# Long-term morphological development of the Accumer Ee tidal inlet and its impact on island beaches and engineering responses

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## Abstract

At the East-Frisian coast (Germany) morphological changes of tidal inlets - anthropogenically or naturally caused - can have substantial effects on the sediment supply of adjacent beaches. Erosion periods of beach and dune areas occur, which necessitate engineering countermeasures to preserve the present shoreline. The East-Frisian barrier islands are integrated into the coastal protection strategy for the mainland as they reduce the impact of sea-forces on the flood defences. On the other hand, shoreline and foredunes have to be maintained to protect the urban and tourism infrastructures on the island itself. The maintenance by solid engineering works, like seawalls and groynes, is not favourable because it has drawbacks on the natural morphodynamic processes. Therefore, the technique of beach- and foreshore nourishment is implemented as an instrument of 'active coastal protection' whenever possible. The paper deals with an actual erosion problem on the island of Langeoog caused by morphological changes of its tidal inlet Accumer Ee. It discusses the long-term morphological development of the tidal inlet with its ebb delta shoals and of the adjacent shoreline. A coastal engineering solution for the coastal defence problem has been achieved by means of an integrative approach regarding the natural morphological processes, the ecological objectives, and the safety of the island population.


## Introduction

The island of Langeoog is one of the seven East-Frisian barrier islands which extend along the North Sea at the western part of Germany (Fig.1). The sandy barrier islands are formed by the interaction of tides, currents, surf and wind-born accretion. The islands are separated from each other by tidal inlets which are connected with tidal flats located towards the mainland. The tides are semi-diurnal and propagate from west to east. The predominant wind direction is north-west. Tides and winds

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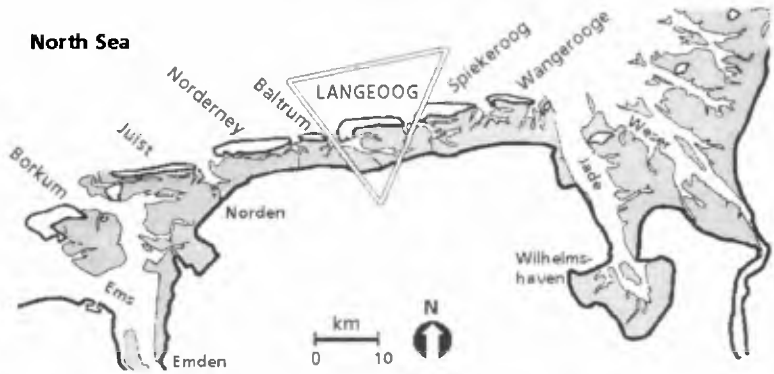


Fig.1: The East Frisian Islands - western German North Sea Coast


Fig. 2: Tidal inlet 'Accumer Ee' between Baltrum (left) and Langeoog (right)

generate a net littoral drift which is directed to the east. The tidal inlets exhibit a very high natural dynamic, which is characterized by morphological changes, both long-termed (structural) and comparatively short-termed. Most of the East-Frisian islands experience erosion of the western spit (Luck 1977). The protection of the barrier islands is part of the German coastal defence system. Consequently, erosion is counteracted by groynes, seawalls and artificial sand supply (Kunz 1996, 1997). The island of Langeoog is one of the two exceptions. Its western part has been subject to accretion as well as to erosion. The natural sand supply is related to the ebb delta shoal system (reef bow). It is created by interactions of tides, waves and littoral drift. The volume of the shoals as well as the movement-direction of the reef bow (downdrift foreshore bars) are essential for the sediment supply of the adjacent island beaches. A migration of the tidal inlet affects the configuration of the ebb delta bar system and therefore can cause a decrease in the sediment supply. The bars of the reef bow are only temporary accumulation areas as the sediment is permanently moved, resulting in a net sediment transport along the reef bow. The sediment bars of the reef bow can reach heights above low water level (Fig.2).

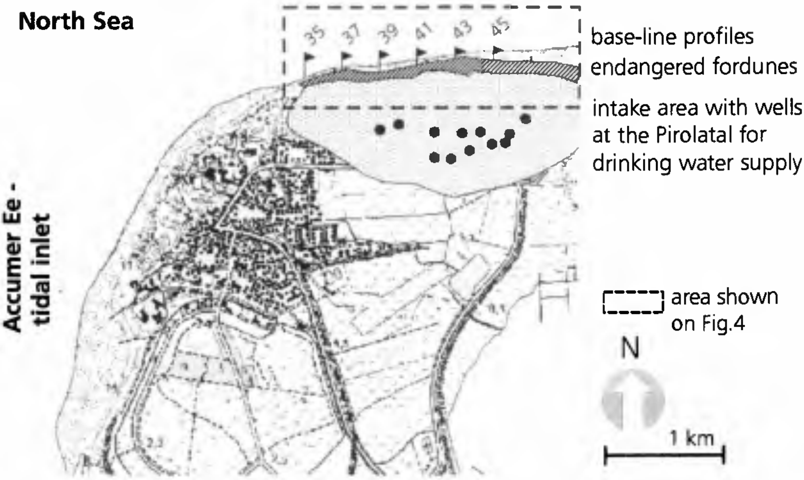


Fig. 3: Western part of Langeoog island with survey-profiles and infrastructures

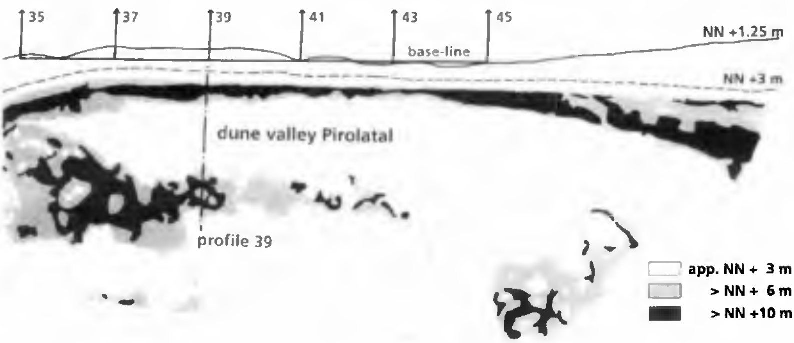


Fig. 4: Dune area Pirolatal (laserscan survey 1996)

The western part of Langeoog, especially the area of the Pirolatal (Fig.3), is endangered by erosion, which is caused by insufficient natural sand supply. The laserscan-survey of the year 1996 (Fig.4) clearly exhibits the weak condition of the foredunes. Especially the part between profile no.39 and no. 43 has the smallest dune widths and the lowest dune heights. The losses after a severe storm surge can be estimated as a retreat of 10 to 20 meters. Consequently, the endangered foredunes in the Pirolatal - with dune widths around 35 meters and very narrow beaches in front - are imminent to break through during a stormy winter season. The average height-level of the endangered dune valley Pirolatal amounts only to 3 meters, and a second closed dune ridge is not existing. A break through would endanger the village by flooding and would affect the drinking-water supply of the island (Fig.3) by intrusion of salt water into the fresh water lense. A further aspect is that the endemic vegetation is classified as a highly protected habitat according to the Lower Saxonian Nature Preservation Statute.

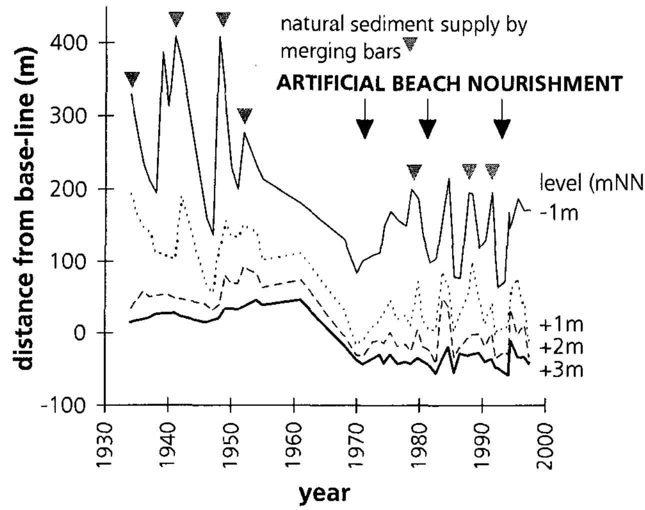


Fig. 5: Time distance diagram for different reference levels - profile 39 (see Fig.4)

Time-distance diagrams provide information about the beach and dune development, exemplary demonstrated by profile no. 39 (Fig.5). Regular surveys have been carried out since 1935. The development can be divided into three periods. First: between 1935 and 1960 a positive trend prevailed, and several "peaks" refer to natural sediment supplies by downdrift foreshore bars until 1950. Second: between 1960 and 1970 a drastic beach and dune decline occurred, retarded in the beginning as long as the beach was large enough to provide substantial aeolean sand transport. During this period the foredunes lost on an average 70 meters in width, considerably intensified by the hurricane storm surge from February 1962. Third: because of the large and lasting dune losses several beach nourishment projects have been carried out since 1972 (their implementation will be described later) partly compensating the beach decline. Furthermore, a renewed natural sand supply can be observed since the end of the seventies but the amount of it seems to be reduced.

Fig.6 demonstrates the extent of the dune losses: profile no. 39 shows a decline of 91m between the maximum in 1961 and the minimum in 1994 (reference level is NN +3m). In comparison with the erosion period (1960 to 1970) no considerable regeneration has occurred; decline and regeneration alternate with each other depending on whether natural or artificial supply take place or a shortage of sediment occurs. In general, no specific trend can be observed (see Fig.5: 1970 to 1996).

## Long-term development of the tidal inlet and its ebb delta bar system

The discussed beach and dune development is determined by the processes within the tidal inlet. Temporal alterations of the tidal inlet configuration - with respect to the ebb delta bar system (reef bow) - can be linked to the processes within the downdrift area of the reef bow itself and thereby to the development of adjacent beach and dune areas.

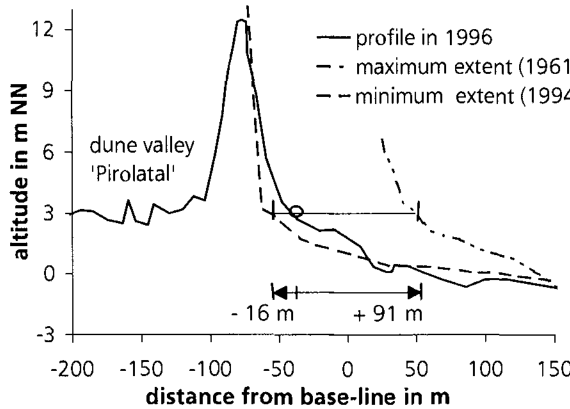


Fig. 6: Minimum and maximum dune extension between 1935 and 1996 - profile 39

The morphological development of the Accumer Ee tidal inlet and its ebb delta shoals is well documented over a period of more than 100 years (Homeier 1956; Homeier & Luck 1971). The large-scale and long-term morphological development was investigated by the evaluation of topographical maps (1866 to 1995). The maps of the last century are mere sea maps with only few information about depths (just enough for navigational purposes). Due to this restriction, only a few horizontal reference levels (SKN, SKN -1m and SKN -2m, where SKN is the low water level at spring tide) were chosen to investigate the sediment distribution within the reef bow (Fig.7). On a visual basis the ebb delta bar system shows over a long period a more or less compact shape; the single bars, as well as groups of shoals, are only separated by small channels. At the end of the investigation period, however, (around 1985) the channels started to expand and the map of 1995 already exhibits a large gap at the vertex area of the reef bow (see Fig.7, marked by an arrow in the map 1995). The solely visual interpretation already indicates that the sediment accumulation within the ebb delta bar system is decreasing.

To get a quantitative overview the morphological changes of the ebb delta bar system were estimated by the determination of the area covered by the bars referring to three distinguished horizontal reference levels (Fig.8). The calculated total area for the three reference levels are named as 'equipotential bar areas'. The development of the equipotential bar area values can be approximately transferred by constant factors to the corresponding changes of the sediment volume providing information on the predominant trends. Due to the limited number of available reference levels the calculation of volumes is not more effective than the applied method. The used German sea map reference level SKN is - in contrary to the fixed German datumn NN - a variable value. However, within the scope of the applied investigation methods these variations (up to 11cm for the entire investigation period) are irrelevant regarding the range of error connected with the small-scale of the maps and the limited accuracy of the survey, which exceeds this source of error to a great extent.

Results are shown in Fig.8. With reference to the entire investigation period, the equipotential bar areas of the reference level SKN -2m and SKN -1m have

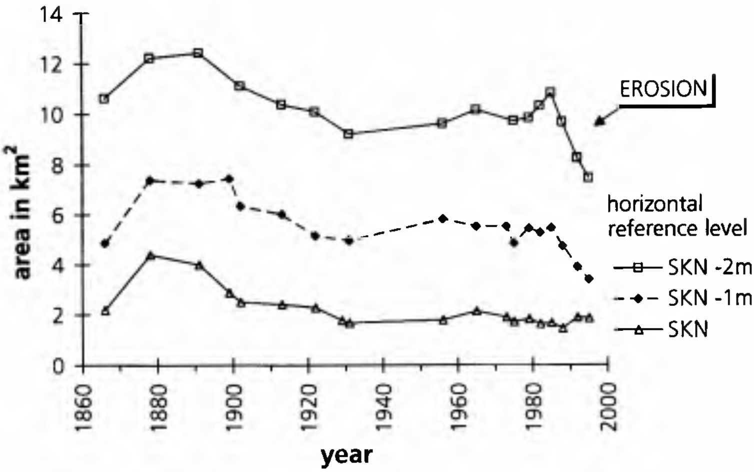


Fig. 8: Development of equipotential bar-areas for three different reference levels

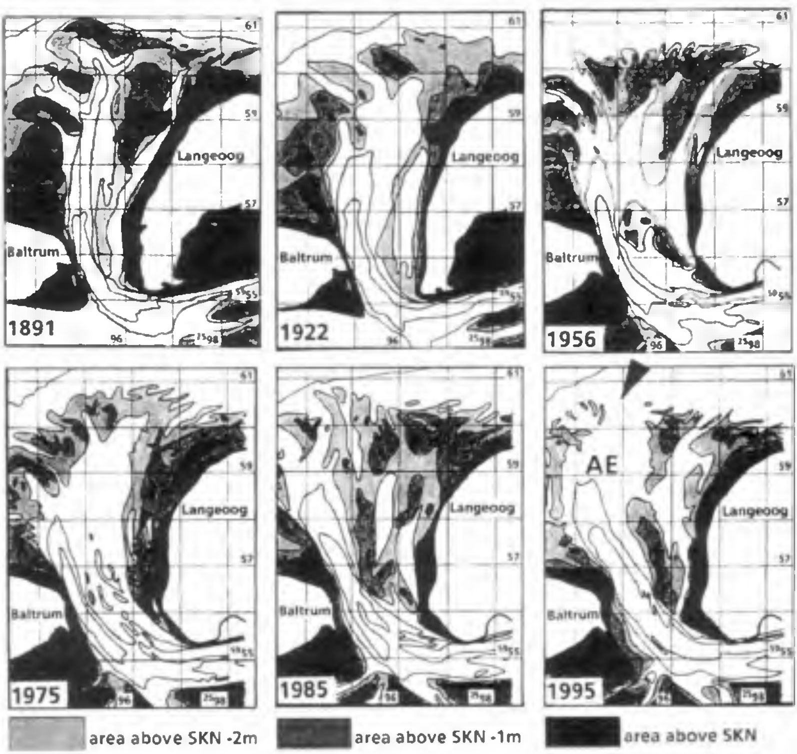


Fig. 7: Development of the ebb delta bar system of the Accumer Ee (AE) - tidal inlet between 1891 and 1995

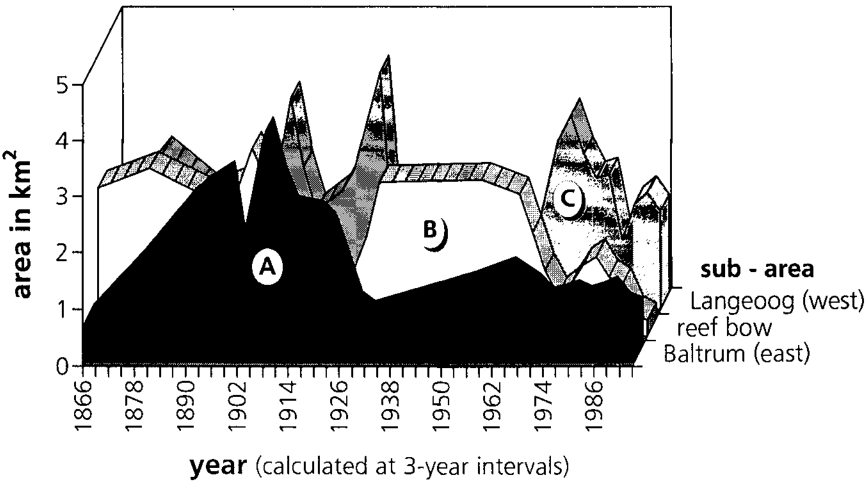


Fig. 9: Distribution of equipotential bar-areas for sub-areas (reference level SKN-1m)

decreased by about 30%; the area of the reference level SKN lost just around 15% of its former size. The decrease did not occur continuously. The ebb delta bar system shows its highest accumulation degree during the last quarter of the 19th century. At the end of the last century the equipotential areas of all reference levels gradually diminished. Between 1930 and 1980 their extent was more or less stable; afterwards the area for the reference levels SKN -2m and SKN -1m lost considerable size. Because of the more or less steady extent of the SKN reference level it is unlikely that the sediment has been transported and deposited in greater depths. Furthermore, the decrease took place rather quickly.

To allow a more detailed analysis the sediment distribution within different sub-areas of the ebb delta bar system - regarding the reference level SKN -1m - was examined. The distinguished 'sub areas' are: the east end of Baltrum, the bars of the reef bow, and the western part of Langeoog (Fig.9). Non available intermediate values have been calculated by linear interpolation (3-year intervals). The diagram does not show the shifting of single bars or groups of shoals but the shift of maximum sediment accumulations. Marked by A,B,C, the following becomes evident: in the beginning the sediment accumulated at the east-end of Baltrum leading to a rise with a maximum in this area between 1866 and 1908 (A); then the maximum moved into the reef bow area (B), where it reached a maximum between 1935 and 1960 (there is no distinct "peak" to be seen because no data were available for the period between 1931 and 1956; the values are exclusively based on calculation). At last, the maximum reached the western shore-line of Langeoog around 1975 (C). This shift of sediment covered a prolonged period. The extent of the subsequent sediment accumulation at the east of Baltrum is by around 40% to 60% smaller than the previous maximum. It accumulated around 1970, passed into the reef bow very quickly, and reached Langeoog around 1985. A further sediment supply is at the moment out of

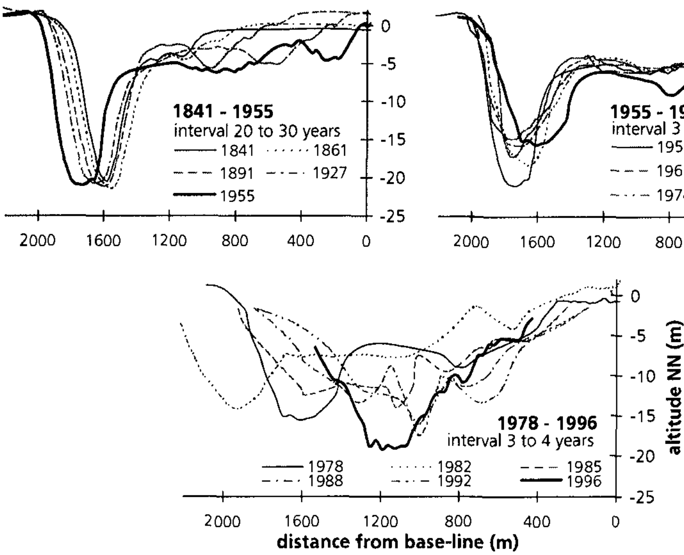


Fig. 10: Cross-sections of the tidal inlet Accumer Ee - profile no.6 (see Fig.2)

sight. Although the sediment accumulation at the east part of Baltrum is recently slightly growing the reef bow exhibits a so far unprecedented minimum. The actual reduced sediment transport indicates that fundamental morphological changes - probably concerning the littoral drift in general - are in progress.

The investigation so far does not explain why there is actually a sediment deficit, which leads to a beach and dune decline in front of the Pirolatal. According to Fig.8, sufficient sediment quantities have reached Langeoog since the seventies. This can be explained by the fact that the sediment supply not only depends on the quantity of sediment (equipotential bar area) but is also dependent on the position at which the downdrift foreshore bars merge with the island beaches. Therefore, the development of the main tidal channel of the tidal inlet Accumer Ee and its impact on the position of the ebb delta bar system were examined.

The morphological changes within an ebb delta bar system are - besides littoral drift and wave climate - mainly determined by the position of the main tidal channel and its residual ebb tide current. The main tidal channel of the Accumer Ee - in this investigation defined by the SKN -5m and SKN -10m contour line - is situated at the western part of the tidal inlet directly at the east-end of Baltrum. Therefore, the morphodynamic situation of Langeoog is favourable with respect to the conditions for a natural sediment supply of the beaches because the downdrift foreshore bars can reach Langeoog at its western part.

The development of the main tidal channel Accumer Ee is represented by a cross-section of the tidal inlet at the seaward boundary of the drainage basin (Fig.10). Over a long time of the entire investigation period (1841 to 1955) the main tidal channel exhibits a more or less steady position and constant depths, whereas the cross-section of the tidal inlet enlarged continuously. However, it has to be taken into account that the diagram for the first period (1841-1955) is based on survey-intervals that amount to 20-30 years, i.e. intermediate short-termed developments are not visible. Afterwards (1955 to 1978) the depth of the main channel decreased, whereas the location within the tidal inlet remained unchanged. After 1978, during the last period (1978 to 1996), shifting tendencies of a larger extent occurred and the position of the main tidal channel became unsteady: at first it moved in a westward direction, finally the shifting process is directed eastwards, so that in the end the resultant new main tidal channel is located more eastward than it had been before. In the course of the last years a newly deepening of the channel can be observed.

The shifting tendencies of the former more or less steady main tidal channel indicate that the drainage basin might be subject to major morphological changes as the cross-section of a tidal inlet is closely connected with the volume of the tidal basin. Current investigations have shown that the volume of the tidal basin is actually increasing, possibly caused by structural erosion processes in the tidal flats (Schroeder et al. 1994).

In the eastern part of the ebb delta bar system there are three different approach directions to be distinguished by 'downdrift foreshore bar'-systems. Fig. 11 shows the average position of a median reef bow representing the ebb delta bars, which are characterized by a split of their alignment: the medium-grey coloured part is lined up eastwards; the dark-grey coloured part is directed southwards. The split is presumably determined by the predominant weather conditions (weather-influenced hydrodynamic factors like wave and current direction, surf etc.). Depending on the direction from which the main amount of sediment reaches Langeoog certain sectors of the beach obtain a sufficient sediment supply, whereas others suffer from a deficit. Fig.12 shows the size of the three downdrift foreshore bar-systems for the period from 1866 to 1995. The varying positions of the downdrift foreshore bars and their extent are obvious; the alternate maxima of the different directions are clearly visible.

The development of the beaches and dunes in front of the Pirolatal is dependent on the eastward directed sediment transport. The periods of supply and deficiency correspond with the development of the beaches and dunes (see Fig.5). During the distinct erosion period between 1960 and 1970 there was no major eastward directed sediment supply to this area, whereas since 1970 larger amounts of sediment have reached the Pirolatal-area again provided by the eastward directed approach of the shoals. The recent development of the downdrift area is characterized by an intermediate position of the downdrift foreshore bars located between the southern and eastern direction (light-grey colour). This development is caused by the north-west extension of the main tidal channel which leads to a more westward situated splitting point of the downdrift bars. A distinct shift of the reef bow in a solely northern direction - which would result in an eastward shift of the downdrift area - has not taken place so far. Consequently, the sediment supply is not affected adversely, and the downdrift foreshore bars reach Langeoog still in front of the western part of the island.

## Coastline and dune management by artificial sand supply

The discussed results demonstrate that the beach and dune decline in the Pirolatal-area can be attributed to a temporal restricted lack of natural sediment supply. This deficit is caused by varying positions of the downdrift foreshore bars which lead to temporary periods of erosion. It was possible to compensate shortages of sand supply

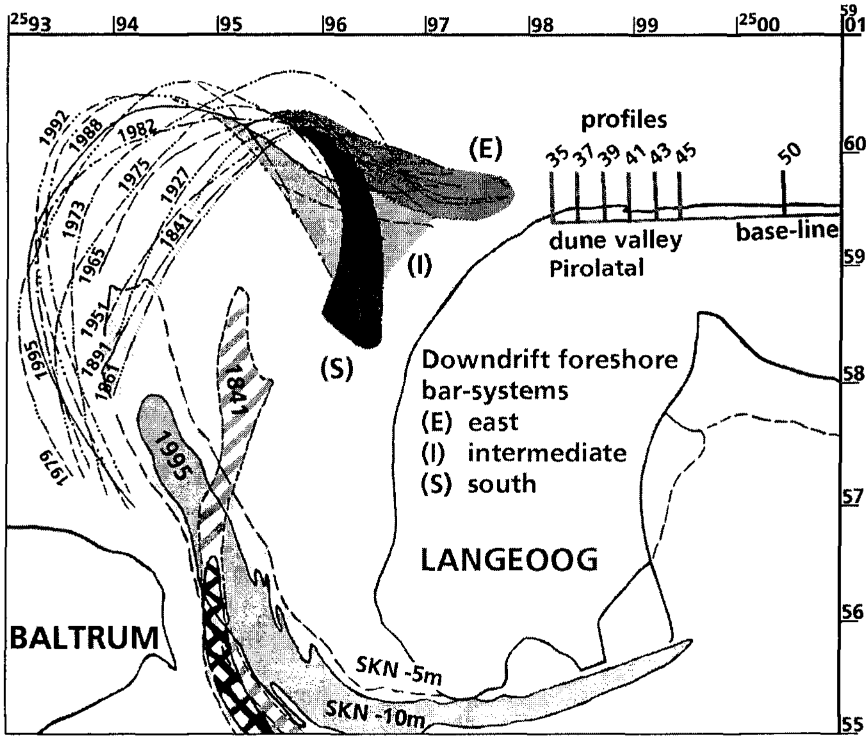


Fig. 11: Shifting of the main tidal channel Accumer Ee and its related ebb delta bar-system with three distinguished downdrift foreshore bar-systems (E), (I), (S)

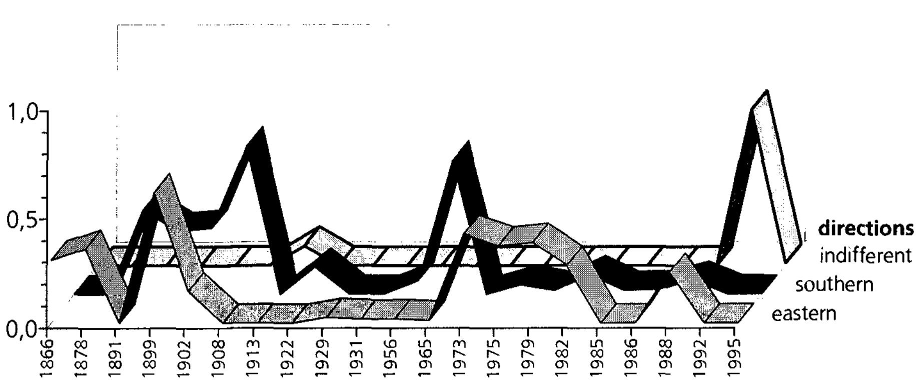


Fig. 12: Equipotential bar-area (reference level SKN) for merging downdrift foreshore bars with respect to different directions (see Fig.11)

| year | profile area | nourishment volume (m³) |
|---|---|---|
| 1972 | 25 -45 | 550.000 |
| 1982 | 28 - 41 | 138.000 sand dam |
| 1982 | 34 -34 | 126.000 dune fill |
| 1982 | 37 - 37 | 7.300 |
| 1984 | 24 - 30 | 206.000 sand dam |
| 1984 | 27 - 27 | 82.000 |
| 1987 | 22 - 32 | 560.000 |
| 1993 | 25 - 28 | 153.000 |
| 1993 | 41 - 41 | 91.000 |
| 1994 | 17 - 19 | 100.000 |
| 1994 | 23 - 37 | 460.000 |
| 1994 | 37 - 47 | 400.000 |

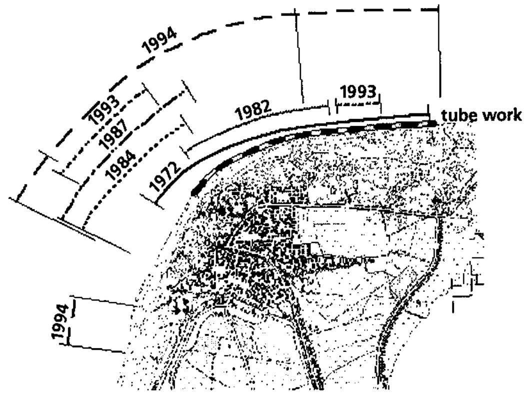


Fig. 13: Nourishment projects on Langeoog island
(Left: volumes. Right: year and location)

by 'soft' engineering means up to now because only limited periods of erosion have to be covered. Since the drastic beach and dune declines (Pirolatal from 1960 to 1970) several beach nourishment projects - functioning as sacrificial structures - have been implemented; Fig.13 shows the nourishment projects carried out on Langeoog up to now. As a further countermeasure against erosion an artificial reinforcement consisting of sandfilled plastic tubes was installed into the beach in 1972 to hold back and secure the artificially replenished sand. During distinct erosion periods the tubes become partly visible again, whereas during periods with sufficient sand supply they are covered. As an additional measure artificial sand dams were constructed in 1982 and 1984, which interrupted the current in a swash channel and thereby turned the merging downdrift bars onto the beach. Furthermore, a very endangered dune area (profile 37, see Fig.3) was reinforced by a dune-backfill in 1982 (Lüders et al. 1972, Erchinger 1986, Kunz 1987).

Barrier dunes are only expected to maintain themselves naturally in strong conditions, if the dry beach in front of them is wide enough to guarantee an aeolean sand transport for regenerational purposes. Concerning coastal defence, the fordunes must be maintained strong enough to withstand the impact of severe storm surges. Based on experience, Erchinger (1986) proposes that the distance between the NN 0m line and the mean high water line (MHWL) should be more than 90m or, alternatively, the distance from the NN 0m-line to the NN +3m-line should be more than 150m. Fig.14 applies these criteria to the time-distance-diagram of profile 39 (focusing on the period after 1960): during the erosion period between 1960 and 1970 the beach was smaller than the minimum according to the criteria. The implementation of the sand filled tubes and the beach restoration could stop the further decline of the foredunes. The several beach nourishments during periods of sediment deficiencies as well as the natural sediment supplies led to a more or less beach and dune stabilisation. Nonetheless, the periods in which the beach had a sufficient width were too short and the amount of natural sediment supply too small to initiate 'natural' dune and beach regeneration processes of a greater extent.

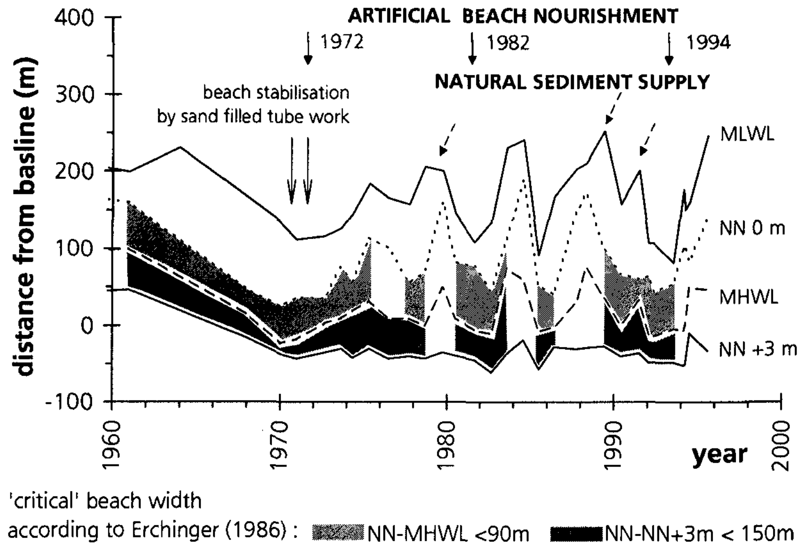


Fig. 14: Development of beach profile no.39 with nourishments and natural sand supply since the beginning of the dune erosion-period in 1960 (see also Fig.5)

## Conclusions

The investigation has shown that the observed beach and dune decline in the Pirolatal-area on Langeoog island is not been caused by structural and therefore non-reversible morphological processes. The discussed development can be attributed to a temporal restricted lack of natural sediment supply caused by varying positions of the downdrift foreshore bars. However, a substantial and presumably structural morphological change revealed itself recently in the detected decrease of sediment accumulations within the ebb delta bar system. Further investigations are in progress to confirm, if there are structural changes developing within the littoral drift. If this assumption proved to be true, it is to be expected that extended beach areas of Langeoog are going to obtain comparatively smaller amounts of sand supply in the near future. Therefore, more beach nourishments will be inevitable, possibly accompanied by foreshore nourishments. A managed retreat of foredunes would provoke the opposition of the island population regarding losses of land. Furthermore, in some areas it would interfere with the existing drinking water supply out of the fresh water lense. As a preliminary answer to the problem, the most cndangered parts of the foredunes were artificially reinforced at the landward side of the foredunes in 1997. By this means the capability of resistance at least for the next storm surges is guaranteed. A further beach nourishment is going to follow in 1998. The time gained by the two combined means (dune fill, beach restoration) allows further investigations of the tendencies of the natural developments and the elaboration of new concepts for engineering responses, which will include cost-benefit considerations. Up until now the strategy for the classified protective fordunes on the German barrier islands is mainly based on the principle of 'hold the line'. Artificial beach nourishment is an effective technique but it has to be applied frequently. Also it has been proven as an effective tool to avoid conflicts with the island population concerned. In a long term perspective the possibilities of an accelerated rise of the relative sea level as well as a steepening of foreshore areas has to be taken into consideration. Concepts have to be proven and there is a need to discuss how we can proceed to more flexible responses creating a resilient shoreline by the process of an improved approach towards integrated coastal protection management.

## Acknowledgement

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