# Thyborøn Barriers – A Mastercase of Coastal Engineering

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## Abstract

Thyborøn, Denmark is placed at the entrance to a fjord system, which connects the North Sea with Kattegat. The inlet acts as a trap for the littoral transport from both sides. The adjacent barrier beaches suffer from severe erosion, which is alleviated by large structures and nourishment. The entrance was formed only 135 years ago and is still undergoing morphological changes. During its lifetime engineers have investigated various schemes for stabilising the shoreline – the most radical suggestion has been to close the entrance to avoid the ongoing loss of beach material. The present paper presents the major findings of a comprehensive study of the hydrographic and geological conditions, the coastal processes and the morphological evolution.

## Background

In 1862 the North Sea breached a since then permanent gap in the 22 km long Thyborøn Barriers and created a coastal scenario which over the years has occupied and challenged Danish coastal engineers. Shortly after the breach the construction of a large groyne system was initiated. Today the barrier beaches are managed by maintenance of the structures, controlled withdrawal, and major nourishment with about 750,000 $m^3$/year of coarse sand.

There are three major reasons for taking a conclusive review of the behaviour of the system:

1. A law of 1970 was prepared on the final assumption, that it was acceptable to leave the Channel open. Danish Coastal Authority is conditioned to monitor the development. Does the assumption hold at the 25-year anniversary?
2. Despite 135 years of dynamic evolution, the system has not yet achieved a full equilibrium since profile steepening is ongoing as well as long-term changes in channel configuration.
3. Modern model tools enable a more detailed and integrated description of processes allowing for improved verification of project assumption such as littoral transport in original and now steep profiles.

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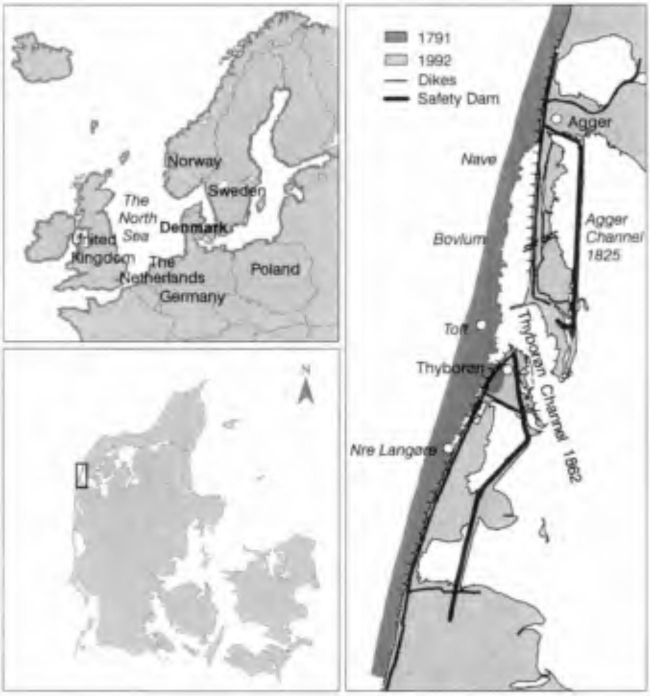


Figure 1. Location map, including overall system description and 205 years of development.

Historical Review

The generation of the present barriers started around year zero as a part of smoothening of the coastline. From the Icelandic sagas is known that there has been a connection between the fjord and the North Sea since there are narratives of the vikings' passing on to the North Sea through the Limfjord in the 11'th century. The barrier system at the earliest closed about year 1100.

There have been multiple breaches in the barriers during the period from 1600 until 1800, but none serious until 1825 where the Agger channel was formed and it lasted until 1868. The most severe breach came in 1862 and formed the Thyborøn Channel. Immediately after this the retreat of the coastline started.

Since the construction of the groyne system, the initial flattening of the coast profiles, caused by the excessive recession of the shoreline, was replaced by a gradual steepening of the sea-bed seaward of the groynes, which is ongoing but declining. In the 1930s, this steepening gave rise to deep concern among the responsible engineers who felt that disaster was looming ahead. They feared that the coast profiles were becoming so steep that even a short serie of severe storms could generate such effects that control of the development would be lost. This was called "The Theory of Disaster".

On this basis an act was passed by Parliament in 1946 whereby the Thyborøn Channel would be closed such that the loss of sand from the seacoasts to the Limfjord would be stopped and the seacoasts thereby stabilised. The project included the construction of 16 km of "safety" embankments placed approximately 2 km behind the coastline as well as the building of two major breakwaters and two sluices for vessels and salt water inflow, respectively.

Before the works to close the Channel were commenced, Per Bruun (1954) in his doctoral thesis, Coast Stability, raised serious doubts as to the "disaster theory" which was the basis for the project and proposed new investigations of the problems. Along similar lines, Helge Lundgren in 1954 and 1956 made specific proposals for new investigations, including scale model tests with movable bed to be carried out in Holland, particularly with a view to keeping the channel open and to saving a major part of the project costs.

The government followed these recommendations and a range of studies of various aspects of the problem were initiated, the most important ones of which were carried out at the Technical University of Denmark headed by Helge Lundgren and Torben Sørensen, Lundgren (1968).

The crucial question of whether the steepening of the coast profiles indicated a risk of disastrous development was resolved by an analysis demonstrating that the steepening was simply a question of the coast profiles adjusting to the reduced shoreline recession achieved by the construction of the groyne system, Sørensen (1961). This realisation in fact eliminated the basis for the very expensive and in many ways controversial project. The soundings of coast profiles over 125 years have confirmed the validity of this analysis.

However, the project had a number of other aspects, which also required analysis and considerations. Among those were the statistics of storm flood levels in the North Sea at Thyborøn.

In consequence of these investigations, the 1946-law was repealed in 1970 under the condition that the Danish Coastal Authority should follow the situation for at least 50 years. This was done the first time in 1975. The major conclusion in this work was that the steepening almost had stopped and that the system to some extent was stable.

Today the system configuration is the following. The length of the barrier islands is 22 km and the number of groynes, about 400 m long, in the system is 78. The maximum retreat of coastline since 1862 is 1.5 km, see figure 1. Coastline retreat rate was previously 1-2 m/year but is now mitigated by yearly nourishment. Net erosion in the system is 1.1 Mio $m^3$/year, channel shoals deposition is about 500 – 700,000 $m^3$/year and longshore transport from each side is 2 – 500,000 $m^3$/year. Coastal protection scheme today consists of maintenance of hard structures and yearly nourishment at about 775,000 $m^3$/year. (485,000 at beach and dike and 290,000 on shore face).

Total value today of the whole system has been estimated to about 1000 Mio DKK (170 Mio US$). Costs of nourishment and withdrawal of groynes and buffer dikes in line with coastline retreat on 1 – 2 m/year are equal, which leaves full flexibility for the detailed policy for coastal maintenance.

## Hydrographic conditions

The astronomical tide on this coast is very small, max. 0.3 m, whereas extreme high water levels caused by wind set-up with westerly winds may reach 3.

To give an impression on the weather conditions at the West Coast of Jutland, wind, wave and extreme water level conditions for Thyborøn are shown in figure 2.

Directional wave measurements have been undertaken since 1991. These detailed measurements supplement 15 years of wave height recordings and have formed the basis for the statistical analysis of the wave conditions.

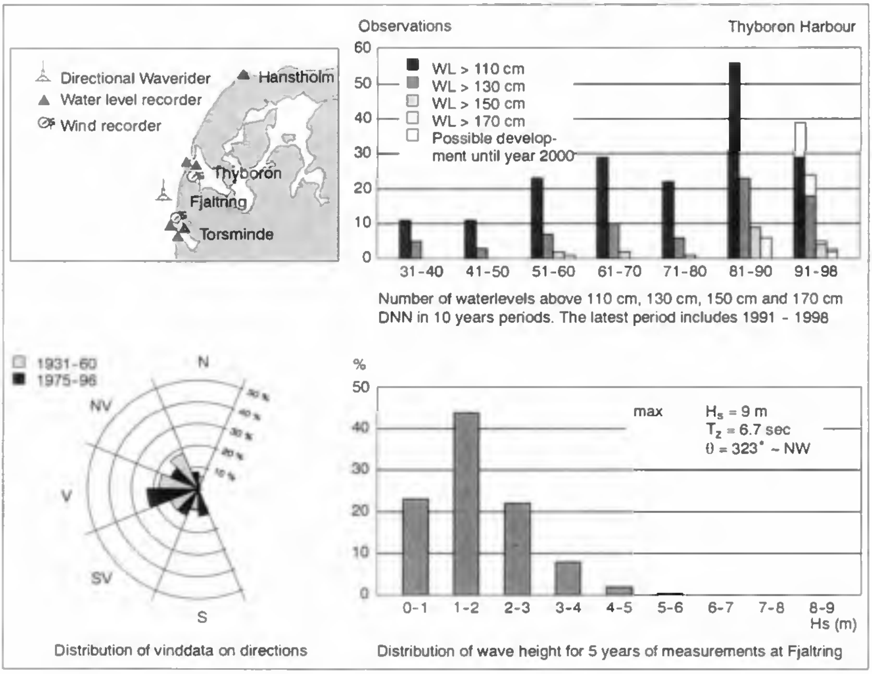


Figure 2. Wave climate and positions of the measurement stations

## Geology

The upper layers of the barriers consist of sand and gravel while below –6 m, marine clay can be found to a great extent, eg. about 30 m at Thyborøn. Underneath this are glacial deposits.

The clay layer has been found until 75 km further to the west of the present coastline out on 'Jutland Reef', which consists mainly of deposits of eroded glacial material. This indicates that the glacial formations in the early Holocene period extended further to the west protecting a calm basin where the clay layer could be deposited.

The start of the barriers buildup as a part of the formation of the present glacial coastline is dating back to the start of our era, and the barriers properly closed early in the 12$^{th}$ century, as explained in the historical review.

Sediment transport processes

The sediment transport processes around the inlet have been studied and quantified through a comprehensive set-up of numerical models, see Brøker et al (1996) for details. The various modules comprise a depth-integrated hydrodynamic model MIKE 21HD, a spectral wind wave model MIKE 21 NSW, which is used to transfer waves from the measurement station to the entrance, a mild slope wave model MIKE 21 PMS for the more detailed calculation of wave fields in the entrance area, and a deterministic intra-wave period model for transport of non-cohesive sediment, MIKE 21 ST, see Deigaard et al (1986). The areas covered by the numerical models and the measurement stations, required to drive the modelling complex, are shown in figure 3.

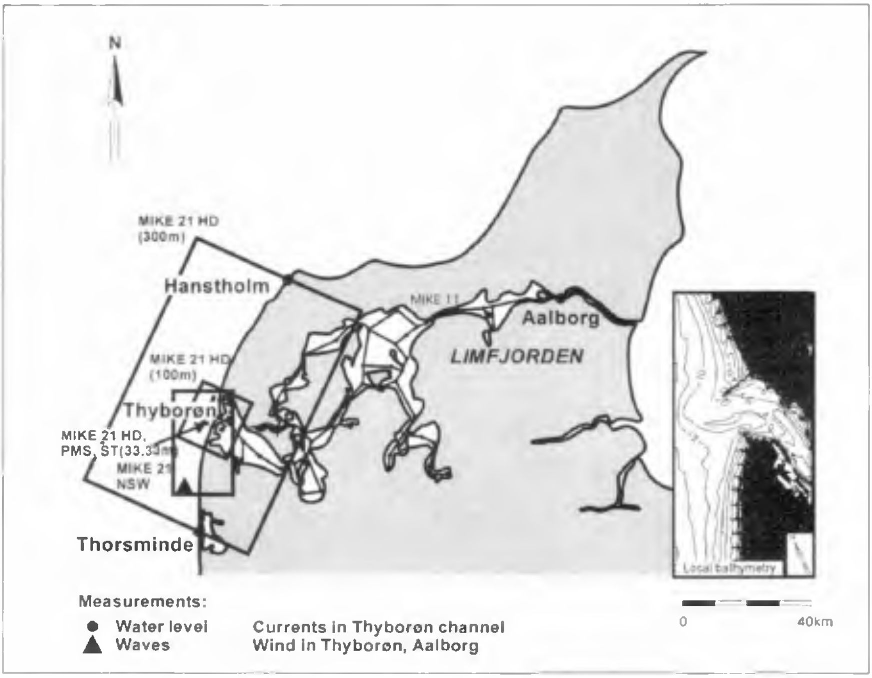


Figure 3. Areas covered by hydrodynamic, wave and sediment transport models, and location of measurement stations.

The meteorology is dominated by low-pressure systems travelling from West towards East. The westerly winds and waves are responsible for the morphological development of the coast. Typically, in the beginning of a westerly storm, the water level rise off Thyborøn, and, due to the connection across the peninsula of Jutland, strong in-going currents may last for the entire storm period, 3 – 5 days. Strong outgoing currents seldom occur in combination with severe wave action. Waves from southwesterly directions cause northward littoral drift along the barrier beaches.

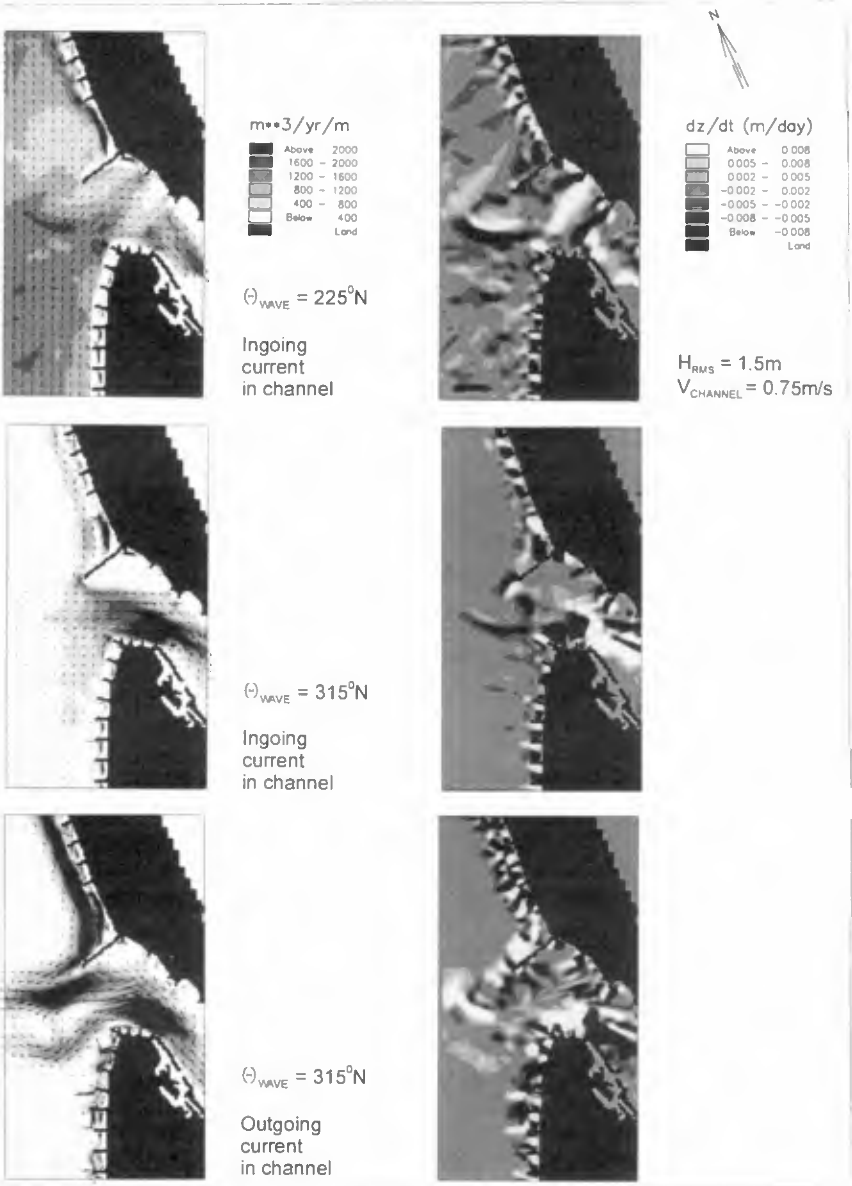


Figure 4. Sediment transport and corresponding initial morphological change, top: south-westerly storm, middle: northwesterly storm, bottom: northwesterly storm. $H_{rms}$ lies in the interval 1-2 m in all 3 cases.

The entrance is too wide to allow for any significant natural bypass and most material is deposited in the entrance area. During northwesterly storms, the littoral drift is southgoing, and for these wave directions the layout of the entrance allows for significant wave penetration into the channel. Therefore, during north-westerly storms, the sediment is kept in suspension further into the channel, and it may be transported all the way through the channel before it deposits on the shoals on the inside of the channel. The net effect of these proceses are that littoral drifts for both barriers are directed towards the central channel.

Transport patterns and the corresponding initial morphological changes for cases with south-westerly and northwesterly waves combined with in-going current and northwesterly waves combined with out-going current are depicted in figure 4. It is seen how the channel tends to migrate to the East during in-going flow and towards west during out-going flow. These calculations correspond to a distribution of sediment properties described from about 240 bed samples in the area.

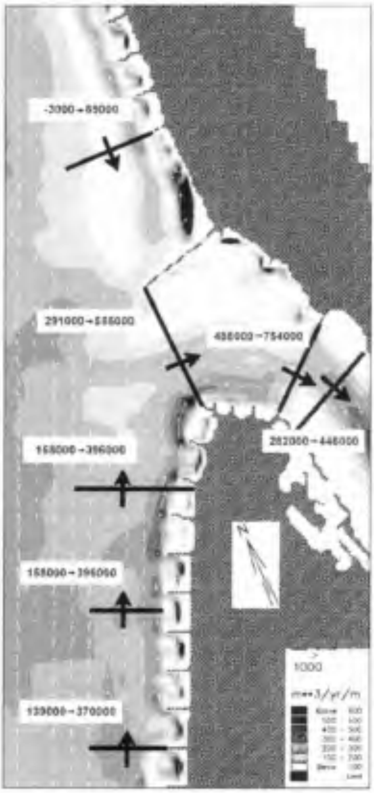


Figure 5. Average sediment transport pattern for the years 1991-1997, net transport across 7 cross-sections for the mildest and the roughest year during the period.

The yearly transport and morphological development are functions of the yearly climate, and at the present location even small variations in the dominant wave conditions change the sediment balances significantly. The modelling complex has been used to quantify this variability. Both the water level and the currents in the channel are strongly correlated to the instantaneous wave conditions. The frequency of occurrence of combinations of wave height and direction, water levels and currents in the channel have been analysed based upon 6 years of simultaneous measurements of water levels and waves, and 1 year of simulations of the currents through the 'fjord' which crosses the peninsula of Jutland, see figure 3 and Brøker et al. (1996).

The waves, currents and sediment transport have been modelled in detail for a number of historical events in total 25 days. 448 different combinations of waves, water level off the channel and current through the channel have been picked from the simulations. These sediment transport patterns are subsequently weighted to reflect the yearly transport pattern for different periods of time. Figure 5 shows the weighted sediment transport pattern for the years 1991-1997 and the integrated transport capacity through certain sections for the mildest and the roughest years of the period.

It appears that the transport capacity off the southern barrier-island increases slightly towards the entrance giving rise to the erosion which today is compensated by nourishment. Inside the channel the calculations indicate ongoing redistribution of material and a loss of material to the internal shoals. The sediment transport capacities inside the channel area have been adjusted to account for the presence of the non-erodible clay surface.

## Profile Steepening

Foresighted engineers started profile surveys only 12 years after the final breach in 1862. With few interruptions, such as during the Second World War, the profiles have been surveyed every second year ever since and the database now forms a unique basis for evaluating the long-term trends of profile development, notably steepening of the profiles. The volume of eroded sand along the coast and profile development have been calculated based on these surveys.

From the geological study, the position of the clay surface is known, which means that it has been possible to calculate erosion along the coast for the sand layers only. The sediment balance has been calculated for 4 periods, 1874-1900, 1900-1936, and 1936-1978 and at last 1978-1992. For the first two periods the calculations are carried seaward to a depth of –8 meter DNN. In 1930s, DCA started measuring seaward to a depth of –16 m DNN. The calculations for the last two periods are therefore carried out to this depth. The results are shown in figure 6.

The results clearly show the large erosions immediately after the breach in the barriers. This continued in the following years also after the construction of the groynes. As the steepening began the erosion decreased.

On the basis of the long series of profile sounding the retreat of the coastline, the cliff and the 7, 8, 10 an 16 meter depth contours have been calculated. The results just off the town of Thyborøn are shown in figure 7.

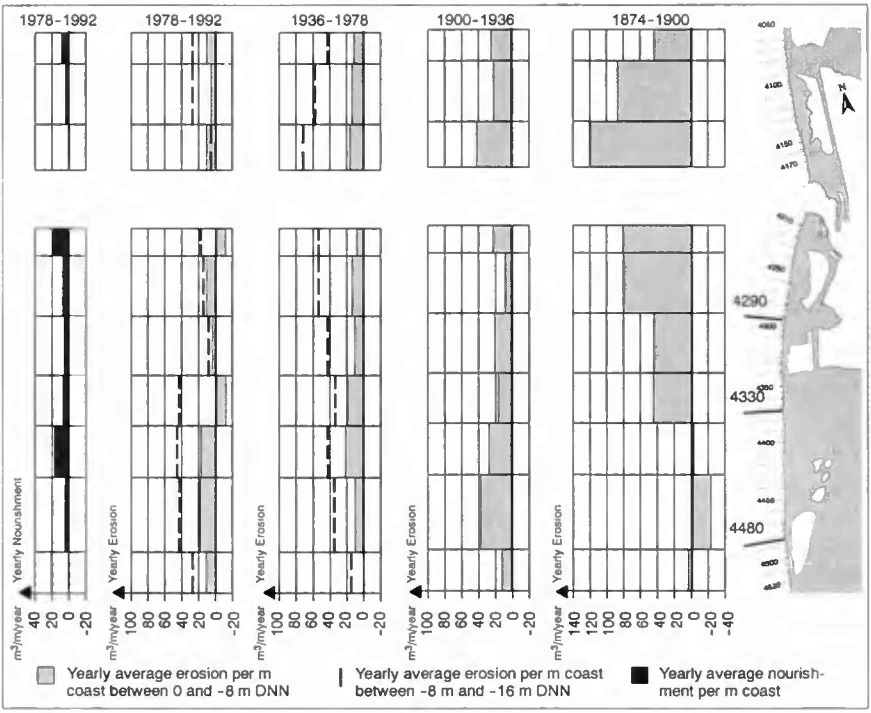


Figure 6. Calculated eroded and nourished volumes for four periods

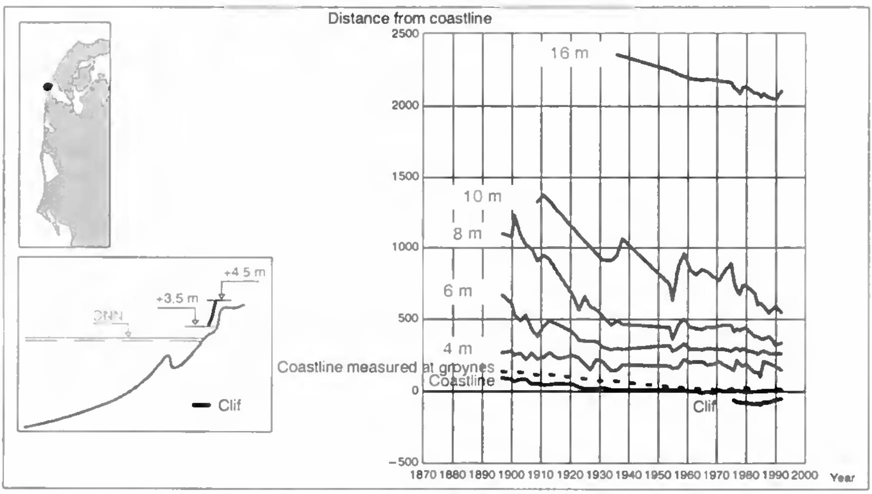


Figure 7. Profile development off Thyborøn town

Figure 7 clearly shows the importance of long-term surveying, the yearly and in periods large fluctuations are so large that say even 25 years of monitoring could have been misleading. Now with 125 years of data at hand it is possible to extract reliable long-term trends from the otherwise confusing data. From figure 7 it is seen that the retreat of all elements was larger in the beginning of the period compared with the retreat today. For the coastline, the four, and 6-meter depth contours, the retreat has stopped. The depth contours off the groynes are still retreating. This leads to the conclusion that the steepening of the profiles has not yet stopped along all sections of the coast as earlier concluded in the 1975. This is especially true close to the inlet. It should however be noted that the wind and wave conditions were extremely severe for allmost 20 years after 1975. Examples of historical and more recent profiles are shown in figure 8.

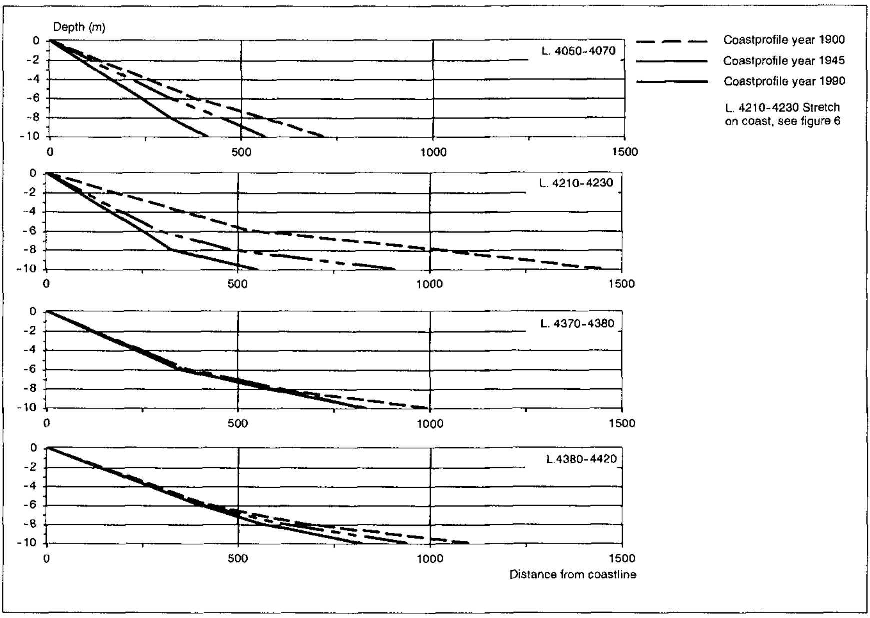


Figure 8. Profile steepening for selected stretches along the barriers.

The effects of the profile steepening on the sediment transport capacity have been quantified by modelling of waves, currents and sediment transport for a historical storm using a recent bathymetry and a bathymetry constructed from the old profile measurements. Figure 9 shows the comparison of simulated sediment transport fields and integrated transport along the barrier islands at one time step during the simulation at which the waves come from southwest, $H_{rms} = 1.5$ m. It is clearly seen that the transport zone has become very narrow in 1994 and the total littoral drift as well as the gradient of the littoral drift have declined. The groynes have been moved backward in pace with the ongoing erosion, however leaving submerged parts still active on the seabed. The erosion rates are significantly reduced compared to a hundred years ago due to the steepening of the coastal profiles. These simulations illustrate the sediment transport processes which are reflected in the measurements of the morphological evolution of the area.

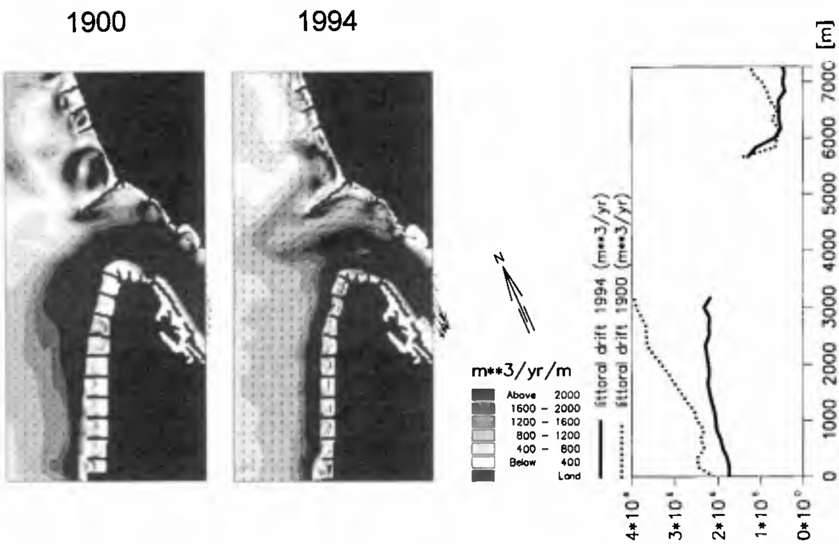


Figure 9. Examples of sediment transport rates, historical and recent bathymetries, $H_{rms}$= 1.5 m, dir. 255°, mean current in the channel 1.25 m/s. Comparison of integrated littoral drift.

Sediment budget

Both south and north of the barriers there exists a nodal point for the littoral transport from which the net transport is directed towards the central channel. Based on the data which lead to figure 6, the total volume of eroded sand between the northern and southern nodal point has been calculated. Depending on the distance from the coastline taken into account, which is from the top of dunes until 12 op to 16 meters depth, the volume range is 450.000-600.000 $m^3$/year for the stretch from the southern nodal point up to the channel and 150.000-200.000 $m^3$/year from the northern point down to the channel. This gives of total of 600.000-800,000 $m^3$/year between the two nodal points.

Calculations of shoal deposit behind the barriers has been carried out based on soundings of the shoals in 1972 and in 1991. The calculations leads to the conclusion that 500.000-700.000 $m^3$ is deposited on the shoals every year.

The numerical model gives some ranges for the transport capacity through 7 sections along the sea shore and through the channel, see figure 5. The transport capacity through the central part of the channel is 5-750,000 $m^3$/year for the mildest and roughest year, respectively, during the period 1991-1997. The transport capacity along the coastline varies between 0-100,000 $m^3$/year for the northern barrier and 150,000-400,000 $m^3$/year for the southern barrier.

Combining these information's ranges for the overall longshore sediment budget can be obtained.The northgoing transport is in the range 3-500,000 $m^3$/year and the south-going is op to 200,000 $m^3$/year. The transport rate through the channel is 500,000-700,000 $m^3$/year. This is illustrated in figure 10.

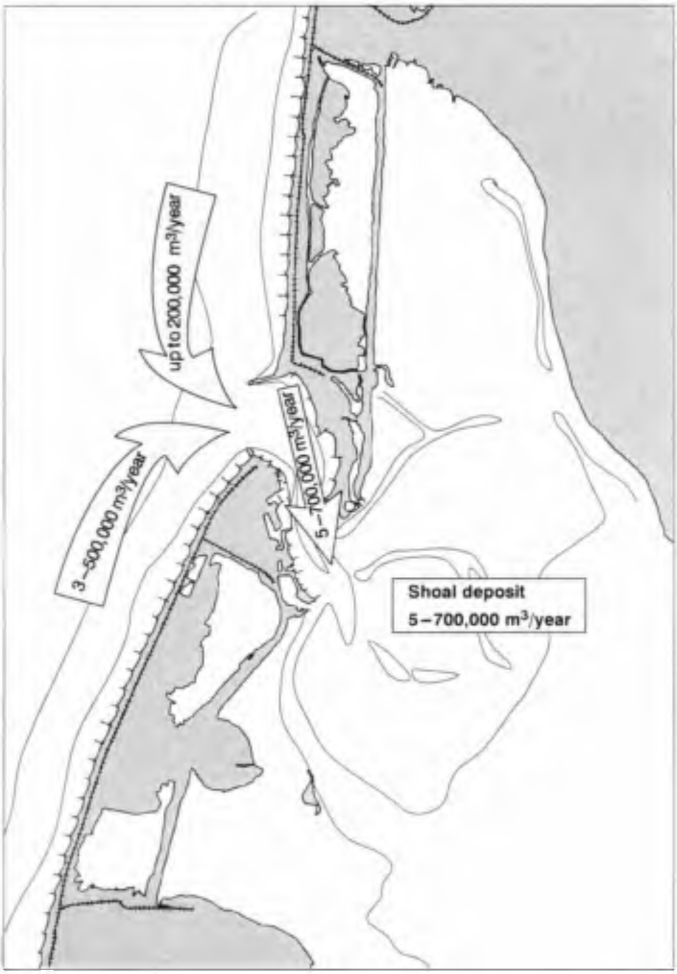


Figure 10. Overall sediment budget for the barriers

The safety level for Thyborøn

The extreme water levels at Thyborøn have been reassessed based on data from the passed 20 years. Figure 11 shows a comparison of extreme analysis results based on the data for the periods 1931 to 1975, from 1975 to 1995 and the full data set. The period just after 1975 covers a number of very extreme events, and therefore the analysis, based on the latest period only, shows a somewhat higher level than the analysis from the first period and the full serie. The dikes have been reinforced, the beach better maintained and the total system will therefor be able to provide flood protection in a 1000 event even accounting for the new analysis of extreme water levels.

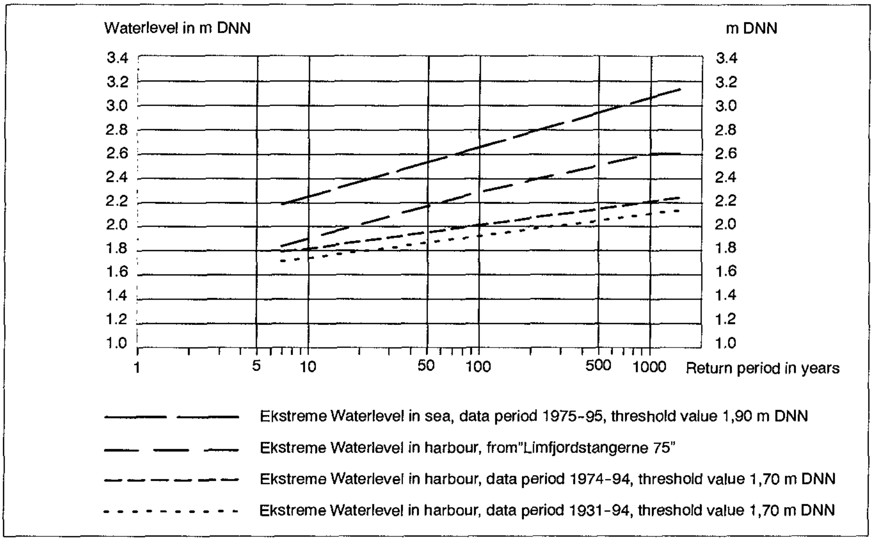


Figure 11. Old and new statistics for the extreme water levels at Thyborøn.

Further, it has been investigated if there should be a certain limit to extreme water levels at Thyborøn due to the nearness of more open and deeper waters to the north. Simulations in a numerical model of the North Sea were performed for a recorded storm scaled to predicted extreme conditions. The simulations showed that the extreme water levels are functions of the barometric conditions mainly, and that a limit could not be identified.

Overall Conclusion

- Although the outer part of the profiles close to the inlet is still getting steeper, the rates of steepening are significantly decreased and the nearshore zone can be kept stable by comprehensive nourishment.
- The safety level at Thyborøn is still 500-1000 years.
- Numerical modelling has greatly supported the understanding of the coastal processes around and in the Thyborøn Channel. Comparison between modelled sediment transport

for a historical and a recent bathymetry has illustrated that relevant processes are sufficiently well represented in the models to reflect the major morphological changes. Inside the channel the modelling has illustrated how different hydrographic conditions lead to different morphological developments such as migration of the channel and very varying depositions in the entrance area.

- Calculations of erosion on the coast, calculations of deposit material on inlet shoals and numerical calculations of the littoral transport capacity have helped gaining a more narrow range for the littoral sediment budget along the barriers.

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