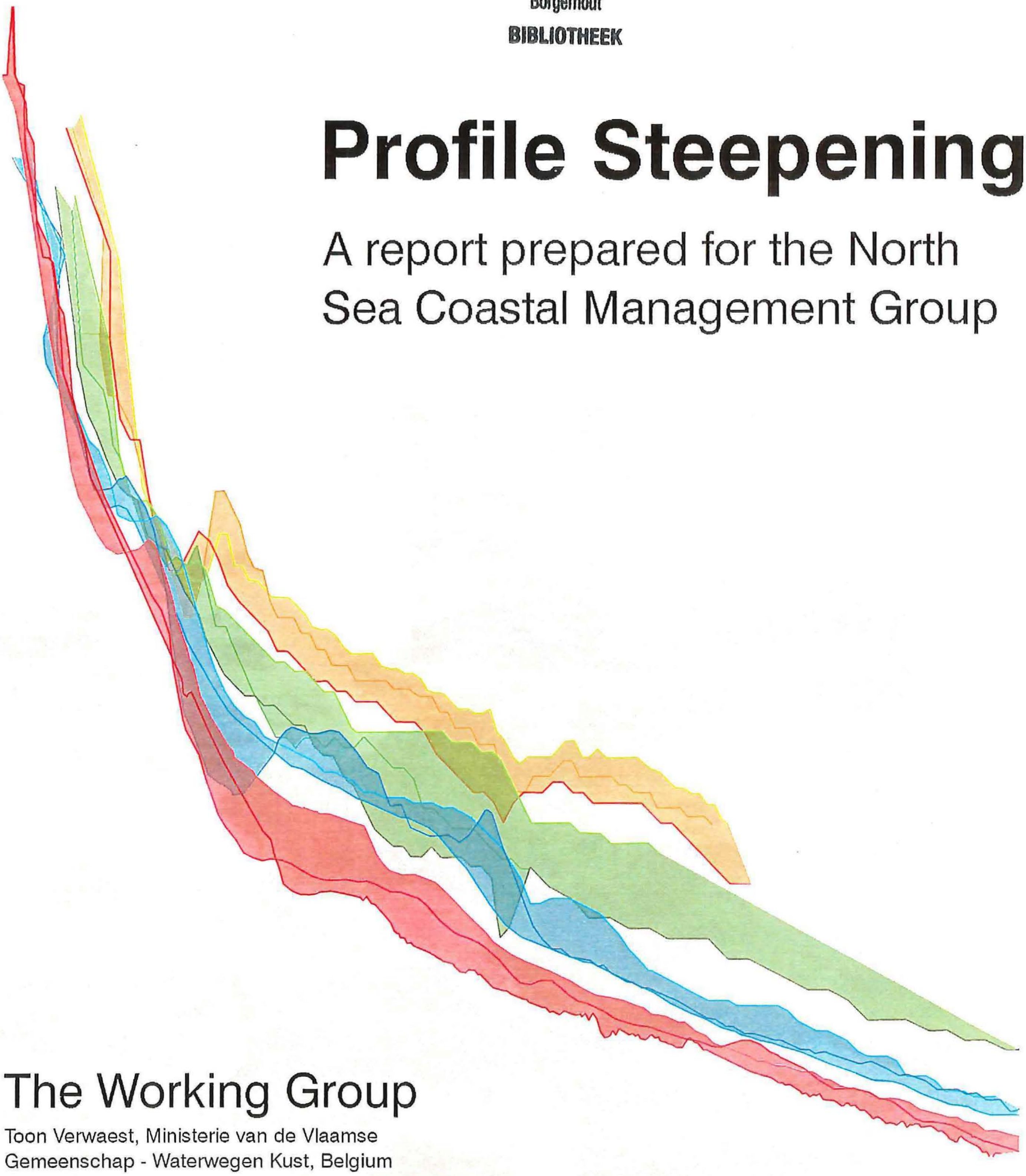
Profile Steepening

A report prepared for the North Sea Coastal Management Group



The Working Group

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1. Introduction

At the meeting of the North Sea Coastal Management Group May 28-30, 1997 some of the members suggested to broaden the scope of the discussions by including more detailed work related to themes of common interest. From the list of themes the themes Profile Steepening and Probabilistic Design were selected for further studies in working groups with the lead of Per Roed Jakobsen, Kystinspektoratet and Richard Jorissen, Rijkswaterstaat respectively.

This report about Profile Steepening has been prepared by a working group with these members:

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At the first meeting in Billund, Denmark January 12, 1999 with the lead of Per Roed Jakobsen, Chr. Laustrup was appointed chairman of the group and Holger Toxvig Madsen, Kystinspektoratet was appointed secretary.

Besides the meeting in Billund, there has been a meeting in Brussels March 2, 1999 and a meeting in Amsterdam April 13, 1999.

2. Summary and conclusions

2.1 Definition

The working group has agreed on the following definition of the term 'coastal steepening':

Coastal steepening is the phenomenon whereby the profile does not retreat or progress as an equilibrium profile, but develops towards a steeper profile. With such a steepening, assumptions of the future development cannot directly be extrapolated from the development up to now.

In this report the magnitude of the steepening is expressed in percentage per year. An annual steepening of 1% means that a coastal profile with an initial average slope of, for instance, 1:100 has a slope of 1:99 one year later.

2.2 Evidence of steepening

In the UK steepening has been reported, and is considered a problem in the more general context of "coastal squeeze". Inter-tidal narrowing defined as the narrowing of the distance between the HW and the LW line is widely recognised. Studies show that between Flamborough Head and the Thames the inter-tidal narrowing is up to 2 m per year in some places. The rate is very variable along the coast and a correlation with the geological setting and the coastal structures was observed. Similar evidence of inter-tidal narrowing has been reported for the south coasts of England and Wales and for coasts in several coastal councils from around the UK.

In Belgium the central part of the coast is getting steeper because the gullies are getting deeper and moving landward. The actual annual steepening is typically 0.4% which has been assessed by comparing the retreat rates of the profile sections MSL +4.5 m to MSL –1 m and MSL –2.5 m to MSL –6.5 m.

In the Netherlands the steepening has been assessed for the Holland coast, by comparing the volume change of the shoreface between 8 and 12 m below MSL with the shoreface between the dune and 8 m below MSL. Most coastal sections of the Holland coast show steepening. Expressed as a percentage per year, this roughly varies from 0 to 0,2%. The northern 10 km of the Holland coast shows a more pronounced steepening of 0,4-0,6% per year due to the deepening of the Marsdiep ebb tidal gully. It should be stressed that specifically at the Holland coast south of IJmuiden, the steepening effect is reinforced by accretion of the near shoreface and erosion of the deep shoreface. In terms of coastal management this is considered an advantageous situation.

In Germany an ongoing study of the development and the processes in the foreshore areas to a depth of 20 m of the German Bight shows a steepening in front of the East Frisian (Ems to Jade) and North Frisian (Eiderstedt peninsula to Sylt) islands. However, the conclusion is preliminary. The ongoing work with correcting the old bathymetric data might change this conclusion.

In Denmark coastal steepening has been studied for the central 110 km of the North Sea coast and for a short section at the northern part. The steepening has been assessed by comparing the retreat rates of the profile sections +4 m to –6 m and –6 m to –15 m. The annual steepening was found to be in the order of 0.4% with a maximum of 1%.

2.3 Main physical causes of steepening

The main causes of profile steepening are discussed and reference is made to the causes in the different countries.

The main cause is regarded to be man-made interference in the upper part of the coastal profile. This interference could be building of structures or nourishment. This will slow down the retreat of the upper part of the profile while the deeper part remains unaffected for some time resulting in a steepening. However, this correlation between coastal protection in the upper part of the profile and profile steepening is not found everywhere.

Other proposed causes are: Converging longshore tidal flow because of dams and harbour moles, decrease of sand supply from rivers, sand extraction, coarsening of beach material, oil and gas extraction and decreasing sea level rise.

Some of the above causes are more convincing than others, but none are fully convincing. Furthermore, many of the underlying processes are still unclear.

2.4 Significance, time scale and actions

It is recognised that a consequence of steepening is increased wave penetration. This leads to increasing erosion of beaches and overtopping and undermining of coastal defence structures.

The narrowing of the inter-tidal zone leads to a squeeze of habitats, which is of particular concern in the UK.

The consequences of steepening on overtopping and undermining have been demonstrated by UK model calculations. The calculations are based on extreme wave conditions and on a 2 m per year narrowing of the inter-tidal zone. After 20 years the overtopping rate is 25% larger and the wave orbital velocity at the toe, which influences the scour, is 3% larger. After 50 years the overtopping rate is 75% larger and the toe velocity is 10% larger.

The effect of steepening on the sediment transport rates, and consequently the demand for nourishment, have been estimated by Danish calculations. A simple formula and a hydrodynamic mathematical model have been used to calculate the longshore transport for the present steepness and for forecast steepnesses in 20 and 50 years. The calculations are based on typical wave conditions and estimated future profiles. The results from the two calculations are in good agreement and indicate that the sediment transport rates are 2% larger in 20 years and 6% larger in 50 years than today. The demand for nourishment will increase accordingly.

Possible actions against the consequences of coastal steepening are:

- To increase the dimensions and the strength of the structures.
- To increase nourishment volumes at the upper part of the shoreface.
- To change the nourishment strategy so that the erosion is compensated not only in the near shoreface but also in the deep shoreface. In this way the steepening process is stopped.

In all countries the coastal managers are aware of the problems related to coastal steepening. However, the general attitude seems to be that a change in strategy should be based on more evidence.

In the Netherlands, Germany and Denmark research projects are or have been carried out specifically on coastal steepening. This is not the case in the other countries. However, in most of the countries research related to steepening is planned or in progress.

2.5 Common problems and future work

The working group has concluded that a number of problems have to be dealt with in relation to coastal steepening:

- How serious is the problem?
- How reliable are the explanations?
- Is the 'wait and see' attitude dangerous?
- If the nourishment option has been chosen, what are the benefits and costs of nourishing only the upper part of the profile compared with nourishing the entire profile?
- Under what conditions is the better option to enlarge the dimensions of the structures compared with the nourishment option?

- Can we calculate a new equilibrium steepness as a result of human interference and a change in the natural impact?

- What is the combined effect of coastal steepening and other long term phenomena (sea level rise, increased storm frequency, etc.)

3. Description of the steepening problems in the different countries

3.1 The United Kingdom

3.1.1 Introduction

Compared with the countries on the eastern side of the North Sea, the UK coastline is very varied. It has long lengths of both hard and soft cliffs, many estuaries and salt-marshes, beaches composed of all sediments from soft mud through sands to shingle, but relatively few deep, straight sandy beaches backed by dunes. Sediments are often of mixed material, and commonly consist of a thin veneer (less than 1 m) of mobile material overlying substrates of hard clay, chalk, or compacted gravel. In addition, wave heights are generally smaller, and tidal currents larger, on the west than on the east coast of the North Sea.

Representatives from regulatory authorities (MAFF, the Environment Agency and maritime councils), coastal engineering consultancy firms, and government research laboratories report a consensus view that narrowing of the beach or inter-tidal zone is widely recognised as an issue, and has been observed over much of the south and east coastlines. However, there is little awareness of steepening of the sub-tidal shoreface, mainly because of lack of data. "Coastal squeeze" as a generic term analogous to coastal steepening covering all the coastal zones is seen as a major issue (particularly on saltmarsh and mudflats), from both a flood defence and a habitat perspective.

This perception is partly because the main evidence in the UK waters is from the inter-tidal zone (i.e. between the lines of Mean High and Mean Low Water Spring Tides). Although repeat hydrographic surveys are made in bathymetrically volatile areas, for navigation purposes, they do not appear to have been analysed to search for evidence of either deepening or steepening of coastal waters.

3.1.2 Evidence

Anglian Water commissioned a study of the historic behaviour of the coastline from Flamborough Head to the Thames over the period from about 1850-1890 to the 1970's (Sir William Halcrow & Partners 1988a,b). As part of the study, combinations of advance/retreat and steepening/ flattening were categorised on scale indicated by –6 to +6 (Fig. 3.1.1). Short lengths of the coast were individually assigned values on this scale. They found that 70% of the coastline was retreating, and 78% was steepening inter-tidally (Fig. 3.1.1). The inter-tidal narrowing in some places occurred at up to 2 m per year. The rate is very variable along the coast, with inter-tidal widening occurring in a few short lengths, and some steepening with net advance also occurs. They observed that the behaviour correlates with the geological setting and coastal structures, such that:

- Glacial till cliffs retreat and cause inter-tidal steepening
- A sand veneer over a clay or chalk bed can give steepening through abrasion
- Deep non-cohesive sediment beds exhibit little steepening
- Beach control structures of all kinds are associated with steepening.

A view contrary to the last point was made in a later study of observed changes in salt-marshes, which did not find any clear correlation between coastal squeeze and the presence of sea defences (Carpenter and Pye 1996).

Similar evidence of beach steepening has been reported on the south coasts of England and Wales. In addition, several coastal councils from around the UK report steepening of their inter-tidal beaches. Further details are given by Soulsby et al. (1999).

3.2 Belgium

3.2.1 Introduction

Some general coastal characteristics are: a tidal range of ca. 4 m, an almost rectilinear coastline, a shallow offshore area which is characterized by the presence of numerous sand banks and gullies.

The coastal management policy is one of maintaining the safety level against flooding, mainly by "soft measures" such as beach nourishments, but taking into account the other functionalities of the coastal zone such as tourism and ecological values, by following an integrated approach.

3.2.2 Evidence

A detailed analysis of bathymetric and photogrammetric measurements has been carried out for a ca. 1.5 km wide strip along the coast, between approximately MSL +5 m and MSL -10 m (the beach, the nearshore zone and part of the gullies closest to the shore).

The analysis of the bathymetric measurements (of the nearshore zone and part of the gullies closest to the shore) showed that in the period between 1954 and 1998:

- In the central part of the Belgian coast (between Nieuwpoort and Blankenberge) the gullies have deepened (~1 m) and have moved landward (~100 m) (see Figure 3.2.1), resulting in a very important net sand-loss of ca. 47 million m^3 (about 1300 m^3/m or 30 m^3/m/year) of the area below Z=0 (see Figure 3.2.2)

- On the contrary, the eastern part of the Belgian coast (from Blankenberge to Knokke-Zoute) shows a very important net sand gain of 28 million m^3 (about 2500 m^3/m or 100 m^3/m/year) since 1976 (=beginning of the construction of Zeebrugge-harbour) of the area below Z=0 (see Figure 3.2.2)

- In the most western part of the Belgian coast (from De Panne to Oostduinkerke) some stable coastal compartments are observed (see Figure 3.2.2)

- There are indications that the seaward flanks of the gullies have been accreting (see Figure 3.2.1).

The comparison between the amounts of retreat/progradation for the beach on the one hand, between MSL +4.5 m and MSL -1 m (Z +7 m to Z +1.5 m) and for the nearshore zone on the other hand, between MSL -2.5 m and MSL -6.5 m (Z +0 m to Z -4 m), showed that in the past 10-20 years (see Figure 3.2.3):

- In the central part of the Belgian coast (between Nieuwpoort and Blankenberge), between 1992 and 1998, moderate steepening of the coastal profile occurred in almost all coastal compartments

- On the contrary, in the eastern part of the Belgian coast (from Blankenberge to Knokke-Zoute), between 1979 and 1998, flattening of the coastal profile occurred which is most prominent near the harbour moles of Zeebrugge, which were extended some 3.25 km into the sea in 1980-1986

- In the western part of the Belgian coast (from De Panne to Oostduinkerke), between 1986 and 1998, some coastal profiles have been moderately steepened and some others have been moderately flattened.

3.3 The Netherlands

3.3.1 Introduction

In 1990, the national parliament decided on a new coastal defence policy, which was termed as 'dynamic preservation'. The policy was aimed at enduring safety and sustainable development of all functional uses and natural values in the dune area (Koster and Hillen 1995). From this point onwards, the coastline would be maintained at a fixed position mainly by means of the flexible method of sand nourishments. Since 1990, the sand volume of the near shoreface is kept constant by means of sand nourishments. Research carried out for the second coastal policy document of 1995 indicated that although the sand volume of the near shoreface was kept constant, the deep shoreface seemed to be eroding. This could, in the long run, have consequences for the dynamic preservation policy and endanger the stability of the near shoreface. In 1996, a study on coastal steepening was initiated by the National Institute of Coastal and Marine Management of the Directorate-General of Public Works and Water Management (RWS-RIKZ), to assess the extent of deep shoreface erosion in terms of volume and location and to suggest an adequate coastal management policy.

3.3.2 Evidence

Studies on coastal steepening in the Netherlands have centred on the uninterrupted Holland coast (see Fig. 3.3.1) and have concentrated on determining the volume change of the deep shoreface (between 8 and 12 m below MSL) compared to the volume change of the near shoreface (between the dunes and 8 m below MSL).

Erosion and accretion rates for near shoreface and deep shoreface were determined by calculating volume change of morphologically homogeneous sections of coastline, as a trend over the last 30 years. Based on the accuracy estimates of the data, the statistical significance of the trend and an error were also determined. The data for the trends were obtained from profile soundings, which were carried out as part of RWS's regular monitoring program. Calculations were made on the central part of the Dutch coast, the so-called uninterrupted Holland coast (see Figure 3.3.1). Soundings for the deep shoreface were available from eight years (1965, 1970, 1975, 1980, 1885, 1990, 1993 and 1996). For the near shoreface yearly soundings were available from 1965 up to 1997.

Figure 3.3.2 shows the results of these trends. Volume calculations from previous studies for the Wadden coast and the Delta coast have been added to give a complete overview of trends along the Dutch coast. However, the data on which these trends are based are variable and nothing can be said about their statistical significance or their error.

For the Wadden coast a trend that can be noted is the erosion of the ebb tidal deltas. However, these estimates are based on little available data, and their statistical significance is still uncertain.

Regarding the Delta coast, accretion can be seen on the near shoreface and erosion on the deep shoreface. This is probably due to the closing of the tidal inlets by the delta works.

The recent studies have concentrated on the Holland coast. The general behaviour can be described in the following points:

- North of the harbour of IJmuiden, the Holland coast shows strong erosion both in the near shoreface ($0.5\text{-}0.7\times10^6$ m^3/year) and in the deep shoreface ($0.3\text{-}0.9\times10^6$ m^3/year). Erosion is statistically significant.

- South of IJmuiden the coastline shows a more variable behaviour, with accretion dominating the near shoreface ($0.3\text{-}0.5\times10^6$ m^3/year). The deep shoreface shows alternation of erosion and accretion, with erosion dominating ($0.4\text{-}0.6\times10^6$ m^3/year).

- Figure 3.3.3 shows these volume changes in terms of steepening, where steepening has been calculated as the difference between the retreat rate of the deep shoreface (-8 to -12 m relative to MSL) and the near shoreface (-8 to +3 m relative to MSL). Areas with highest steepening rates are the northern coastal sections of Den Helder and Callantsoog (ca 5 m/year and nearly 4 m/year respectively) and the southern section of Ter Heyde (nearly 4 m/year).

- The steepening rates have been translated to a percentage by the following procedure: 1) calculating the average slope from the distance of the 10 m below MSL isoline to the Dutch reference shoreline (i.e. the RSP-line); 2) assuming the MSL –10 m isobath moves shorewards at the rate determined by the difference between the retreat rate of the deep shoreface and the near shoreface; 3) calculating the change of the average slope as a percentage. Percentages of steepening vary between 0 and 0.2% per year for most of the Holland coast. For the northern 10 km steepening is between 0.4 and 0.6% per year. For the section of Ter Heyden, steepening is also approximately 0.4% per year.

3.4 Germany

3.4.1 Introduction

The German North Sea Coast can be divided into three regions. In the west between the Ems and Jade estuary are the East Frisian Islands and north of the Eider estuary to the island of Sylt are the North Frisian Islands. These islands are sheltering back barrier mudflats from the impact of the open sea. In the central part of the German Bight between the Eider and Jade Estuary open tidal flats occur, and here are located the estuaries of the river Elbe and Weser. The tidal range in the outer part of the German Bight is about 2-2.5 m. The tidal range increases in the inner German Bight and its estuaries up to 3-4 m.

The barrier islands and their foreshore area mainly consist of sand. In the inner German Bight between Heligoland and the estuaries of the big rivers is an accumulation area. It consists of mud with fine sand with a thickness greater then 10 m, except at the foreshore of Sylt and Amrum where moraines constitute the seafloor.

In the foreshore of the East Frisian Islands are several 10-30 km long and 2-5 m thick sand ridges in depths of -15 m to - 30 m. These lie above a Holocene layer which rises towards the coast. In the foreshore of the North Frisian Islands the older underlying geology is more structured and covered only by a thin layer of mobile sand.

A mapping of mobile sand in the German Bight shows a structure of 3 coast-parallel zones (see Fig. 3.4.1). Accordingly, a thickly covered zone with mobile sand (up to 10 m) extends from Wangerooge to Amrum (Jade, Weser, Elbe estuaries) in water depths less then -10 m. In comparison, on the shoreface of the East Frisian Islands and Sylt only a thin layer (0.4 to 1.5 m) of mobile sand was found in depth up to -15 m. This sediment deficit is responsible for the negative sediment budgets of some islands. The complete German Bight in depths between -15 and -20 m is covered with accumulated mobile sand (between 2 and 5 m thick). The origin of this sand is the adjacent zone close to the coast. The cross-shore transport is more significant than the long-shore transport (Zeiler, M. and K. Figge 1998).

3.4.2 Evidence

Surveys of the German Bight exist since 1950. In the Fifties and Sixties the measurements were repeated approximately every 10 years. More recent surveys are repeated at an approximately 5 year interval. Most surveys were carried out in the foreshore area from the low water line to the -10 m line, with only a few surveys in deeper water.

The surveys were mainly processed for shipping purposes. The necessary accuracy for morphological studies, including studies of coastal steepening, is often not achieved. An uncertainty of several decimetres due to an inaccurate method for the reduction to the reference level has to be taken into account.

In some local investigations a steepening of the profile was observed (see Fig. 3.4.4). A general trend at the East- and North Frisian Islands was supposed. Based on these observations, the KFKI-research project 'Morphologische Gestaltungsvorgänge im Küstenvorfeld der Deutschen Bucht' (morphological developments and processes in foreshore-areas of the German Bight) was initiated in 1995. It deals with the question of coastal steepening for the area of the German North Sea coast (from foreshore to -20 m) between the Ems-estuary and the Danish-German border. The detailed study is based on bathymetric data from the last 50 years. The project is not finished yet, but first preliminary results have been gained.

Surveys of the German Bight since 1950 indicate an increase of depths in the foreshore of the East Frisian (Ems to Jade) and North Frisian (Eiderstedt peninsula to Sylt) islands. The increase of depths occurs predominantly in depths between -5 to -10 m NN, resulting in a steepening of the profile (see Figs. 3.4.3 and 3.4.4).

The rate of increase in depth seems to be in the order of 1 cm per year. In the foreshore areas of the East Frisian Islands the rate seems to be greater than in the foreshore areas of the North Frisian islands. In the inner

German Bight between the Elbe and Eider estuaries sedimentation is observed. The increase in depth is associated with 'coastal steepening', especially if the shoreline is stable (e.g. by armouring or artificial beach nourishment).

Coastal steepening is apparent for different foreshore areas in Germany from long term data (profiles and sea charts). The steepening often is a local (site specific) phenomenon (examples for literature on local coastal steepening: Stephan et al. 1998, Jetses et al. 1999). Sound conclusions with respect to large scale trends might be possible in combination with the results of the research project indicated above.

Even if the analyses of the steepening seem to be clear (see Fig. 3.4.3 and 3.4.4), it cannot be excluded that the steepening is a result of insufficiently comparable measuring techniques or is within the uncertainty of the measurements. Statistical investigations have shown that the accuracy of older surveys, in particular, should not be overestimated. Open questions of the investigations are also the seaward limit of the deepening processes (closure depth) and the predominant accumulation areas (sand transport processes).

Attention:
All conclusions are limited by the poor quality of the available bathymetric survey data. A final answer to the question on coastal steepening cannot be given at this moment.

3.5 Denmark

3.5.1 Introduction

The Danish North Sea coast consists of a part with sandy beaches north of Esbjerg and the Wadden Sea coast to the south. Compared with other parts of the North Sea coast the tidal range along the Danish part is small. For the part north of Esbjerg the tidal range varies between 0.8 m to the south and 0.3 m at the Skaw Spit. For the Wadden Sea part the tidal range is 1.5-2 m. However, the wind waves are large, with a 100 year significant wave height of about 7.5 m at Thyborøn.

On the part of the coast north of Esbjerg the coastal protection works started at the end of the last century with the construction of a number of large sea groynes on both sides of the entrance to the Thyborøn Channel. The purpose was to stabilize the new channel formed when the North Sea broke through the narrow sand barrier in a gale in 1862.

The construction of groynes was continued in the first half of this century with the result that there are groynes on nearly the whole stretch between Lodbjerg and Fjaltring.

Apart from the construction of groynes, coastal protection was kept at a low level until the mid-70's. At this time funds for coastal protection were increased gradually and it became possible to initiate the construction of revetments and breakwaters just outside the coastline, and the first nourishment programmes were implemented.

Today the necessary revetments and breakwaters have been constructed between Lodbjerg and Nymindegab, so the only ongoing coastal protection measure is nourishment. The policy for most of the stretch is to stop or reduce the retreat of the inner part of the profile between the 6 m depth contour and the dune top. This is done by nourishment with a volume of sand equal to the autonomous erosion in this zone. The total nourishment volume is about 3 mill. m^3 of which 84% is dredged at 20-22 m depth outside the stretch.

3.5.2 Evidence

Profile steepening has been an important issue among Danish coastal engineers since the 1930's. The reason is that the construction of the groynes at Thyborøn caused a gradual steepening of the coastal profiles, see Fig. 3.5.4. Many feared that the steepening would end with a disaster, and plans were made for a closing of the entrance to the channel. However, in the 1950's new analyses and investigations were made, indicating that the steepening of the profiles was just an adjustment to the reduced coastline retreat. Based on this realization the plans for closing the entrance were abandoned.

For these historical reasons, steepening has always been an issue in the status reports prepared for the different parts of the Danish North Sea coast (Kystinspektoratet 1975 and 1999). Fig. 3.5.3 is taken from the latest report about the coast between Lodbjerg and Nymindegab (Kystinspektoratet 1998). For coastal sections each 3-5 km long, the retreat rate for the inner part of the profile (-6 - +4 m) is compared with the retreat rate for the outer part of the profile (-15 - -6 m). For cases where the first is the smaller, the profile has become steeper in the considered period of time.

For the period 1977-86 the steepening is seen mainly on the northern part of the stretch due to the groynes. In the period 1986-96 where the nourishment has been intensified the steepening has been extended to the nourished stretches further south. The average annual steepening is about 0.4% and the maximum is 1%. As can be seen, there are many deviations from the general trend. By a more thorough analysis of the individual sections of the coast it will probably be possible to explain many of the deviations.

Profile steepening has also been analysed for a section of the coast at Lønstrup (Laustrup et al. 1994), see Fig. 3.5.1. On this section a revetment and breakwaters were constructed in 1982-83. Initial nourishment in 1983 has been supplemented with annual nourishment ever since, so it has been possible to maintain the 1982-83 coastline position. As can be seen in Fig. 3.5.2, the effect has been a steeper inner part of the profile.

As it appears, the cause for profile steepening at some parts of the Danish North Sea coast is assumed to be the fact that the coastline zone is kept at a fixed position by structures, nourishment or a combination thereof. However, other possible causes have been considered.

In order to evaluate the possible effect of oil and gas extraction, Niels Peter Christensen, Head of Reservoir Geology, Geological Survey of Denmark and Greenland was asked to study the problem. Based on this study he came up with the following statement: "For the Danish North Sea coast the distance to the extraction areas is more than 200 km. The local subsidence in these areas has no effect on the Danish coast".

The dredging of nourishment sand at 20-22 m depth is another possible cause. Over the years, the depth limit for how close to the coast it has been acceptable to dredge has been pushed from 10 m in the 1970's to 20 m today. Whether this limit is far enough away from the coast to avoid steepening and/or increased profile retreat is not completely clear. However, the effect if any is small. It is the hope that some of the studies presently in progress at Kystinspektoratet will clarify this problem, see section 5.5.3.

4. Main physical causes of coastal steepening

4.1 Introduction

This chapter gives an overview of the possible physical causes for coastal steepening. In general it is difficult to attribute coastal steepening to one single factor (e.g. sea-level rise). This is reinforced by the fact that the term 'steepening' has been used to describe slightly different phenomena along the North Sea coasts, such as erosion of the shoreface (5 to 10 m below MSL) and ebb tidal deltas of the German Wadden islands, the deepening caused by gully migration along the Belgian coast, the erosion on the shoreface of the uninterrupted Dutch coast (between 8 to 12 m below MSL) and the narrowing of the U.K. inter-tidal zone. In this chapter several factors have been listed, both natural and man-induced. Most of them are hypotheses in various stages of verification. Some of these items are fairly consistent hypotheses, while some are reinforcing effects, and still others are factors with a very local effect. In the following, each cause will be briefly described and an assessment will be made of its contribution to coastal steepening. The conclusions are given at the end of the chapter.

4.2 Keeping the coastline at a fixed position

The widely hold explanation for coastal steepening is that when retreating coastlines are kept at a fixed position, by hard or soft engineering (e.g. dykes or sand nourishments), the retreat of the near shoreface is slowed while the retreat of the deeper shoreface continues at the same pace. In this case coastal steepening would be a symptom of a receding coastline artificially maintained in place. This is probably the case for the Thyborøn barrier (Denmark) even after coastal recession had been countered by groynes and for other parts of the Danish coast which have been protected by nourishments.

Along the Dutch coast, only some areas of deep shoreface erosion and near shoreface accretion correlate with the areas protected by groynes (only the areas between Den Helder and Petten and between Scheveningen and Hook van Holland are protected by groynes). Furthermore, research carried out in the UK into the observed changes in salt marshes, particularly those on the North Sea coast, did not show any clear correlation between coastal squeeze and the presence of defences (Carpenter and Pye 1996), although earlier research (Halcrow and partners 1988) had suggested some correlation.

4.3 Effects of dams and harbour moles on tidal currents

Constructions protruding into the sea, such as harbour moles, have two effects on the shoreface profile:

- Accretion of the near shoreface due to blocking of longshore sand transport
- Erosion of the deep shoreface due to converging of tidal flow at the upstream side of the construction (van Rijn 1997).

As a rule of thumb, the influence of harbour moles on the local currents extends for a distance along the coast of approximately seven times the length of the mole.

If the whole profile is considered, steepening will be observed due to a combination of nearshore accretion and deep shoreface erosion. The area around the harbour moles of IJmuiden serves as an example of this. They have been constructed in the middle of the Holland coast and extend roughly 2000 m into the sea. This could be the cause of the erosion of the deep shoreface, along 10 to 15 km north and south of these harbour moles (Van Rijn 1997). If, on the other hand, only the near shoreface is considered, a flattening of the coastal profile may be observed due to accretion, e.g. the case of the Zeebrugge harbour (section 3.2).

4.4 Decrease of sand supply

A reduction in the sand supply from the rivers, due to e.g. damming, leads to erosion of the adjacent coast (well known examples include erosion along the Israeli and Egyptian coasts by sand entrapment by structures in the Nile (Golik 1997)). If this reduction does cause steepening, it should affect the deeper part of the profile. However, it is uncertain if this coastal recession is really accompanied by profile steepening, and, if so, what mechanism would be responsible for this. Moreover the sediment load from the North Sea rivers (Rhine, Meuse and Scheldt) has always been relatively small - even during the Holocene transgression they contributed little to the progradation of the Dutch coastline (Beets et al. 1995). Therefore this is unlikely to be a cause for the coastal steepening along the North Sea.

4.5 Sand extraction

Sand and shingle extraction for commercial purposes generally occurs at depths greater than 15 m below LAT in the UK and 20 m below MSL in the Netherlands and Denmark. Sand extraction for maintenance dredging of harbour entrances occurs at smaller depths. Recent studies on the morphological behaviour of sand pits (Walstra et al. 1998) and of harbour entrances (Hoitink 1997) seem to indicate that their effect is confined to their immediate surroundings. Walstra et al. (1998), using model simulations, conclude migrations of 260 to 800 m (depending on the water depth) in 50 years. Hoitink (1997) indicates that morphological activities of the Euro Maasgeul (the approach channel for Rotterdam main port) will be restricted to a strip of 300 m at either side of the channel for the next 50 years.

4.6 Increased wave penetration

Once the shoreface evolves to a steeper profile, this development may be reinforced by the following process: a steeper profile leads to an increased wave penetration resulting in a winnowing of fine sediments. As a consequence, beach sediments become coarser and the beach profile becomes steeper. It is uncertain whether this steepening is accompanied by coastal retreat. The hypothesis has not been verified up to present; indeed, in some publications (Halcrow and partners 1988) coastal retreat even seems to correlate better with tidal currents than with wave energy.

4.7 Subsidence due to extraction of oil and gas

Oil and gas extraction occurs in several off-shore areas of the North Sea, but also in some nearshore and on-shore areas such as the Frisian tidal inlet, the Groningen gas field and the Slochteren gas field (both in the

Netherlands). Oil and gas extraction will cause subsidence, which progresses gradually taking the shape of a flat dish. The rate of subsidence is affected by many factors, among which is the subsurface stratigraphy. Model calculations for the Slochteren field, which is by far the largest gas field of the Dutch continental platform, have given estimates of a maximum subsidence of 20 to 30 cm in the period of 20 to 40 years (Louters and Gerritsen 1994). There seems to be no subsidence due to the exploitation of this gas field beyond a radius of approximately 35 km. Most of the other gas fields have a much smaller production (by a factor 20), will cause less subsidence, and will have a much smaller area of influence. Recent research (Oost et al. 1999) seems to indicate that the subsidence in the Dutch Wadden Sea is largely compensated by sediment transported to the Wadden Sea from the islands and the ebb tidal deltas. Therefore, oil and gas extraction does not seem to be coupled with coastal steepening.

For the Danish oil and gas extraction there is no effect on the Danish coast because the distance to the coast is more than 200 km.

4.8 Increased cross-shore transport induced by decreasing sea-level rise

In considering natural causes for profile steepening, sea-level rise is often proposed as a possible agent. For this to happen it is important that a combination of two factors should occur: a decreasing rate of sea-level rise and a coastline that naturally (e.g. fixation through vegetation) or artificially (e.g. groynes) remains in place instead of receding according to the Bruun rule. When these two factors happen, the so-called active part of the profile becomes relatively narrower, while the deep shoreface zone becomes relatively larger. The decreasing rate of sea-level rise allows sediment on the deeper part of the shoreface to be transported to the near shoreface by cross-shore transport (second-order Stokes wave-asymmetry and also salt water upwelling). The erosion of the deep shoreface and accretion on the near shoreface result in a steepening of the whole profile. Stive and de Vriend (1995) verified this hypothesis using a panel-type model and applied it to both the recent evolution (1898-1975) and the long term evolution (5000-2200 years BP) of the uninterrupted Dutch coast. It is considered (Stive, pers. comm.) that despite the long-term nature of this effect, it can be recognised in the sediment budget of the Dutch coast of the last 30 years.

4.9 Conclusions

In this chapter several possible causes of shoreface steepening have been examined. They are summarized in Table 4.9.1. The group responsible for the present report could not find any of them conclusive. The most probable effects are keeping the coastline at a fixed position, an increased cross shore transport induced by decreasing sea-level rise, and dams and harbour moles. Other reasons such as decrease of sand supply, oil and gas extraction and sand extraction were considered less probable.

Table 4.9.1 Possible causes of coastal steepening.

Factor	Contribution to Steepening	Observed Location	Local/General
keeping coastline at a fixed position (by hard or soft defences)	possible; hypothesis does not always correlate with observations	Thyborøn barrier (Denmark)	general/local
dams and harbour moles	possible; hypothesis correlates with observations	IJmuiden (The Netherlands)	local
decrease of sand supply	not probable	not observed	general
sand extraction	not probable	not observed	local
increased wave penetration	possible, not verified	not observed	general
oil and gas extraction	not probable	not observed	local
increased cross shore transport induced by decreasing sea-level rise	possible; hypothesis verified by model	Holland coast south of IJmuiden (The Netherlands)	general

5. Significance and time scale in each country

5.1 The United Kingdom

5.1.1 Introduction

The UK regulatory authorities for coastal flood defence and erosion (MAFF and Environment Agency) are conscious of the potential impact of coastal steepening/inter-tidal narrowing on flood defence and habitats. They perceive that coastal steepening makes defence more difficult, possibly unsustainable, and affects operational management decisions. This occurs because increased wave penetration leads to greater wave overtopping, beach erosion, and damage to, and undermining of, coastal defence structures such as sea-walls, breakwaters and rock groynes.

Narrowing of the inter-tidal zone also leads to squeeze of habitats, which is a major concern in view of the Habitats Directive. In many cases there is a conflict of socio-economic pressures with technical pressures (e.g. the best technical solution to a problem may not be acceptable to the populace environmentally, or may be in breach of law relating to Habitat Directives).

5.1.2 Effects after 20 and 50 years

Allsop et al (1995) performed tests in a wave flume that showed that damage to beach control structures is significantly increased by steep (local) beach slopes, even for simple slopes subject to normal wave attack. Their conclusion is supported by field measurements of the damage done to almost identical rock groynes at Barton-on-Sea and Milford-on-Sea (only 5 km apart on the south coast). The inshore wave climates are similar but the groynes at Milford-on-Sea, where the foreshore has a slope of 1:25, suffered much more damage than those at Barton-on-Sea where the foreshore slope is only 1:90.

Hawkes et al (1998) performed a series of laboratory tests to measure the overtopping of, and damage to, coastal structures, which included the effect of varying the local beach slope in front of the structure. Figure 5.1.1 shows the overtopping rate against beach slope for three wave conditions.

In all cases the overtopping rate increases with beach slope up to a steepness of between 1:20 to 1:10, and is then approximately constant for greater slopes. Figure 5.1.1 also shows the percentage damage to the structure for eight wave conditions, each of which propagated over beach slopes of 1:20 and 1:50 before reaching the same structure. In all cases the steeper beach slope gave a substantially greater amount of damage.

Numerical models have been used to investigate the effects of differences in the steepness of the beach slope in front of a seawall on the overtopping rate, damage and undermining potential. The layouts for these tests are shown in Figure 5.1.2. A combination of two numerical models were used: COSMOS-2D to model wave propagation from a point 3 km offshore up to the vicinity of the seawall, and the newly-developed research model OTT to model the run-up and overtopping behaviour within the last 120 m.

The key results are shown in Figure 5.1.2. The upper part shows the variation in bathymetry, and the wave height distribution determined by COSMOS-2D, for six approach beach steepnesses between 1:200 and 1:20, with offshore significant wave height of 8 m, and mean water level 3 m above the toe (10-year return period conditions). Decreased dissipation on the steeper approaches causes the significant wave height at 120 m (the start of the OTT run) to increase from 2.54 m to 6.64 m. The middle panel shows that the mean overtopping rate increases markedly as the beach slope in front of the structure steepens, from almost zero at 1:200 slope to 0.54 $m^3/m/s$ at 1:20 slope. The bottom panel shows that the maximum velocity at the mid-point of the structure (U_{max2}), and the r.m.s. velocity at the toe (U_{rms1}), both approximately double as the beach slope increases from 1:200 to 1:20. This is an indication that both structural damage and toe-scour will be greatly increased if the adjacent beach steepens.

As an illustration of the effects of coastal steepening on coastal flood defence, consider the results of the above modelling study applied to a part of the North Sea coast with a spring tidal range of 4 m, an initial inshore slope of 1:100 and a narrowing of the inter-tidal zone of 2 m per year (typical values). Taking the modelled conditions, we find that after 20 years of coastal steepening the mean overtopping rate is 25% larger, the maximum midpoint velocity is 1.9% larger, and the toe r.m.s. velocity is 3.3% larger. The corresponding increases after 50 years are 75%, 5.7% and 9.7%. Thus, bearing in mind that damage and scour increase as a high power of velocity, there could be adverse consequences for flood defence as a result of coastal steepening if the defences are not improved.

Further details of the laboratory and computational modelling studies are given by Soulsby et al (1999).

5.1.3 Past, present and future research

To the author's knowledge, there have been no generic research projects specifically on coastal steepening in the UK to date, although some regional studies have considered it (section 3.1.1).

Nor do there appear to be any research projects specifically on coastal steepening approved for imminent funding from UK sources at present. MAFF and the Environment Agency recently commissioned a report (Penning-Rowsell 1998) into research needs for flood and coastal defence. Coastal steepening was not specifically identified as one of these needs, but it could be part of a wider theme of Long-term Macro-scale Sediment and Morphological Processes.

There are also some other broad-scope proposals (either suggested or submitted) and recently approved projects that could include coastal steepening as an element of study:

- Environment Agency (Anglian Region) are making offshore bathymetric surveys to a depth of –10 m at 5-year intervals (Environment Agency 1997), which they will analyse when there is sufficient data.

- Coastal sediment super-budgets (MAFF). A proposed new study, by HR and BGS, into the "lifetime" of beach sediment, including its "birth" (sources), transport along the coast and eventual "death", e.g. losses into estuaries, or to the offshore seabed.

- Southern North Sea Sediment Transport Study – Phase 2. A possible extension to an earlier study funded by MAFF via Waveney DC to determine seabed sediment transport pathways from a variety of types of evidence. Partners include Environment Agency, coastal authorities, Crown Estates.

- FORCE and OC4Z. Projects within the Core Strategic Programme (1999-2004) of NERC, designed to improve the present ability to predict the evolution of coastal morphology and biology over a range of scales, in response to climate change, coastal erosion, flooding and policies of flood defence.

- INDUS. A NERC/DTI LINK project to develop a new technique for measuring beach profiles by using SAR images to determine the boundary between land and sea as the tide rises and falls.

5.1.4 Management considerations

Coastal steepening is not commonly tackled as a management problem *per se*, but rather as a localised part of an erosional problem. Coastal erosion (where it has implications for coast defence) is tackled more strategically.

There is strong evidence that coastal steepening is occurring within the inter-tidal zone (at least) along many parts of the east, south and west coasts of the UK. Beach erosion is both a symptom and a consequence of coastal steepening. The findings from field data, laboratory data and numerical modelling all indicate that over time this will lead to greater overtopping, damage, and undermining of sea defences. Although this only becomes significant on time-scales of 20 to 50 years, other factors such as sea-level rise, increased storminess, increased storm surge and tidal levels, may combine with steepening to increase the vulnerability of beaches and defences.

5.2 Belgium

5.2.1 Past, present and future research

The results of the present study of the morphological changes of the near-shore zone, which are presented in section 3.2, have led to the planning of further investigations:

- a further analysis of the bathymetric and topographic measurements seaward and landward (on the beaches) of the studied zone
- trying to make long-term and global sand-budgets ("missing volumes": dredging works, sand-extraction of the sandbanks, changes in the volumes of the beaches, dunes...)
- considering the need for a change from an "ad hoc" nourishment policy to a more strategic, long-term policy.

5.2.2 Management considerations

Coastline managers are concerned about the observed sand losses in the nearshore and upper seabed zone, because it is felt that this could increase the erosion rates of the beaches and it could increase wave conditions at coastal structures resulting in higher costs for maintaining the beaches and higher risks for damage caused by storms. However, due mainly to a lack of understanding of the causes and effects of the observed sand losses in the nearshore and upper seabed zone, no changes of coastline management strategy have been considered until now.

5.3 The Netherlands

5.3.1 Introduction

It is important to assess the consequences of deep shoreface erosion for the actual policy of dynamic maintenance. As yet there is no conclusive evidence that there are negative consequences for coastal zone management. Consequences will be considered negative if they affect coastal safety or coastline maintenance. According to the coastline maintenance policy, part of the near shoreface is maintained by sand nourishments. Nourishments compensate the sediment volume lost through erosion. Compensating losses in the near shoreface, however, does not re-establish the whole equilibrium profile. It is considered that erosion of the deep shoreface of the uninterrupted coastlines will increase nourishment losses and therefore decrease nourishment efficiency.

5.3.2 Future research

Future research is being conducted in several areas:

- Studying the behaviour of shoreface nourishments; a less costly option than beach nourishments. Research will be conducted within the framework of the MAST-SAFE programme.

- Research to gain insight into processes, by a combination of process-based modelling and field measurements. Specific effort will be made in understanding the processes in the tidal inlet south of Texel.

- Data analysis and case-studies to understand long term coastal behaviour. These include:

    - Case-studies based on 30 years monitoring data (i.e. the extension of the harbour moles of IJmuiden, the effects of the Delta works) to use as calibration/validation cases for models.

    - Data gathering of the geological development of the Holland coast, based on the work of Beets et al. (1995). This study will increase the insight into the natural evolution of the closed coastline in terms of temporal and spatial amplitude of erosion-accretional phases, and evolution of the equilibrium profile under the influence of sea-level rise.

5.3.3 Management considerations

Regarding coastal management policy of the deep shoreface, three options are being considered:

- Compensation of the near shoreface: this is the continuation of current policy; erosion is compensated with some efficiency losses. In accounting for these losses by using an efficiency factor, erosion of the deep shoreface is compensated up to some measure.

- Compensation of near shoreface and deep shoreface erosion: the whole shoreface is nourished and an equilibrium profile is maintained. Nourishment of the deep shoreface does not require an efficiency factor.

- Compensation of near shoreface, deep shoreface and erosion of some of the ebb tidal deltas: this is the most extensive nourishment option and the most proactive; therefore the safest.

In 1995 it was decided to compensate deep shoreface erosion. However, a definite choice between these three policy options has yet to be made.

5.4 Germany

5.4.1 Introduction

There is an awareness in Germany that coastal management problems might be amplified by ‘coastal steepening’, but there is no short term significance concerning the possibility of large scale and long term (structural) coastal steepening at this moment. There might be consequences for coastal managers, if the KFKI-research project (see above) does provide sound results which quantify coastal steepening, or even shows an acceleration of the steepening phenomena.

5.4.2 Past, present and future research

A research project dealing with the question of coastal steepening is the KFKI FV „Morphologische Gestaltungsvorgänge im Küstenvorfeld der Deutschen Bucht". It was initiated after some local investigations have shown steepening. The project is a cooperation of the Coastal Research Station Norderney, the ALR Husum and the Bundesamt für Seeschiffahrt und Hydrographie, Hamburg. The aim of this KFKI research project is to explain the morphodynamics in the shoreface of the German Bight. In the programme running from 1996 probably to June 2000 extensive sea surveys are being examined. First results of this programme are listed above.

Regarding the problem of coastal steepening and the management considerations, related research projects are NOURTEC, investigations of beach and foreshore nourishments on Sylt island, an attempt of combined protection system (groynes, seawall, nourishment) on Norderney island and the reinforcement of foredunes (management retreat of the shoreline) on Borkum and Langeoog islands.

5.4.3 Management considerations

An example of a change in coastal protection strategies is the north eastern part of the East Frisian island Borkum. Strong shoreline erosion at the north-eastern part of Borkum occurred during the last decades. A retreat of the coastlines and dunes of approximately 500 m in the next fifty years is expected. The morphological changes of this part of the island with its foreshore areas are predominantly caused by the alteration of the flood- and ebb-stream channel system as the development of the channels results in an intensified strain. It is shown that in this case, coastal protection with sand nourishment or even solid engineering constructions are not favourable; consequently a renunciation of shoreline protection is suggested for the near future.

Local effects of coastal steepening, like the examples listed above, lead in Germany to related management responses, which increasingly integrate different aspects according to the basic principles of a CZM-process.

5.5 Denmark

5.5.1 Introduction

The problems arising from coastal steepening are due to the fact that the wave impact on the inner part of the profile increases with a steeper profile. This means that the design conditions used for groynes, breakwaters, revetments and nourishment can be outdated after some years. This effect is illustrated in Fig. 3.5.4. It appears that the average profile slope between the coastline and 10 m depth at Thyborøn has changed from 1:100 in 1940 to 1:50 today.

5.5.2 Steepening effects after 20 and 50 years

The way to combat the effects of profile steepening will either be by a reinforcement and enlargement of the coastal structures, or by nourishment to counteract the steepening itself, at least in the inner part of the profile. Because of the intensive nourishment on the Danish North Sea coast today, the appropriate solution to the Danish steepening problems is considered to be increased nourishment. The ultimate solution will naturally be an increase of the nourishment volume, so the loss in the whole active profile is compensated. However, this is not for the time being a politically realistic option. Therefore, it is more relevant to calculate the annual nourishment volume in the future based on the assumption that the present nourishment strategy will be continued, see section 3.5.1, and that the steepening observed in the last 10 year period continues.

If the autonomous profile retreat rate between dune top and –16 m is r and the initial profile slope is 1:110, the profile slope after y years will be:

$$20 \text{ m} / (2200 \text{ m} - y \times r) = 1 / (110 - (y \times r) / 20)$$

With r = 5 m/year it gives the following results:

Time	Slope
0 years	1:110
20 years	1:105
50 years	1:97.5

To get an impression of the change of the longshore sediment transport and with that the profile erosion due to the change of profile slope, a formula saying that the longshore sediment transport is proportional to the square root of the bed slope is used (Deigård et al. 1986):

$$Q_l = k \times \tan\beta^{0.5}$$

It means that the profile in the example after 20 years with a slope of 1:105 has a 2.4% larger longshore sediment transport than the profile with a slope of 1:110 and the profile after 50 years with a slope of 1:97.5 has a 6.2% larger longshore transport. The increases of the nourishment volumes are similar.

The longshore sediment transport has also been calculated by the use of the module LITDRIFT from the hydrodynamic model complex LITPACK developed by Danish Hydraulic Institute. The future profiles used in the model were constructed by multiplying the distances from the coastline to points in the initial profile with an appropriate constant so the new slope is correct. The wave climate and grain size distribution used were the actual for the site. The increases in the longshore sediment transports calculated in this way were nearly identical to the ones found by the use of the simple formula. However, these calculations shall only be considered to give an indication of the order of magnitude of the effect of profile steepening. More analyses and calculations will be necessary to reach more reliable results. For instance an analysis of how the steepening develops in details and how the grain sizes change accordingly, will improve the basis for the model calculations.

5.5.3 Past, present and future research

The analysis of the steepening at Thyborøn mentioned in section 3.5.2 was included in Per Bruun's doctor's thesis (Bruun 1954). Also Helge Lundgren and Torben Sørensen contributed to the understanding of the problem. Besides this research Kystinspektoratet has no knowledge of past or present Danish research into the topic.

A package of studies related to coastal steepening is in progress at Kyst-inspektoratet:

- An overall sediment budget for the North Sea coast based on volume calculations. The calculations have shown large erosion volumes in the outer part of the profiles. It is not clear which mechanisms can explain the transport of those volumes.

- A study of the sediment movement in the offshore zone aims to model the combined current and wave forces acting on the sediment using prototype measurements of current and waves.

- A study focused on the migrating bed forms outside 8 m depth. The bed forms will be analysed geologically.

- An overall geological mapping of the zone between the dune top and 25 m depth will also be undertaken. With more information about the history of the sand formations, we hope it will be possible to trace the patterns of the sand.

5.5.4 Management considerations

Kystinspektoratet's attitude towards coastal steepening is expressed in the status report to the government and the local authorities issued 1998 concerning the central part of the Danish North Sea coast (Kystinspektoratet 1998). In English translation the following is written: ”Steepening is a process, which develops slowly. It has been recognized for the land spits of Thyborøn for the last 135 years and the population should not be alarmed because of this process. Kystinspektoratet intends to initiate further investigations of the steepening in the coming years”. Some of these investigations are already in progress, see section 5.5.3.

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The United Kingdom

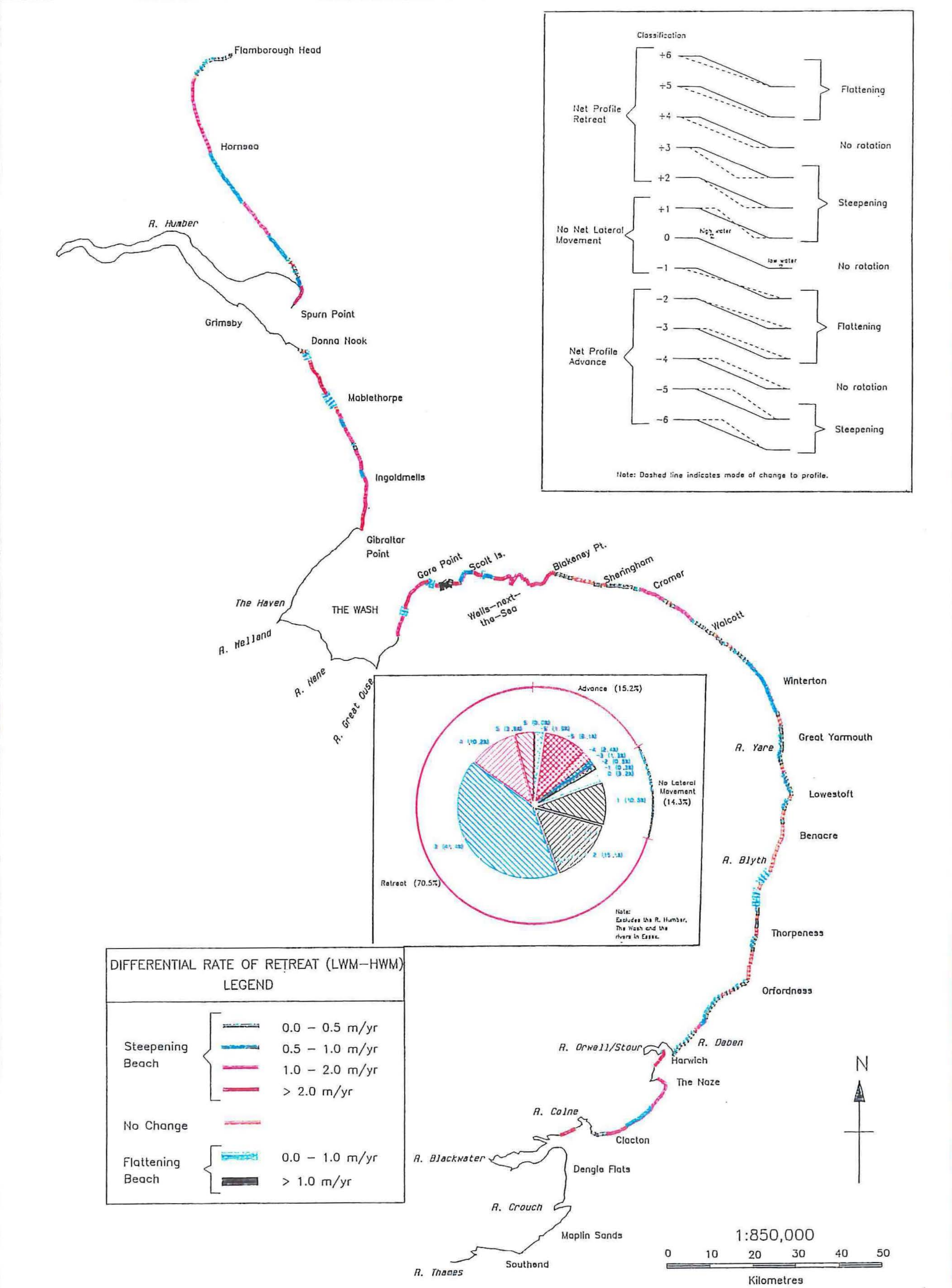
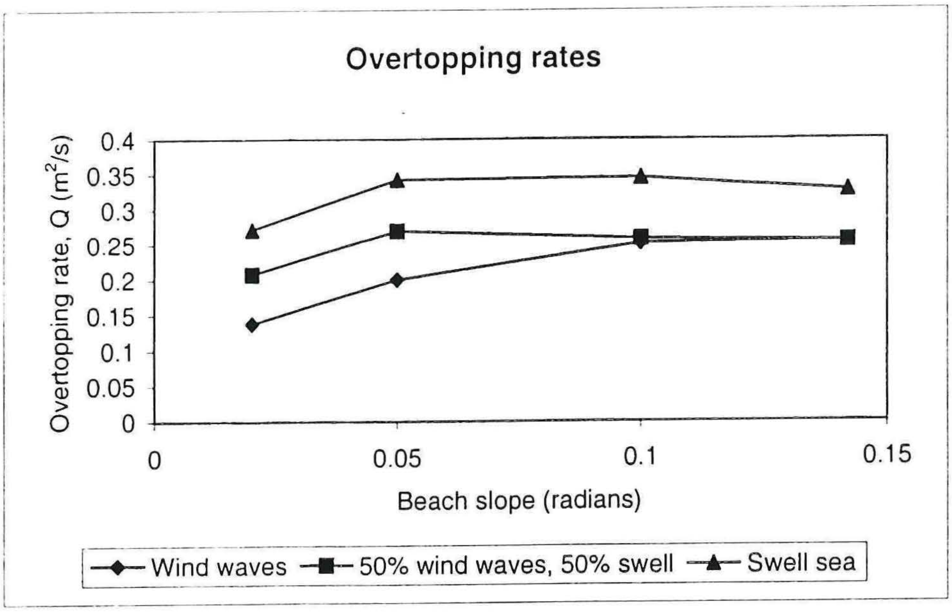


Fig. 3.1.1 Changes of intertidal width, Anglian coast, approx. 1870 – 1970. Adapted from Sir William Halcrow & Partners, 1988a,b

The United Kingdom



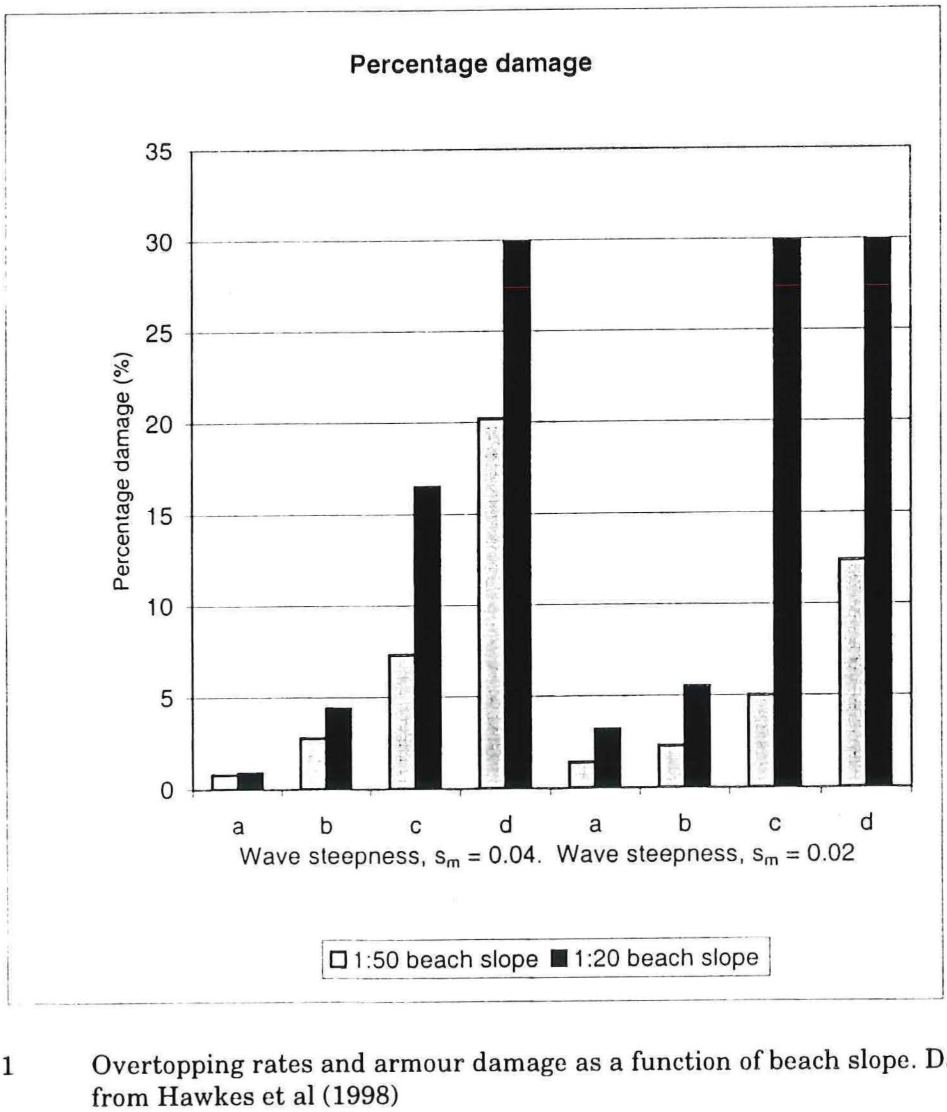


Fig. 5.1.1 Overtopping rates and armour damage as a function of beach slope. Data taken from Hawkes et al (1998)

The United Kingdom

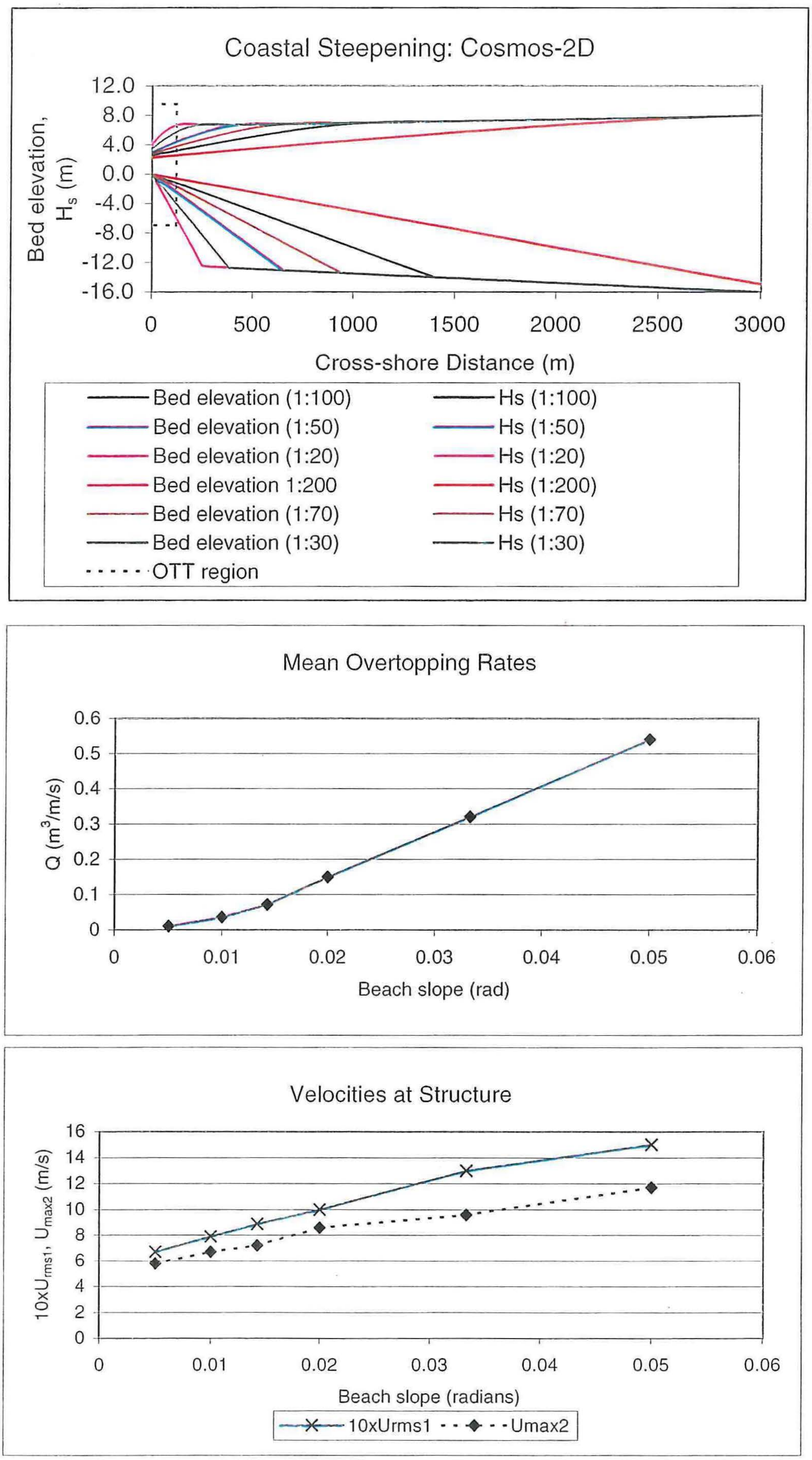


Fig. 5.1.2 Bathymetries, wave-heights, overtopping rates, and orbital velocities from runs of the COSMOS-2D and OTT models

Belgium

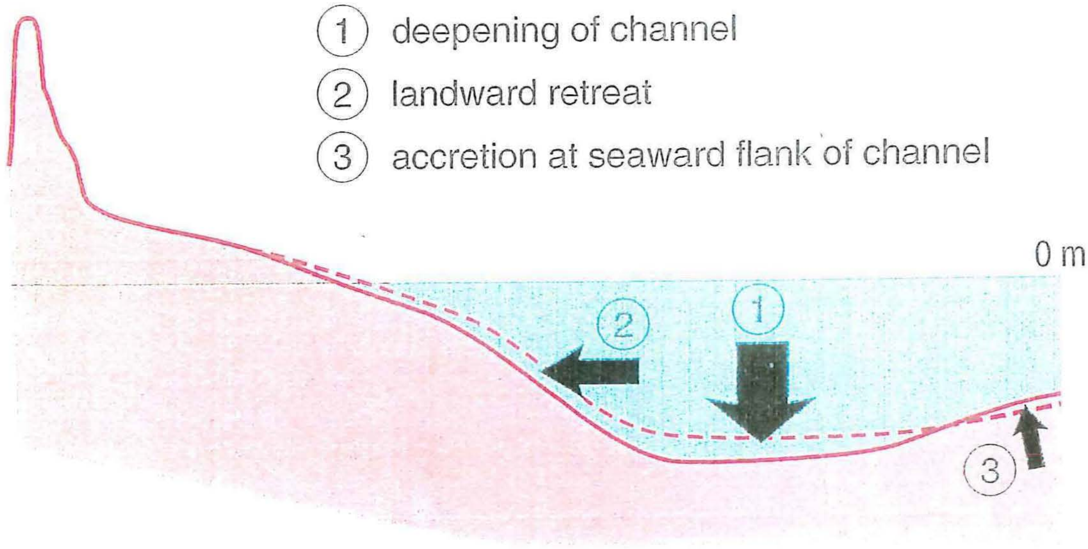


Figure 3.2.1 Observed morphological changes of Belgian nearshore and upper seabottom in the past 30-40 years. The sizes of the arrows are proportional to the net volumes of transported sediments.

Belgium

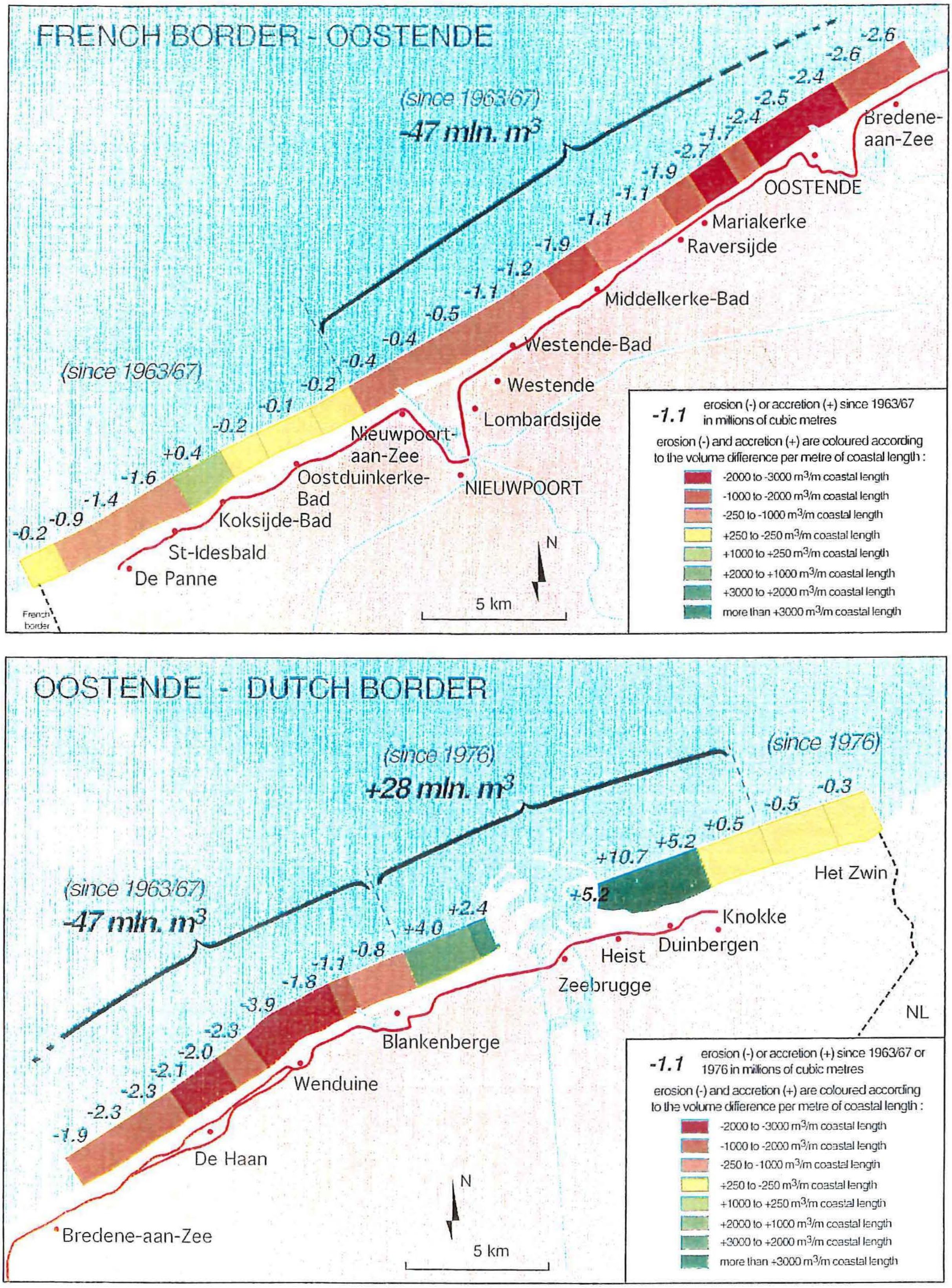


Figure 3.2.2 Volume differences of nearshore and upper seabottom between 1963/67/76 and spring 1998.

Belgium

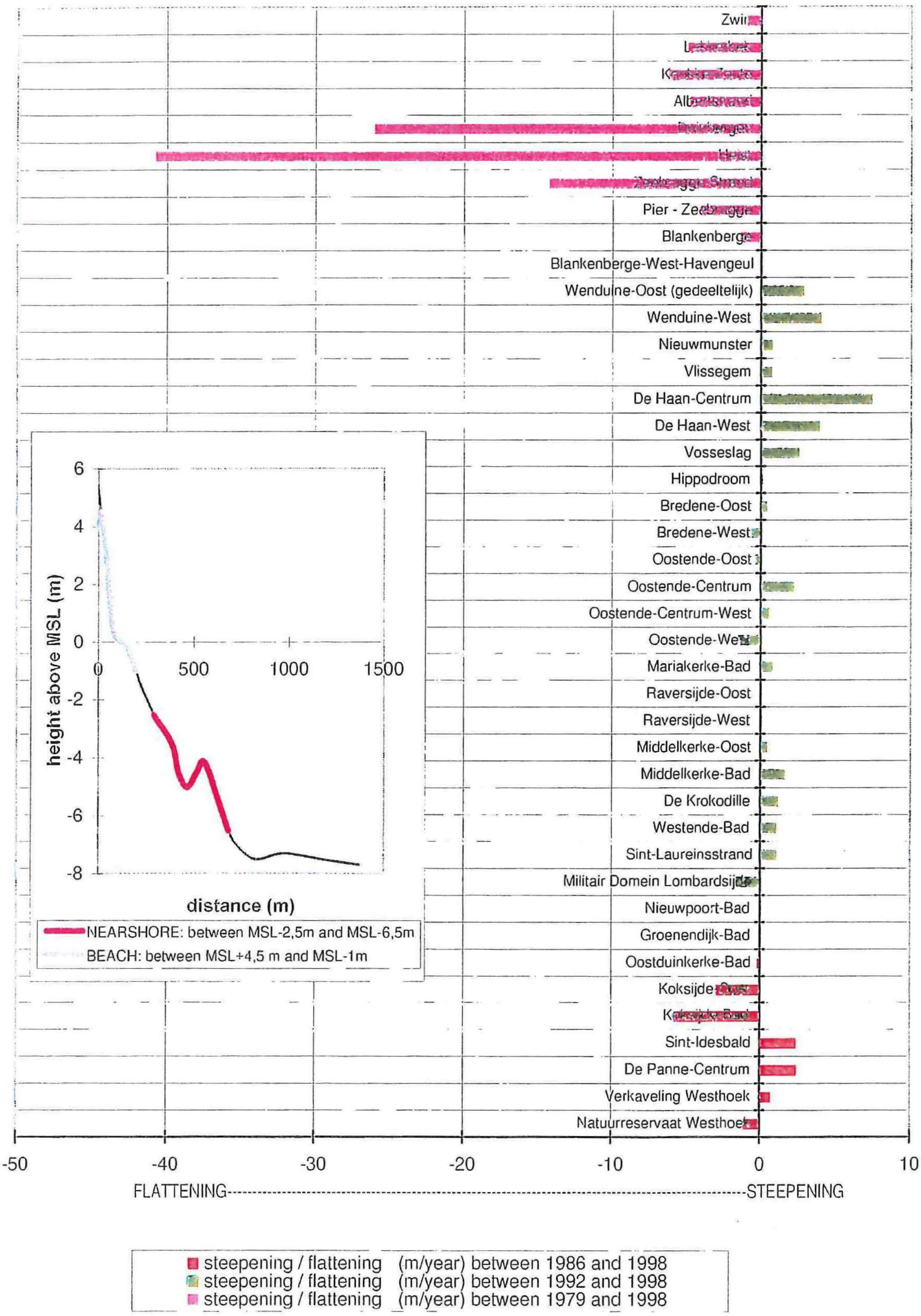


Figure 3.2.3 Profile steepening/flattening calculated as the difference between the retreat/progradation rates of the beach and the nearshore.

The Netherlands

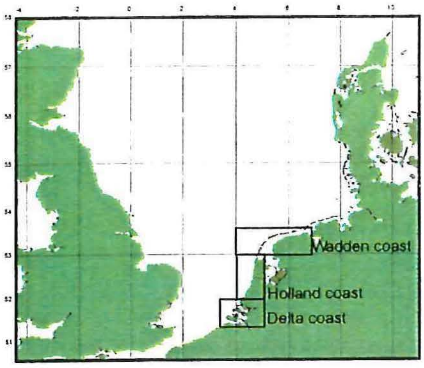


Figure 3.3.1 Situation map, showing the three morphological units of the Dutch coast

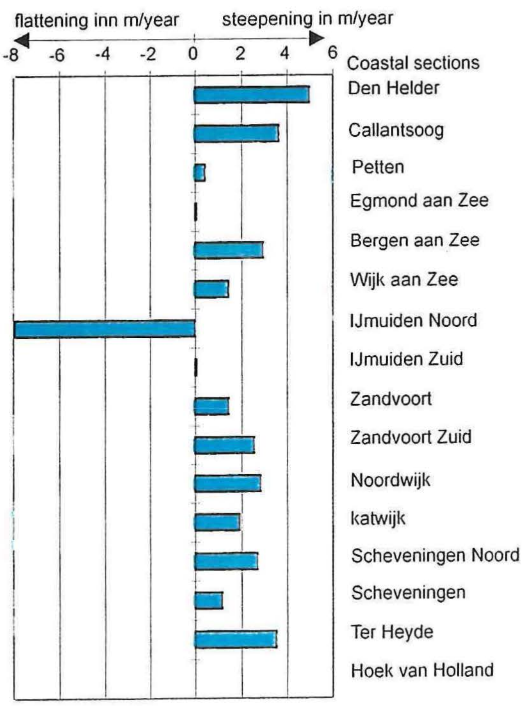


Figure 3.3.3 Profile steepening for the Holland coast; calculated as the difference between the retreat rate of the deep shoreface (-12 to -8 with resp. to MSL) and nearshoreface -8 to +3 with resp. to MSL)

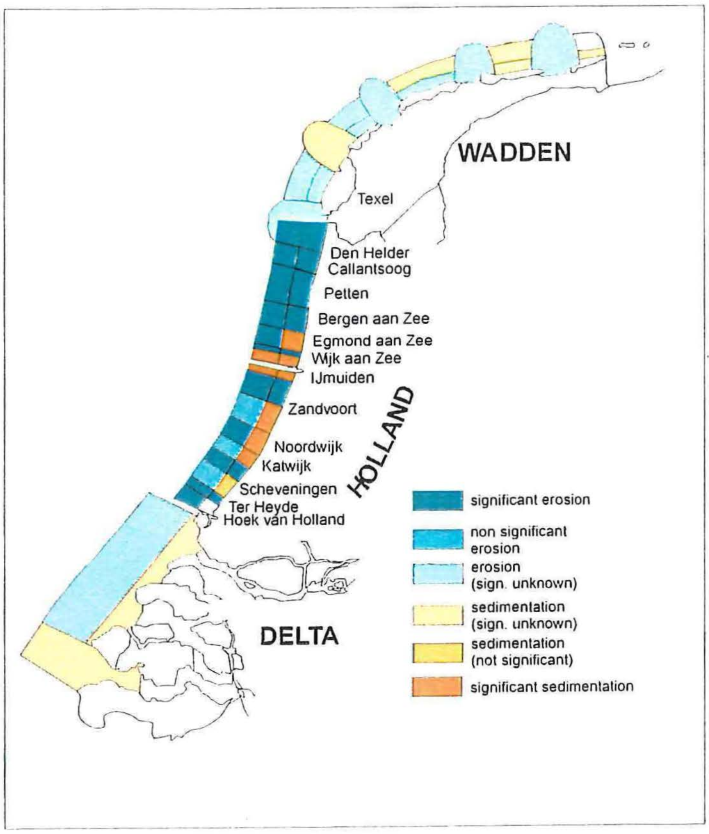
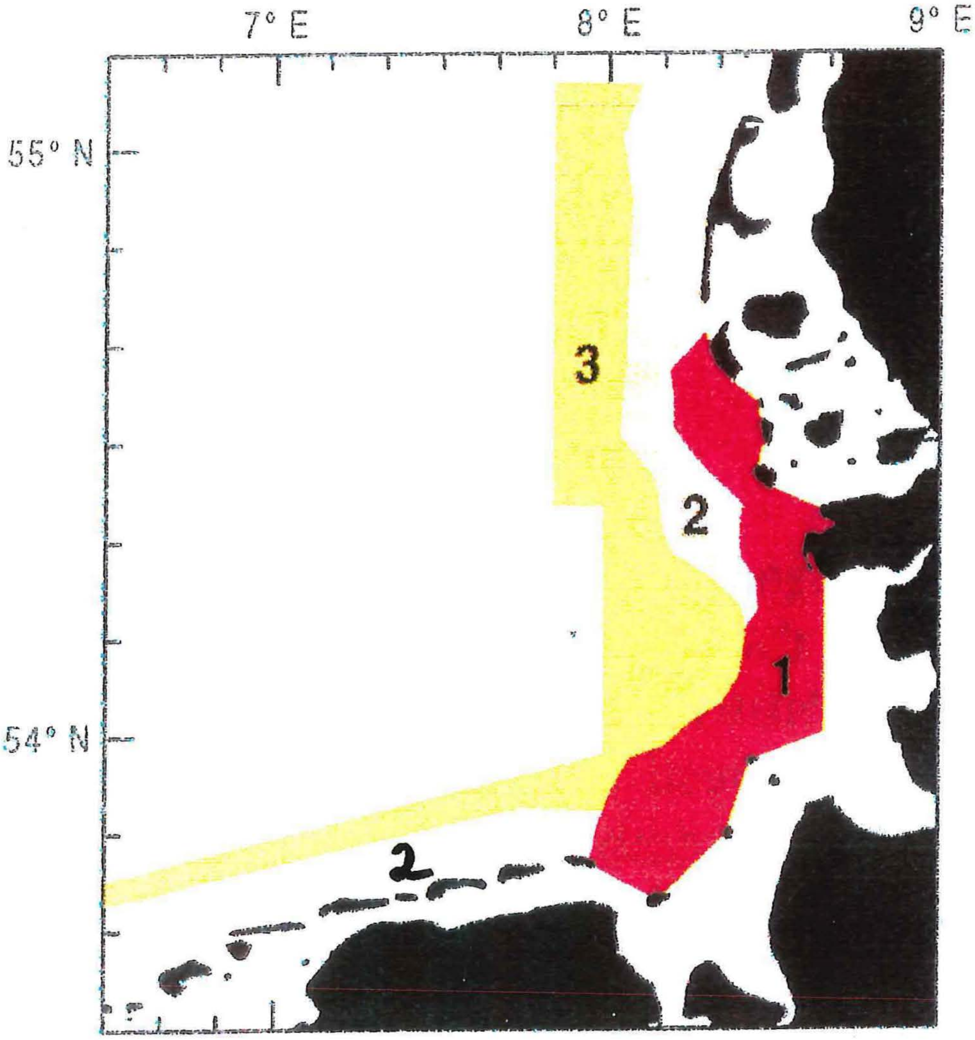


Figure 3.3.2 Sediment balans of the Dutch coast. Period: 1965-1997

Germany



Zone 1 From low water line to depth of -10 m NN, up to 10 m thick layers of mobile sand on older sediment.

Zone 2 From low water line to depth of -15 m NN, covered only with a thin layer of mobile sediment, thickness between 0.4 - 1.5 m. The sediment deficit is responsible for the negative sand balance of some islands.

Zone 3 Depth between -15 and -20 m NN, accumulation of mobile sand in a 2 to 5 m thick layer. Seaward a 1 to 1.5 m thick accumulation mobile sand is observed.

Figure 3.4.1 Coast parallel zonation of the foreshore area of the German Bight based on the distribution of mobile sediment (Zeiler, M. & K. Figge 1998).

Germany

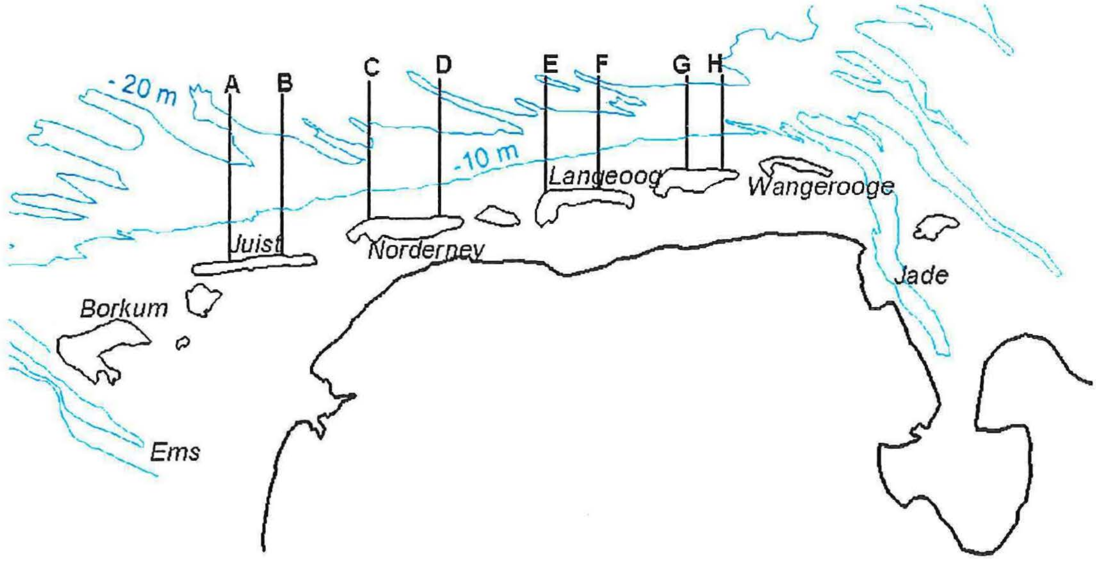


Fig. 3.4.2 Location of investigated profiles in the foreshore of the East Frisian Islands

Profile A

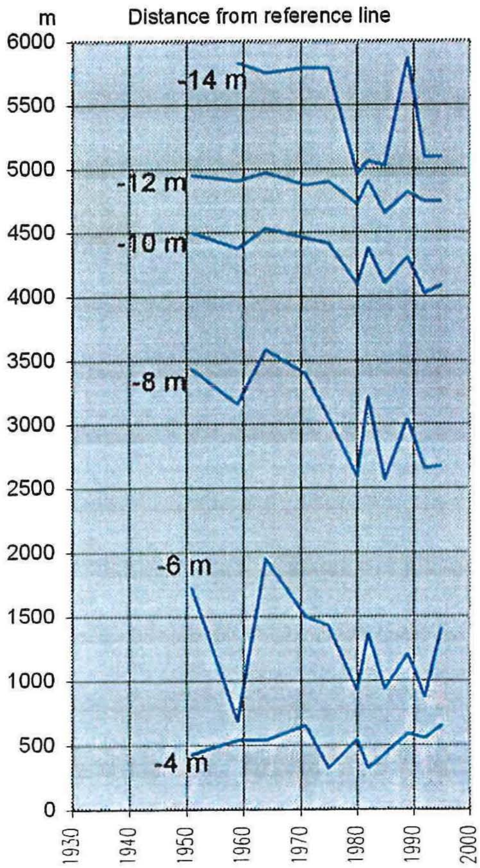


Fig. 3.4.3 Development of profile A (see fig. 3.4.2) for depths between NN -4 m and NN -14 m from 1951 to 1995 (depth - distance - line)

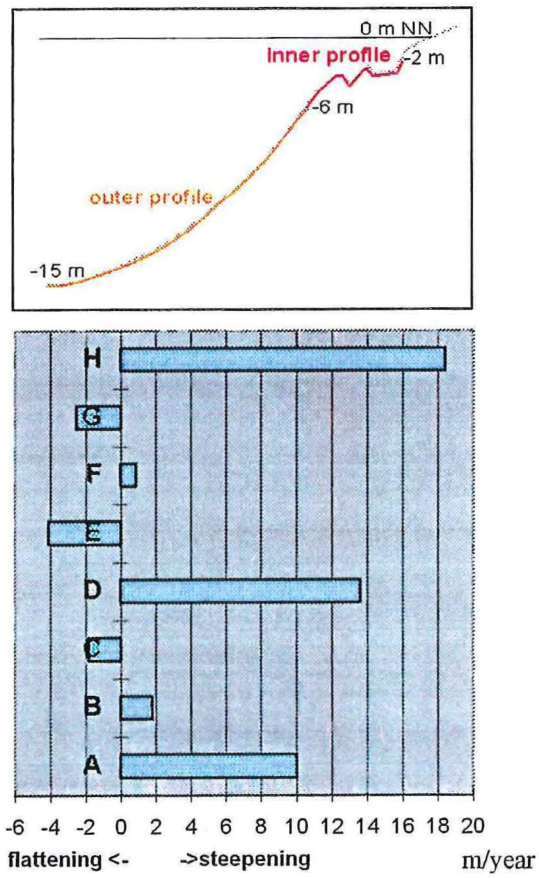


Fig. 3.4.4 Profile changes (steepening/flattening) calculated as the difference between the retreat rate in the outer (-15 m to -6m) and inner profile (-6 m to -2 m)

Attention

All conclusions are limited by the poor quality of the available bathymetric survey-data. A final answer to the question on coastal steepening can not be given at this moment.

Denmark

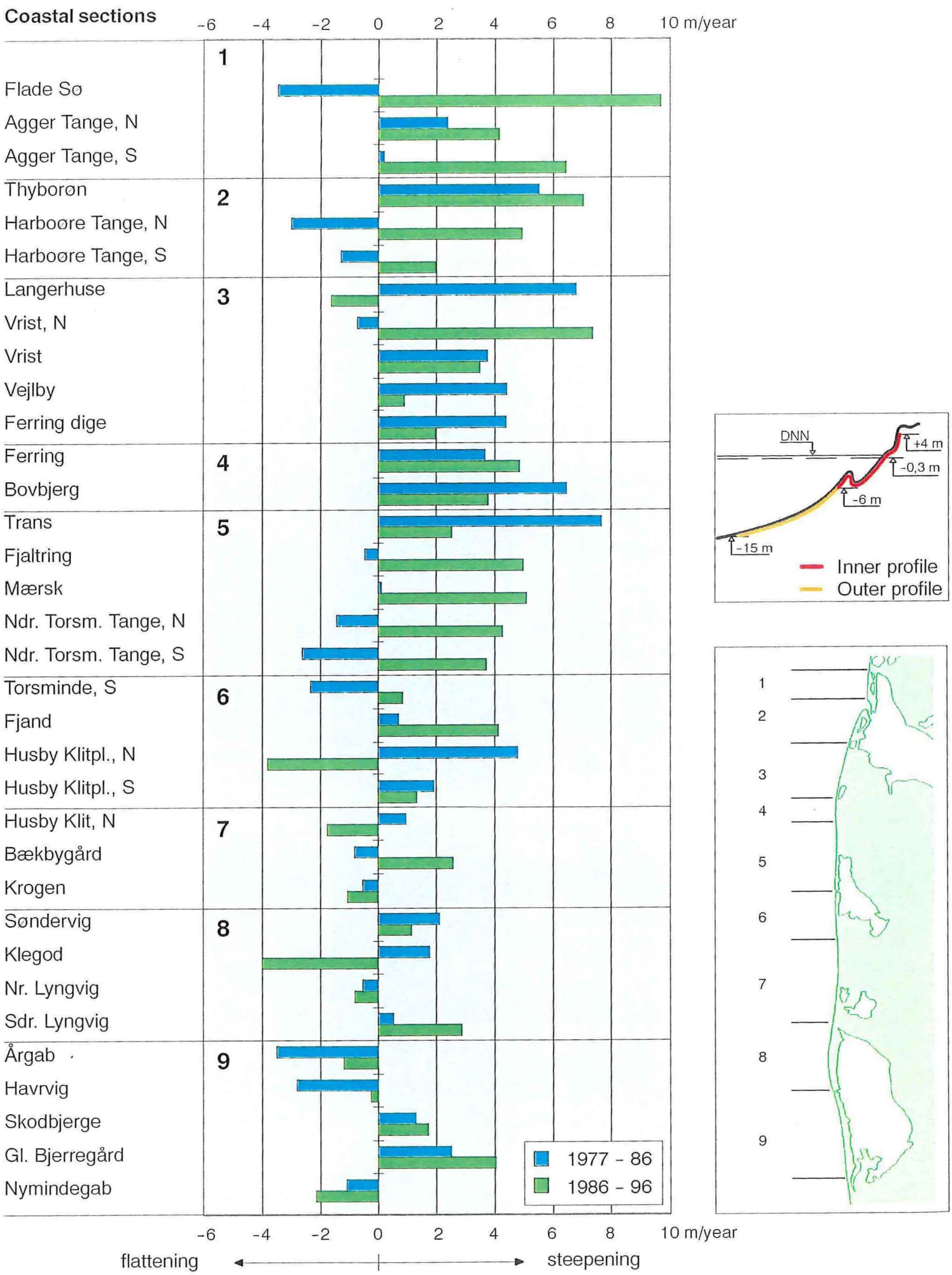


Figure 3.5.3 Profile steepening calculated as the difference between the retreat rate in the outer and inner profile

Denmark

Figure 3.5.1 Situation map

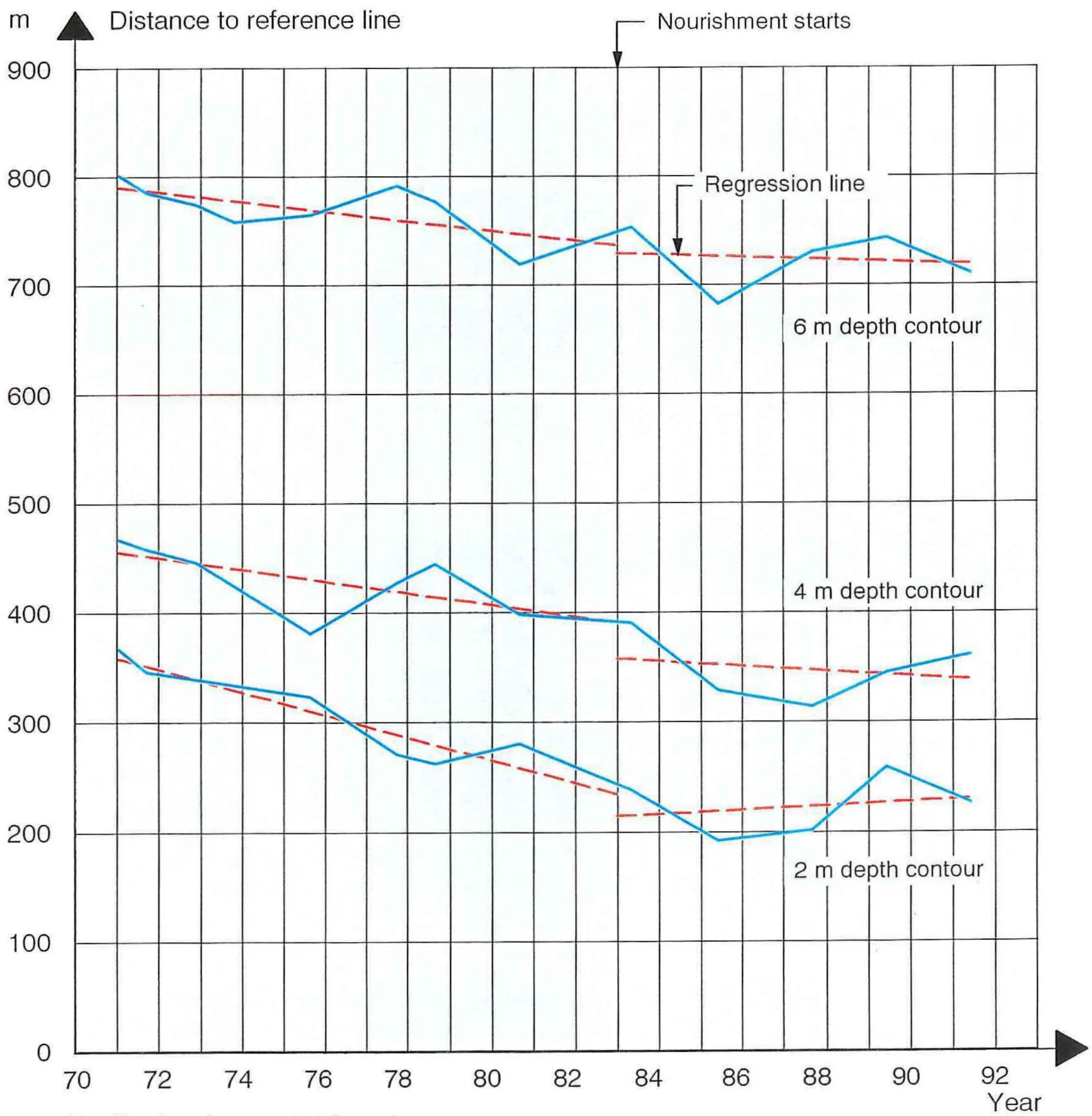


Figure 3.5.2 Profile development at Lønstrup

Denmark

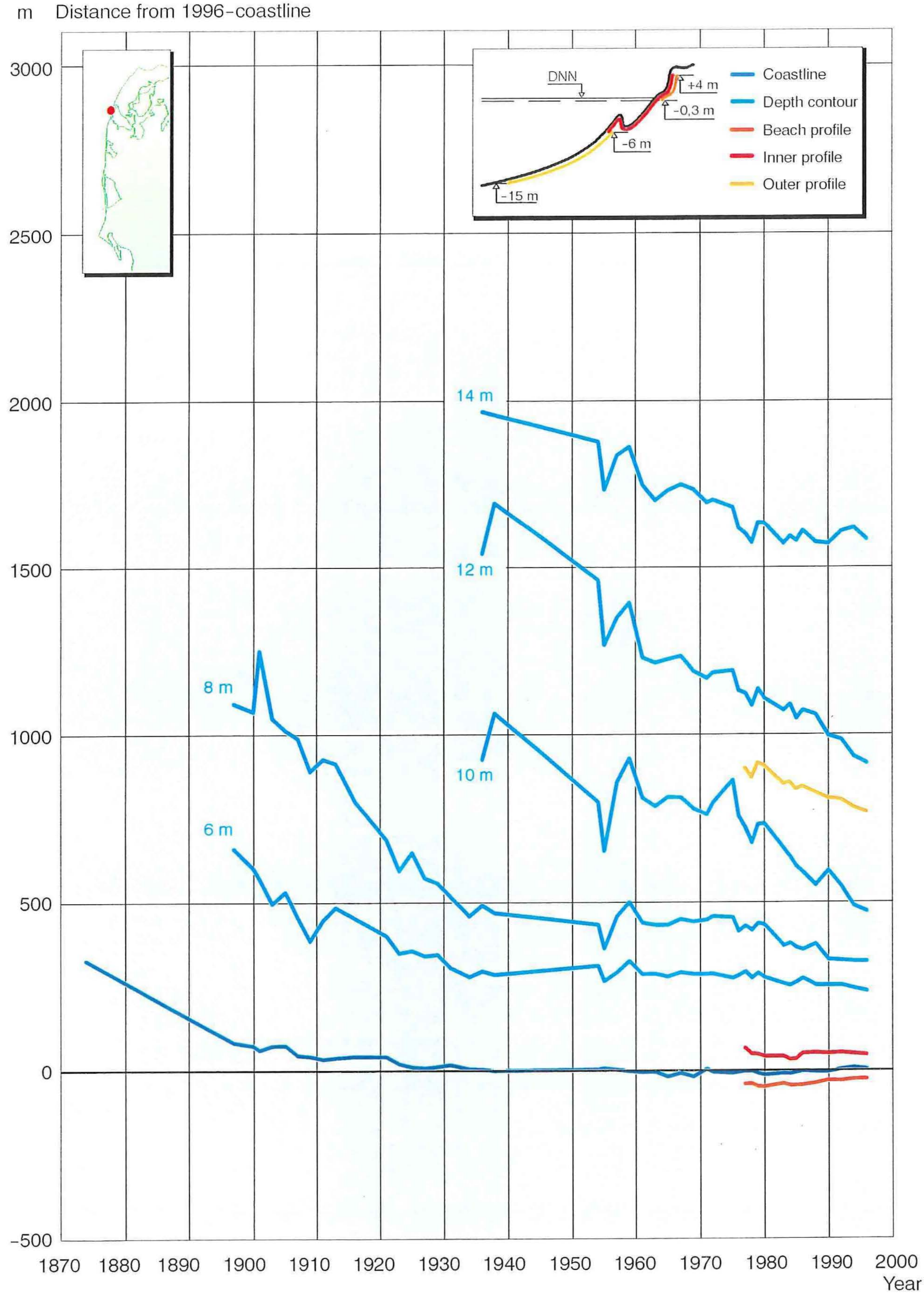


Figure 3.5.4 Profile development at Thyborøn