The calculations were performed by the computer program 'WK1', made by the Tidal Waters Division of Rijkswaterstaat (Ministry of Transport and Public Works).

Recently, VAN VESSEM and STOLK (1990) described a horizontal plane method for calculating the sand balance of the entire Dutch coast, including the Delta and Wadden coast (Figure 1). The balance was based on the yearly soundings only, which makes comparison with this paper difficult.

RESULTS

The discussion of the results is split into two parts: the spatial diversity, and the year-to-year variability.

First, the overall trends of sand gains and

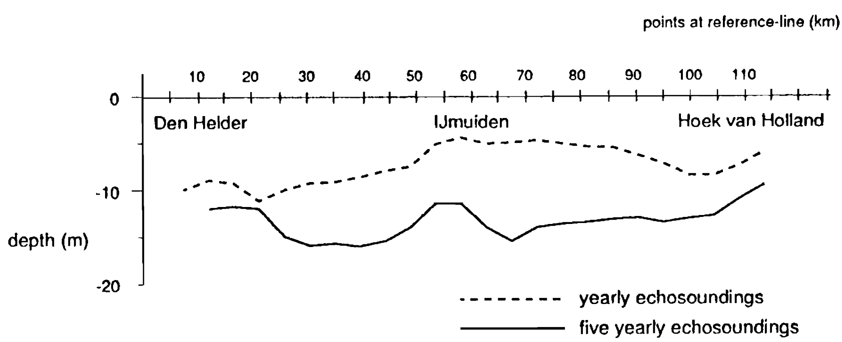

Figure 4. Maximum depths reached at the seaward boundaries of the yearly (length about 1000 m) and five yearly (length 2500–3000 m) profile measurements.

losses for the entire coastal zone of Holland in the period between 1963 and 1986 are discussed. Next, the results of a subdivision of the study area in shore-normal direction (dune and beach, breakerzone, lower shoreface) are presented, followed by the results of the longshore regions.

In the second part, year-to-year fluctuations around these trends in sand volume receive attention. They give an impression of the magnitude of the yearly net sand displacements. Secondly, some possible morphological phenomena are identified.

Spatial Variability

The Entire Holland Coast

Figure 5a shows the averaged yearly sand budget changes along the Holland coast for 10 kilometers length stretches and for the entire width of dune to shoreface. On the average, sand volume within the entire study area between Hoek van Holland and Den Helder, is constant in time. In terms of mass conservation this means that the sum of input and output terms is zero (Figure 3). The amount of sand entering the area is equal to the amount of sand leaving it. However, the budget is based on measurements of absolute heights and depths to a fixed reference level (N.A.P.). During the study period (1963–1986) the (relative) sea level rose by about 5 cm (DE RONDE, 1988). Bringing this into account a simple computation indicates that the sand volume of the entire study area with respect to MSL would decrease with about 7.10^5 m^3/year.

The landward boundary of the study area lies at the back side of the foredune. It was placed at a position where transport of sand further landward appeared to be negligible. Therefore transport term 'D' in Figure 3 is probably very small.

The seaward boundary is situated somewhere 2½ to 3 kilometers offshore, with water depths between 11 and 16 meters below mean sea-level

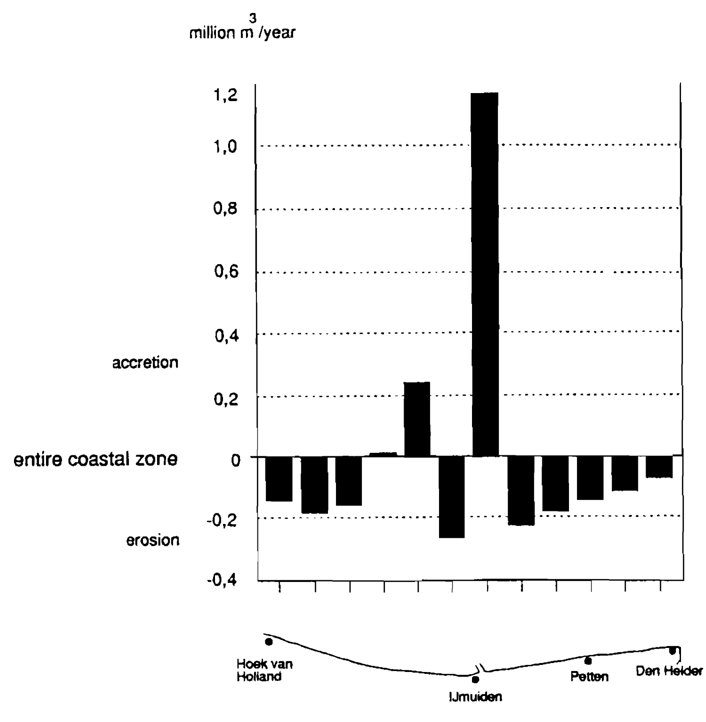

Figure 5a. Averaged yearly sand budget changes (1963–1986) of the entire coastal zone of the Holland coast for stretches of 10 kilometer length.

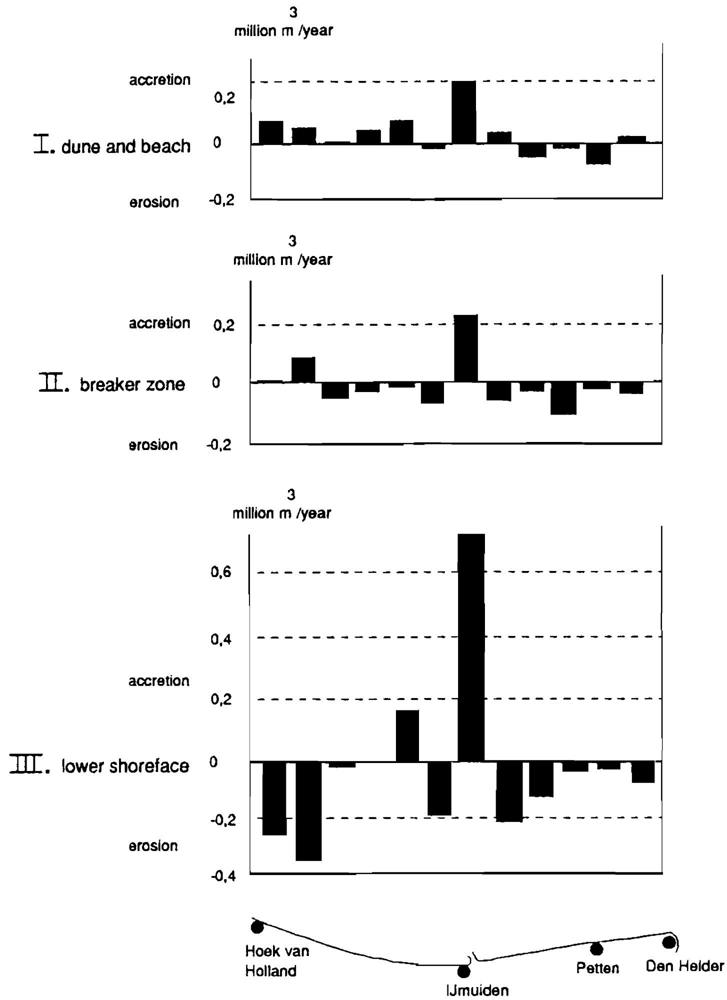

Figure 5b. Averaged yearly sand budget changes of the three morphologic zones: (I) dune and beach, (II) breaker zone, and (III) lower shoreface, for stretches of 10 kilometer length.

(Figure 4). In general, changes in depth in this area are small but significant. Therefore, sand transport term 'C' cannot be neglected. Recent studies (STIVE *et al.* (1990) and ROELVINK and STIVE (1990)) indicate that transport of sand from the lower shoreface to the active zone (breaker zone, beach and foredunes) is of great importance for the morphological development of the Holland coast. This onshore transport, in the order of $10m^3$/m/year across the 10 m depth line (ROELVINK and STIVE, 1990) and about $6m^3$/m/year across the −5 m line (DIJKMAN *et al.*, 1990), is caused by the dominating influence of residual currents (tidal currents, wind- and density-induced circulation and asymmetric waves) with an onshore direction. According to these studies, coastal retreat along the Holland coast would increase by half a meter per year without this onshore transported sand volumes. As a consequence, nearly the entire Holland coast would be erosive.

The southern boundary of the study area consists of the long (± 3500 m) jetty of Hoek van Holland, which minimizes sand transport across this boundary ('A') in both the southern and northern direction.

Estimating the magnitude of transport term 'B' is difficult. The northern limit of the area partly overlaps the ebb tidal delta of the Texel Inlet (Figure 1). The hydraulic and morphologic behaviour of the Wadden Sea seems to be a dominating factor with respect to sand exchange in this area. This shallow lagoon is filled with sand derived from the North Sea as well as from the coasts adjacent to the Texel Inlet, *i.e.* the coast of Texel Island and the northern part of the Holland coast (SHA, 1989).

An increase in knowledge of any of the abovementioned sand transport terms will certainly produce a better understanding of the resulting behaviour of the coast.

Shore-Normal Variability

In shore-normal direction the study area is subdivided into three zones (Figure 2): dune and beach, breaker zone and lower shoreface. The position of the boundary between the latter two is chosen at the seaward extent of the yearly surveys.

In the dune and beach zone, accretion exceeds erosion by about 0.4 million m^3 per year. Erosion dominates in the breakerzone and on the lower shoreface, by about 0.05 and 0.35 million m^3 per year, respectively. Figure 5b clearly points out the importance of sand volume changes of the lower shoreface ('III' in Figure 5b) within the total sand budget. Because of the low monitoring frequency in this zone, trends are less accurate. They only serve as a rough indication of the actual budget changes.

Expressed in other units, the mean yearly sand gain of the beach and dune zone ('I' in Figure 5b) is 3 to 3.5 m^3 per meter coast length. In accretional sections, this amounts to an average of 10 m^3/m per year. These changes are the net result of different, sometimes opposing processes such as aeolian transport and storm surge erosion.

The present dune system acts as a sink, even when the breakerzone ('II' in Figure 5b) shows a net sand loss (Figure 6). This means that the combined effect of loss of sand due to storm surge erosion and wind erosion, and gain due to wind effects, greatly favours the sand volume of the dunes. Accretion of sand in this zone mostly takes place in the foredune area. Perhaps the rigid management of the foredune zone, with the intense use of lyme-grass (*Ammophila arenaria*) and permeable sand fences, is the cause of both phenomena: 'artificial' increase of the sand volume within the dunes may induce a deficit in the breakerzone (WIERSMA, 1989; an overview of the positive and negative effects of artificial dune building is given by LEATHERMAN, 1987).

For this part of the Dutch coast it can therefore be stated that onshore losses of sand from the shoreface into the dunes must not be ignored.

Longshore Variability

Variation of accretion and erosion along the coast is indicated in Figure 5a. Within areas of 1 kilometer length the maximum mean (period 1963–1986) erosion rate is about 150 m^3/m per year. The maximum mean accretion rate is approximately 250 m^3/m per year. These high values are related to the effects of the jetties of Hoek van Holland and IJmuiden, respectively. Ignoring these specific locations, yearly rates of accretion and erosion usually fall within the stable and mild categories of erosion/accretion (up to 48 $m^3/m/year$), according to the classification of OERTEL *et al.* (1989). This does not mean that coastal problems are insignificant. Since the dune area is narrow at some places, even minor coastal erosion may easily lead to sea defence and other problems.

A more general inspection leads to the observation that two thirds of the coastal area suffers erosion (on average 23 m^3/m a year), leaving one third with accretion (on average 49 m^3/m a year). Accretion particularly takes place in the central region, the concave part of the study area (km 55–97): the total amount is 0.45 million $m^3/year$. The southern and northern regions exhibit erosion, 0.25 and 0.20 million $m^3/year$, respectively. This partition of the Holland coast into an accreting central region and eroding ends is, according to the present state of knowledge, caused by the combined effect of onshore transport and entrapment of sand in the concave part of the coast due to longshore transport (ROELVINK and STIVE, 1990; DIJKMAN *et al.*, 1990).

This general first order picture is disturbed at several locations. Most evident is the effect near IJmuiden (km 55; Figure 1). The outer jet-

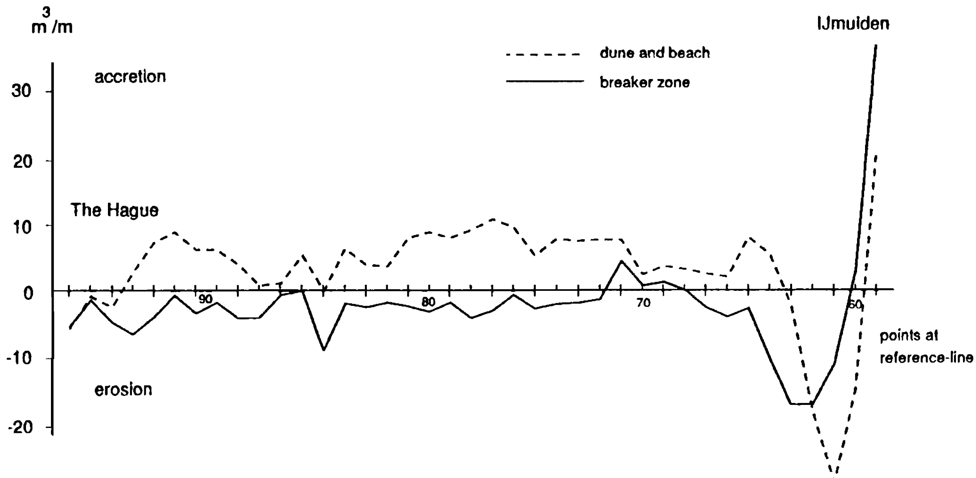

Figure 6. Averaged yearly sand budget changes of coastal units of 1 kilometer length between the jetty of IJmuiden and The Hague (km 58–97).

ties were extended in the period 1962–1967. They reach out about three kilometer offshore from the original shoreline. Due to this construction, broad sand bodies accreted both immediately north and south of the jetties. On average, accretion here amounts to about 1.15 million m^3 per year over a distance of 8 km.

This huge amount of sand is coming from deeper water and from coastal sections further (about 4–8 km) along the coast in northern and southern directions. Here, local erosion has become a significant issue. In longshore direction the erosion site moves away from the jetties in the course of time. At present the holiday resort of Bloemendaal (km 62) suffers from severe beach and dune erosion. The process of this moving erosion site starts at deeper water: the shoreface is gradually lowering, some years later followed by beach and dune. The actual result of this erosion phenomenon therefore shows a 'depression' with an orientation oblique to the coast (Figure 7).

A second major disturbance is located near the southern edge of the study area. In 1971, after an extension of the northern jetty of Hoek van Holland, it was decided to extend the beach immediately north of the jetty. Almost 19 million m^3 sand, dredged from the navigation channel and harbour of Rotterdam, was dumped north of the jetty on a stretch of coast of three kilometer length. Apart from creating recreational and natural areas, the objective of this nourishment was to compensate for erosion further away from the jetty.

Afterwards it became evident that the design of the nourishment scheme was less than perfect. Severe erosion arose directly north of the jetty. The sand was transported to the north. The bulk (± 180.000 m^3/year) was deposited in the coastal area about three kilometers north of the jetty (Figure 8), while the rest (± 75.000 m^3/year) benefitted the beach and dunes over a length of 15 kilometers, as far as Scheveningen (km 102). At present, repeated nourishments near Hoek van Holland more or less maintain this situation.

Several other objects along the coast (discharge sluices, the harbour and seawall of Scheveningen (km 99–102), boulevards and sea-dikes) cause smaller distortions within the general trend.

Not only man but also nature itself may cause variations within this general trend. Near Groote Keeten (km 6–10), located in the eroding northern part of the study area, a significant growth of the foredunes (60.000 m^3/year) is observed (Figure 9). This phenomenon may be explained by accretion on the shoreface caused by local effects of migrating channels and shoals within the ebb delta of the Texel Inlet.

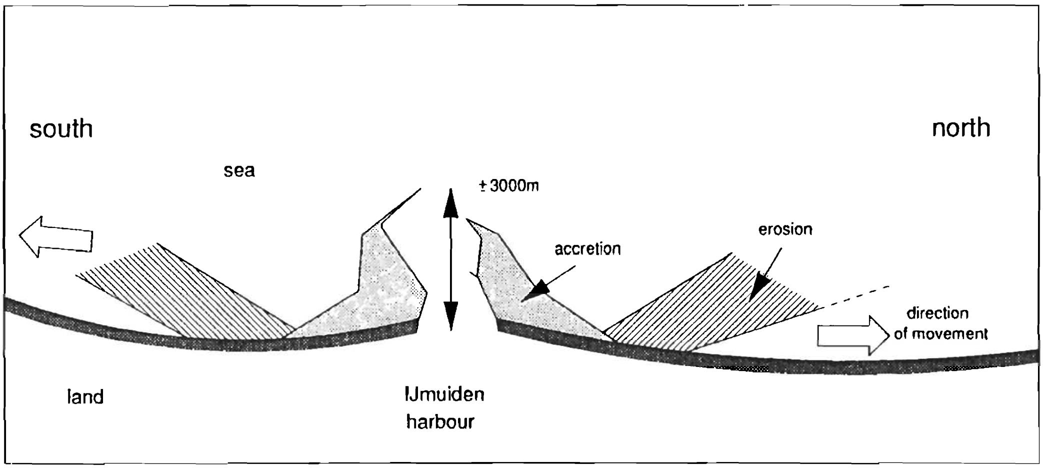

Figure 7. Sketch of the migration of the erosion depressions near the IJmuiden jetty in northern and southern directions.

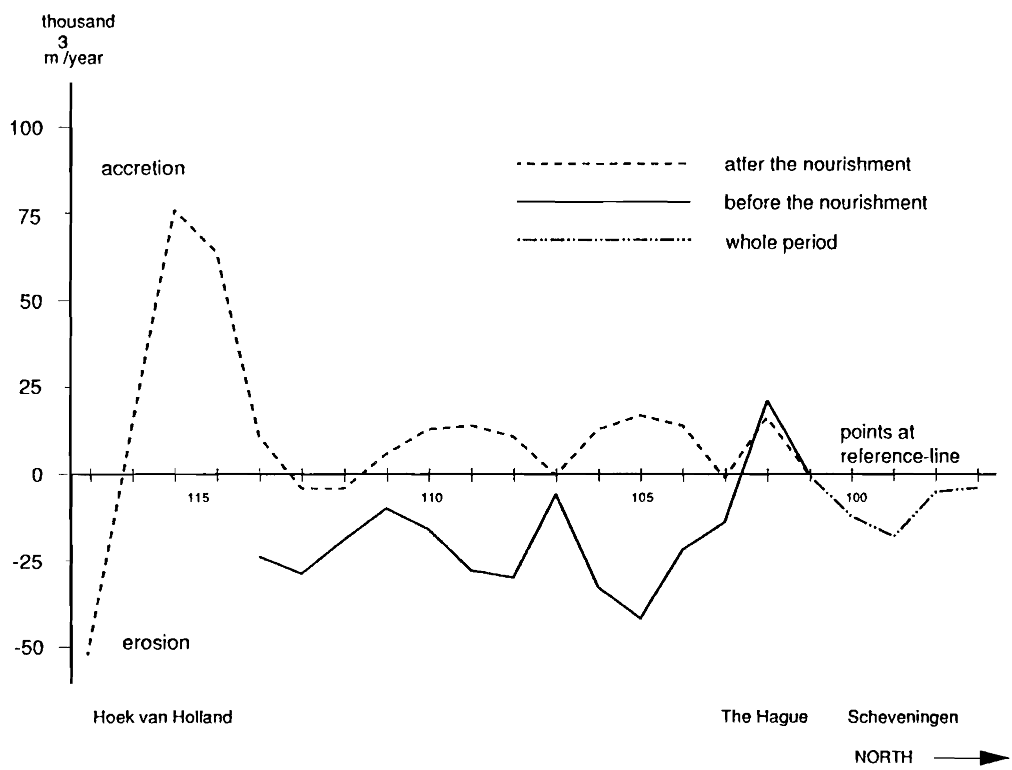

Figure 8. Averaged yearly sand budget changes of dune, beach and breakerzone between The Hague and Hoek van Holland (km 97–118) before and after the nourishment project in 1971.

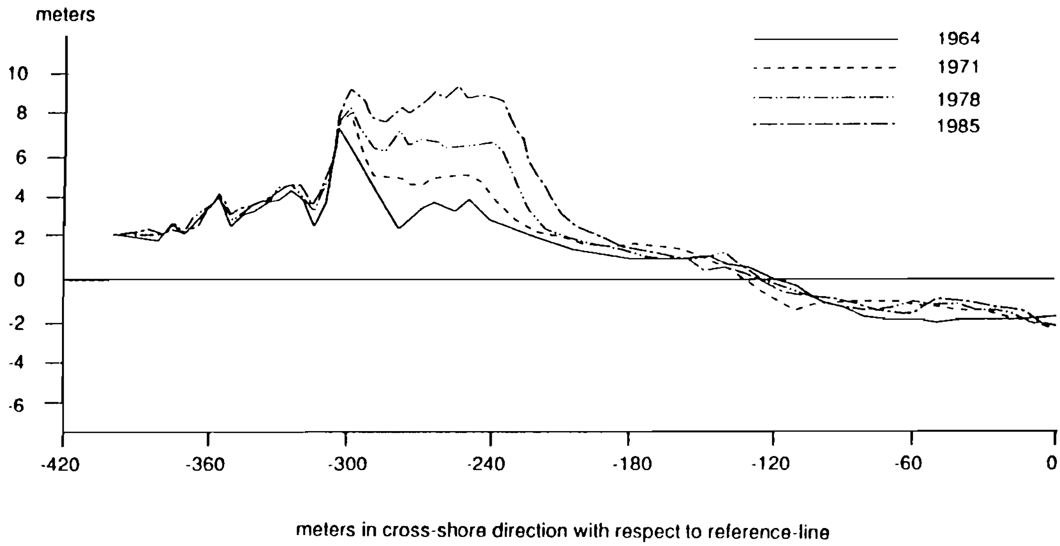

Figure 9. Natural growth of the foredune (km 6–10) in the eroding northern region.

Wave action results in onshore transport of sand towards the beach. From there, aeolian transport induces dune growth with the help of sand fences and lyme-grass.

Year-to-Year Variability

From a coastal management point of view, consideration of the yearly fluctuations in the sand volume of this area is as important as the mean trends discussed above. The yearly variations are simply identified as the differences between the volumes of sand in the selected areas for two consecutive years.

Figure 10 shows the results for the entire coastal area and for the beach and dune- and breakerzone separately. Within one year a maximum amount of about 2 million m^3 (17 m^3/m) sand exchanges between the areas of dune and beach and breakerzone, assuming a closed transport boundary at the landward side. Compared with the net yearly accretion rate of 0.4 million m^3 within the dune and beach zone, it seems clear that on a timescale of years, the amount of sand can vary considerably. The yearly fluctuations of the separate zones (dune and beach zone and breaker zone) indicate a different behaviour of both zones at this time scale. The response of the breaker zone is much more pronounced than that of the dune and beach zone. The maximum yearly fluctuations in the breaker zone are about 6 million m^3. This is in accordance with what one should expect from the function of the breakerzone as the main area of energy dissipation, and thus adaptation of morphology. Given the fairly low response of the dune and beach zone, the variability in sand volume of the breaker zone, must lead to the conclusion that on a timescale of years, a considerable exchange of sand with the lower shoreface occurs.

Figures 11a and 11b depict the same parameters for three distinguished coastal regions. There is a rather strong correlation between the fluctuations of the three regions in the dune and beach area (Figure 11a). This is the more striking since, mainly due to coastal management, conditions vary largely between the various coastal regions (*e.g.* by extension of jetties (IJmuiden, Hoek van Holland, Scheveningen) and by large-scale beach nourishments (Hoek van Holland)). This indicates that some morphological phenomena have a very large scale and are probably generated by large-scale hydrodynamic processes. There are some features that point at the role of storms in the yearly fluctuations of the sand volume. Storms may have a serious impact on the condition of

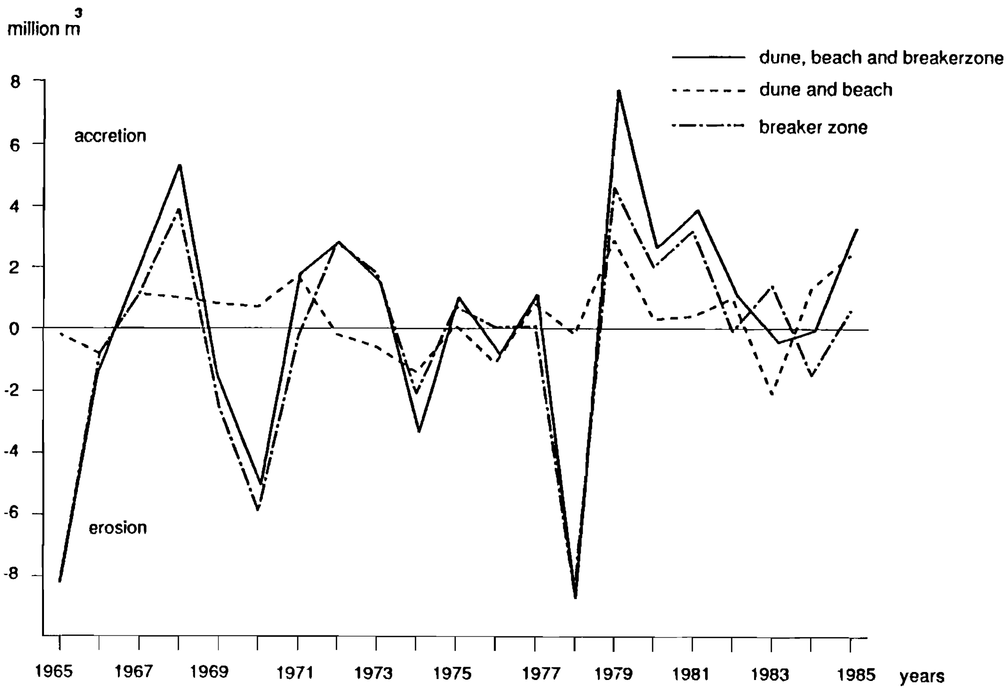

Figure 10. Year-to-year variability in the sand volumes of the various morphologic zones.

the coast. The effect depends upon storm conditions, as for instance storm surge level, storm duration, intensity and direction, and may therefore vary largely between different events. The occurrence of storms varies strongly over the years. This might cause a sequence of fluctuations in the yearly sand volume of the nearshore area. Verifying these speculations would require a thorough study of the potential effect of series of storms throughout the period of the sand volume data. Research on this topic has already been started.

CONCLUSIONS

For the entire study area it is concluded that the total sand budget is constant through time. A subdivision in shore-normal direction shows that in the beach and dune zone, accretion exceeds erosion by about 0.4 million m^3 per year, while both in the breakerzone and on the adjacent part of the lower shoreface erosion dominates, with losses of 0.05 and 0.35 million m^3 per year, respectively. The mean sand gain of beach and dunes is 3 to 3.5 m^3 per meter length of coast per year. In accretional sections this amounts to an average of 10 m^3/m per year.

Also, in longshore direction, a distinction can be established: a net accretion in the central part of 0.45 million m/year, and net erosion in both southern and northern regions, 0.25 and 0.20 million m^3/year, respectively. This general picture is disturbed at several locations, especially around the extended jetties of IJmuiden and Hoek van Holland. Bringing sea level rise into account, the sand volume of the entire study area with respect to MSL would decrease with about 7.10^5 m^3 per year.

There is a strong correlation between the yearly fluctuations in the three regions along the coast, indicating that some morphological phenomena have a very large scale and are probably generated by large-scale hydrodynamic processes. The yearly fluctuations of the

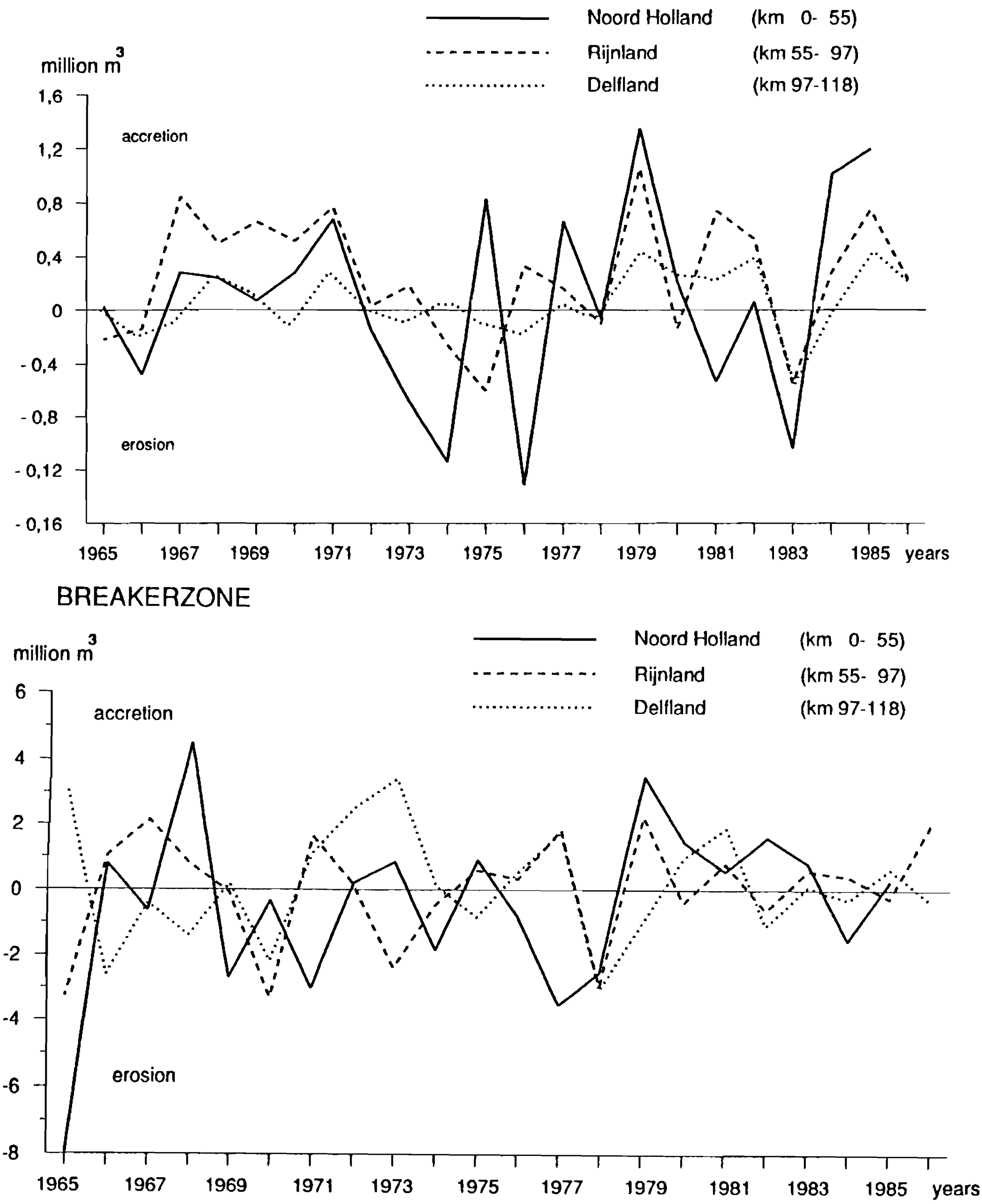

Figure 11. Year-to-year variability in the sand volumes of three complementary regions of the Holland coast (longshore). (a) Dune and beach. (b) Breakerzone.

sand volumes of the shore-normal zones (dune and beach, breaker zone and shoreface) are hardly related to each other. The breakerzone exhibits a more pronounced response to (daily) external conditions than the zone of beach and dune.

Concluding Remark

This study is part of a series which aims to reveal information on morphologic phenomena and processes along the Dutch coast. In addition to this study, for instance, a conceptual model is being performed, leading to an estimate of the transport terms at the boundaries of the study area. The data set also enables studies of morphologic processes on smallerscales. The availability of a data set of this extent appears to be a very valuable tool for further morphological and coastal management studies.

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□ RÉSUMÉ □

Les côtes hollandaises comprennent des dunes sableuses, des plages et des avant-plages. On a régulièrement controlé depuis 1963 la morphologie de ce système, ce qui a permis de réunir un ensemble de données morphologiques valable. Ces données ont permis d'étudier le bilan sédimentaire de la partie centrale de la côte hollandaise. La zone littorale s'étend depuis la face continentale de la dune sableuse jusquà 3 km au large depuis le pied de la dune. Le but de cet article est la description spatio-temporelle des ensembles morphologiques distincts dont on a calculé la tendance de l'évolution en termes de volume de sable.—*Catherine Bousquet-Bressolier, Géomorphologie EPHE, Montrouge, France.*

□ ZUSAMMENFASSUNG □

Die niederländische Küste besteht vor allem aus Sanddünen und Stränden. Seit 1963 wurde dieses System regelmäßig beobachtet, so daß sich eine sehr wertvolle morphologische Datensammlung ergeben hat. Aufgrund dieser Daten wurde eine Massenhaushaltsstudie über die Sandmengen am zentralen Teil der niederländischen Küsten, nämlich der 120 km langen Holland-Küste unternommen. Der untersuchte Küstenbereich erstreckt sich vom landwärtigen Rand der Sanddünen bis ca. 3 km seewärts vom Dünenfuß. In diesem Beitrag werden die großmaßstäblichen Entwicklungen in Raum und Zeit dargestellt. Daraus lassen sich Regionen mit einem eigenen morphologischen Charakter erkennen und für diese Gebiete auch das Sandvolumen kalkulieren.—*Dieter Kelletat, Essen, Germany.*