CHAPTER 366

THYBORØN COASTAL INVESTIGATIONS 1995: NEW LESSONS FROM AN OLD COASTAL PROBLEM

by
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INTRODUCTION AND BACKGROUND

Thyborøn channel is located on the West coast of Jutland, Denmark, and connects the Limfjord with the North Sea, see figure 1. The channel was naturally opened following a major storm event in 1862. In the years after the opening of the channel, the neighbouring coasts experienced substantial erosion, which put the town of Thyborøn at risk. For historical background and previous investigations and analysis, please see References.

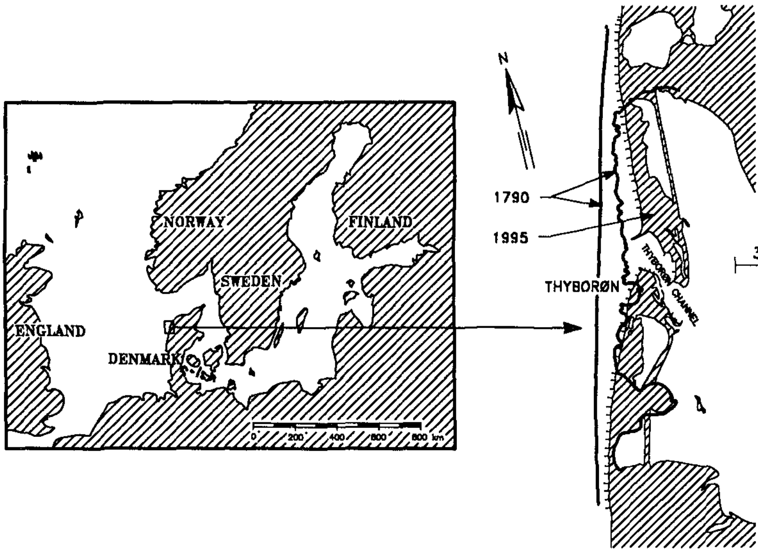

Figure 1 Location map, including indication of development over 205 years

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The geology in the area can be briefly described as postglacial sediments, mostly fine to medium sand, overlaying hard clay in depths of 10 to 12 m below seabed level. The area is exposed to severe storms from directions between southwest and northwest. Along the coast the conditions are influenced by a northgoing sea current. In the inlet area the currents are determined by the differences in water level across the peninsula of Jutland. The tidal variations are small, with a maximum tidal range of ~40 cm. The yearly net sediment transport along the narrow barrier beaches is directed towards the inlet from both sides. The undisturbed net transport rates are of the order of magnitude of 1 million m^3/year. A dense groyne system reduces the longshore sediment transport rates to about 2-300,000 m^3/year from each side; the sediment transported into the channel ends up on large shoals inside the Limfjord, giving a yearly deposition of approximately 0.5 mill m^3.

The groynes along the coast have decreased the rate of shoreline retreat to about 50% of the natural erosion. This means that the land ends of the groynes have to be extended inland in pace with the erosion. The tips of the groynes experience continuous deterioration due to severe pressure arising from the wave action. The submerged groyne elements are left on the seabed as they are still considered as active parts of the coastal system.

NUMERICAL MODELLING STUDIES

As a part of the study of the processes around this inlet numerical models were established, both for the quantification of the overall sediment budget along the barrier beaches, and for the study of the details of the morphological evolution under storm conditions inside and around the inlet.

Sediment budget along the barrier beaches

The sediment budget along the barrier beaches has been studied by the LITPACK model, and the details around the inlet by a morphological model constructed from various modules of MIKE 21. **LITPACK** is a model complex for calculation of waves, wave-driven currents (possibly coupled with a general sea current) and longshore sediment transport on an arbitrary coastal profile. A basic assumption of quasi-uniform conditions in the longshore direction allows for simulation of all combinations of waves, water levels and sea currents and establishment of a complete sediment budget. The calculated budget is illustrated in figure 2. The budget was validated through comparisons with the transport rates derived from measured erosion/deposition during 15 years.

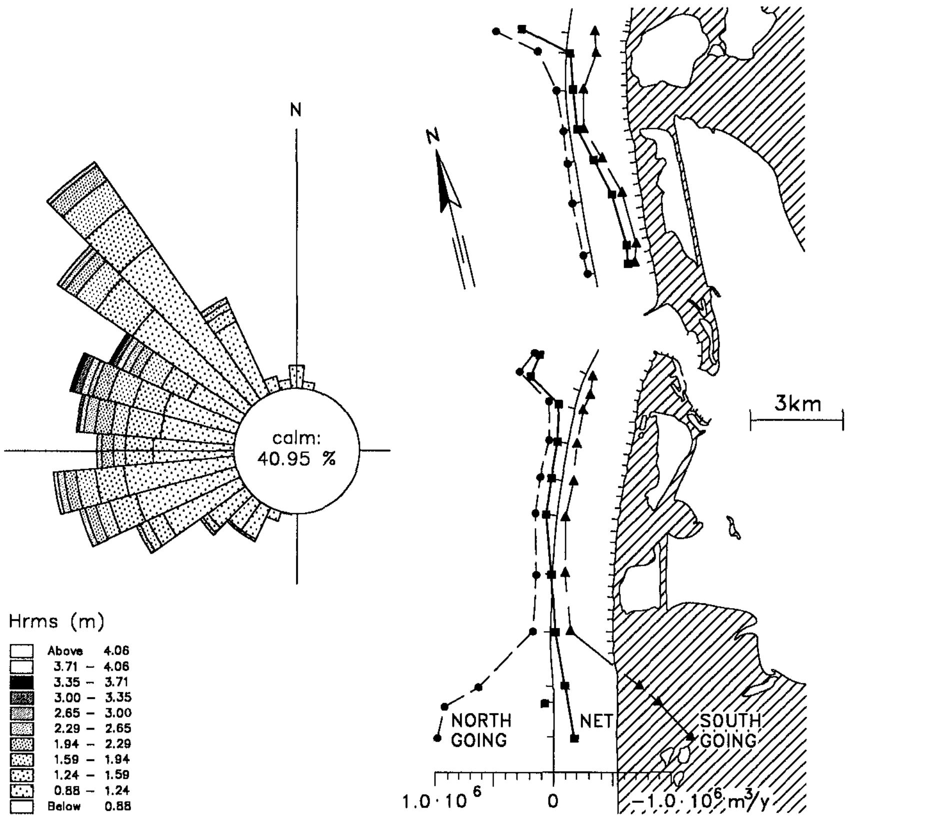

Figure 2 Left: Illustration of wave statistics
Right: Sediment budget along the barrier beaches

Wave level, wind and directional wave data were available for a three-year period. Two characteristic storms (Storm 1 and Storm 3) were selected for detailed studies of sediment transport and morphological evolution in the area around the inlet. Furthermore, the littoral transport along the barrier islands during each storm was calculated using LITPACK to give an indication of the representativeness of the two storms. The distributions of the littoral drift in the longshore direction and along a selected profile are shown in figure 3. The comparison showed that the storms represented approx. 20 % and 15 % of the southgoing and northgoing yearly transport, respectively. The distribution along the coastal profile is, however, more concentrated over the bars under storm conditions than in average over the year.

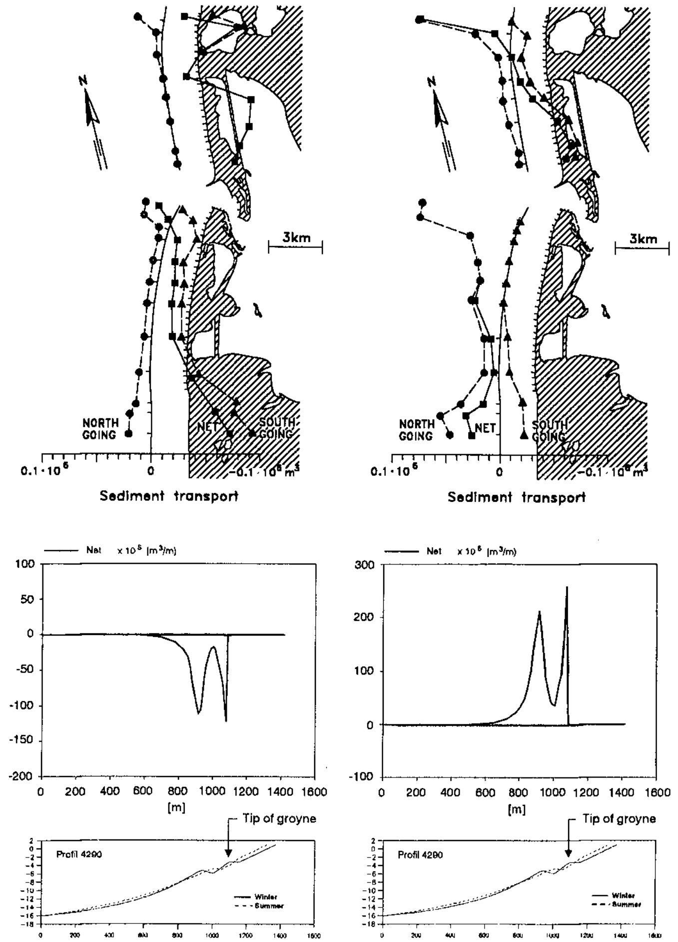

Figure 3 Upper, left: Storm 1, littoral drift along the coasts
Upper, right: Storm 3, littoral drift along the coasts
Lower, left: Storm 1, littoral transport along a profile
Lower, right: Storm 3, littoral transport along a profile

Detailed studies around the inlet

Model setup and boundary conditions for the morphological model

A comprehensive set of models was established in order to transfer measured data into boundary conditions for a morphological model covering the area of interest. The measured data comprised: directional wave measurements at Fjaltring, water levels at Thorsminde, Thyborøn, Aalborg and Hanstholm, wind at Thyborøn and Aalborg, see figure 4. Current speed and direction were measured in the channel during one month for calibration purposes. The model areas and the positions of measurements are indicated in figure 4. It must be noted that the fluxes across the eastern boundary of the general hydrodynamic model are calculated from a 1D river model, MIKE 11, which covers the entire Limfjord from Thyborøn to Aalborg, see Figure 4.

The general and the regional hydrodynamic models have a resolution of 400 m and 100 m respectively. The model is MIKE 21 HD, which is depth-integrated. In the general model the driving forces are wind and variations in tidal levels and fluxes along the boundaries. The effect of Coriolis force is included.

The regional wave model is a parameterised, spectral wind wave model, MIKE 21 NSW.

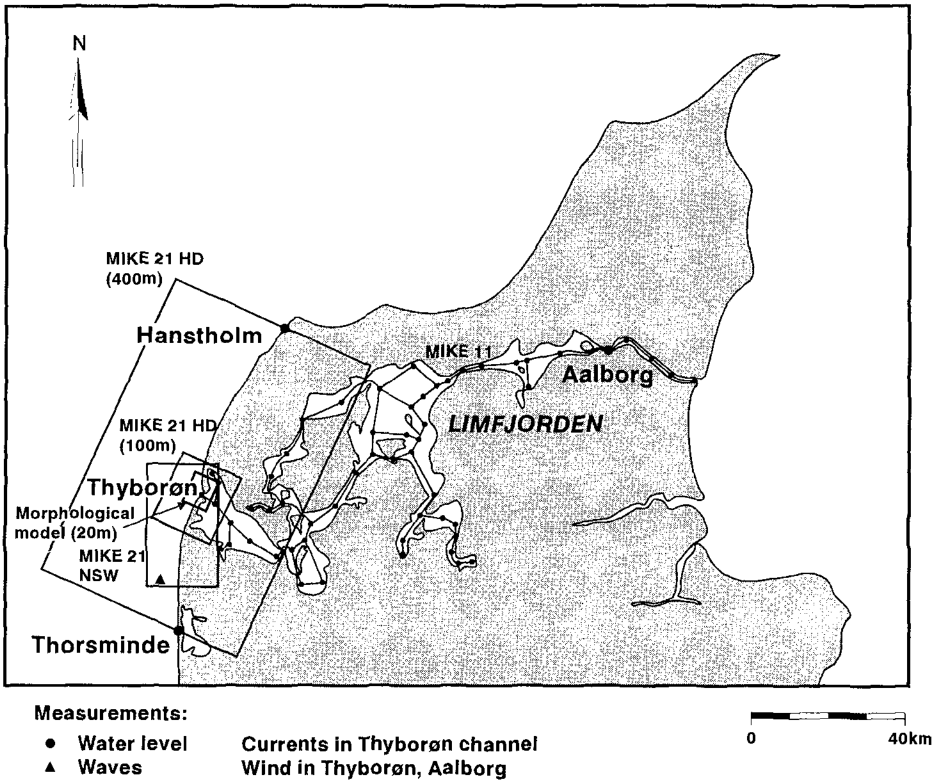

Figure 4 Areas covered by the general and regional hydrodynamic model
Area covered by the regional wave model
Area covered by the morphological model
Locations of measured water levels, wind, waves, currents

The regional models give boundary conditions to the morphological model, see figure 4 for the extent of this model. In the morphological model, wave-, current- and sediment transport modules are coupled as described below. A mild-slope wave model, based on the parabolic approach, was applied in the morphological model complex. Inside the morphological model area, the time- and space-varying radiation stresses were included as an extra forcing term for the hydrodynamic model. The resolution within the morphological model area is 20 m.

Brief description of the morphological modelling complex

DHI's morphological modelling complex is centred around the hydrodynamic model. A morphological simulation is 'warmed up' by calculation of initial wave and current fields on a fixed bed. After the 'warm-up period' the sediment transport field and the corresponding rates of bed level change rates, $\partial z/\partial t$, are calculated. $\partial z/\partial t$ is incorporated in the continuity equation of the hydrodynamic model, and the hydrodynamic simulation proceeds for a period of time corresponding to a so-called 'morphological timestep', which is determined so that the maximum Courant number for the migration of bed forms is less than 1. At the end of this (typically short) period of time the sediment transport field is recalculated using the bathymetry evolved within the morphological timestep. The wave field is recalculated every k'th morphological timestep, where k is an arbitrary integer. (In the present simulation k equals 3). A second-order accurate finite-difference method is used for the calculation of $\partial z/\partial t$ and the truncation errors are eliminated by a modified Lax-Wendroff scheme.

This setup meets the requirements of offering the capability of running with time-varying boundary conditions, and of minimizing the computational effort by avoiding recalculation in the hydrodynamic model. A block flow chart of the morphological model complex is shown in Figure 5.

Three different types of **wave models** are presently built into the morphological complex: an elliptic mild slope model, MIKE 21 EMS, a parabolic mild slope model, MIKE 21 PMS, and a spectral nearshore wind wave model, MIKE 21 NSW. The second one was used in the simulations described here.

The **hydrodynamic module** in the morphological modelling complex is MIKE 21 HD, which solves the vertically integrated equations of conservation of mass and momentum in two horizontal dimensions. The hydrodynamic model operates with a space- and time-varying hydraulic roughness, accounting for the apparent bed resistance in combined waves and current. This apparent roughness is updated every morphological time step.

The deterministic intra-wave period model for **transport of non-cohesive sediment**, STP, is applied. The model covers the range from pure current to combined current and waves (breaking or non-breaking), see Deigaard et al (1986). It is a basic assumption in the present model complex that the transport capacity is a function of the local conditions.

The hard-clay layer described in the Introduction section was included in the model as a non-erodible surface over which transport was allowed to take place.

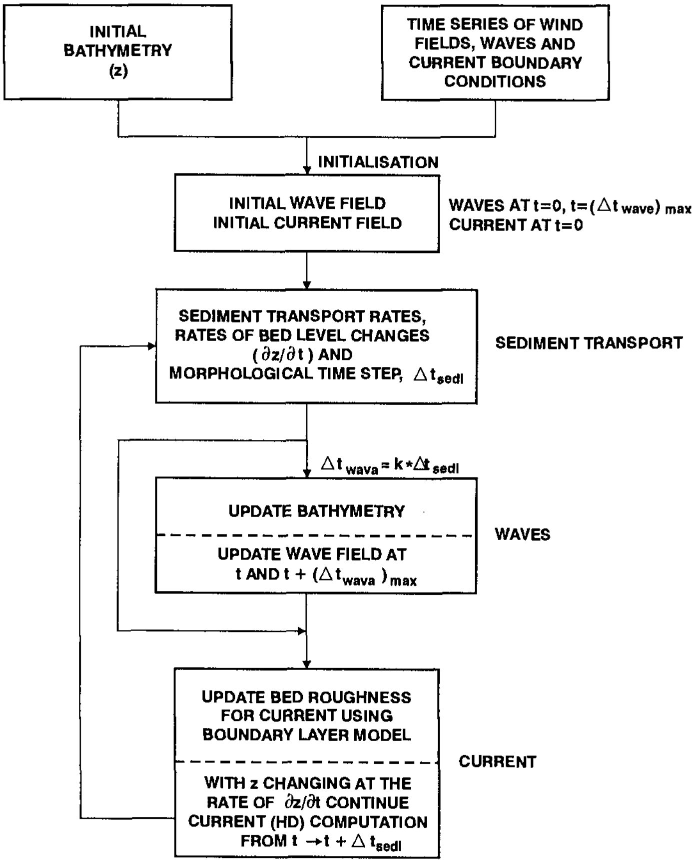

Figure 5 Block flow chart for the morphological modelling complex

Examples of results from the morphological modelling

As mentioned above, two historical storms, each of a duration of 4 days, were modelled in detail. The two storms represented typical storms from the two dominant directions, namely southwest and northwest.

Results from one of the storms, covering the period 20/1/1993 0:00 - 24/1/1993 0:00, are presented in figures 7 and 8. Figure 6 gives a brief overview of some of the important parameters, i.e. water levels at 3 stations, wind speed and direction and wave height and direction. Figure 7 shows wave-, current and sediment transport patterns at the peak of the storm, 22/1/1993 12:00. Figure 8 shows the bed level changes after 1 day, 2 days, 3 days and 4 days. The results show that sediment is 'sucked' out of the cells between the groynes, some of it is deposited off the groyne system in this storm, but most of it, as well as littoral drift which enters the model area, is trapped in the inlet area.

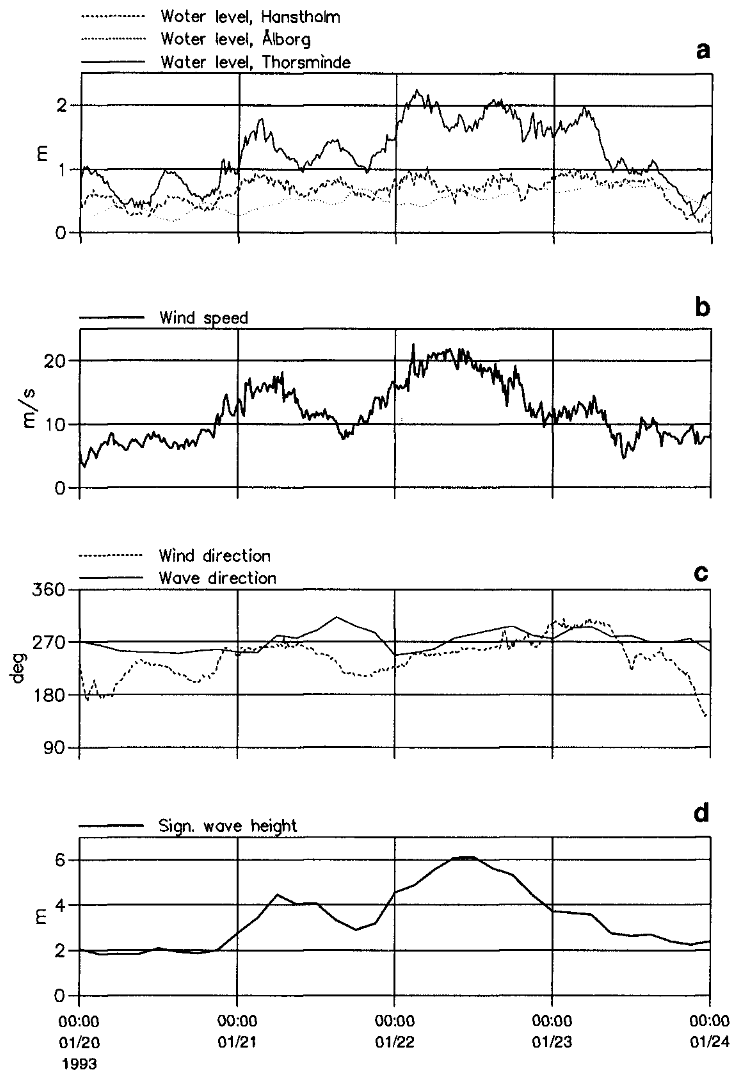

Figure 6 Time series of: a) water levels at Thorsminde, Thyborøn, Hanstholm and Aalborg
b) wind speed at Thyborøn
c) wind direction at Thyborøn, wave direction at Fjaltring
d) wave height at Fjaltring

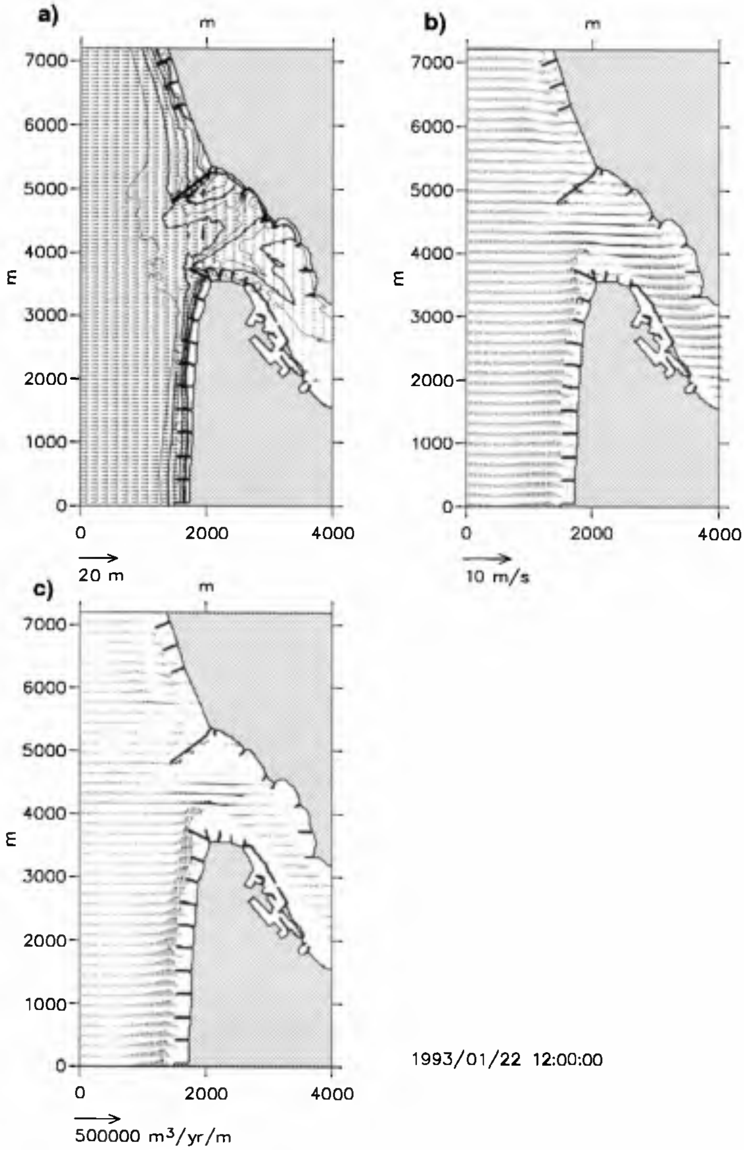

Figure 7 a) Calculated wave field, 22/1 1993 12:00
b) Calculated flow field, 22/1 1993 12:00
c) Calculated sediment transport field, 22/1 1993 12:00

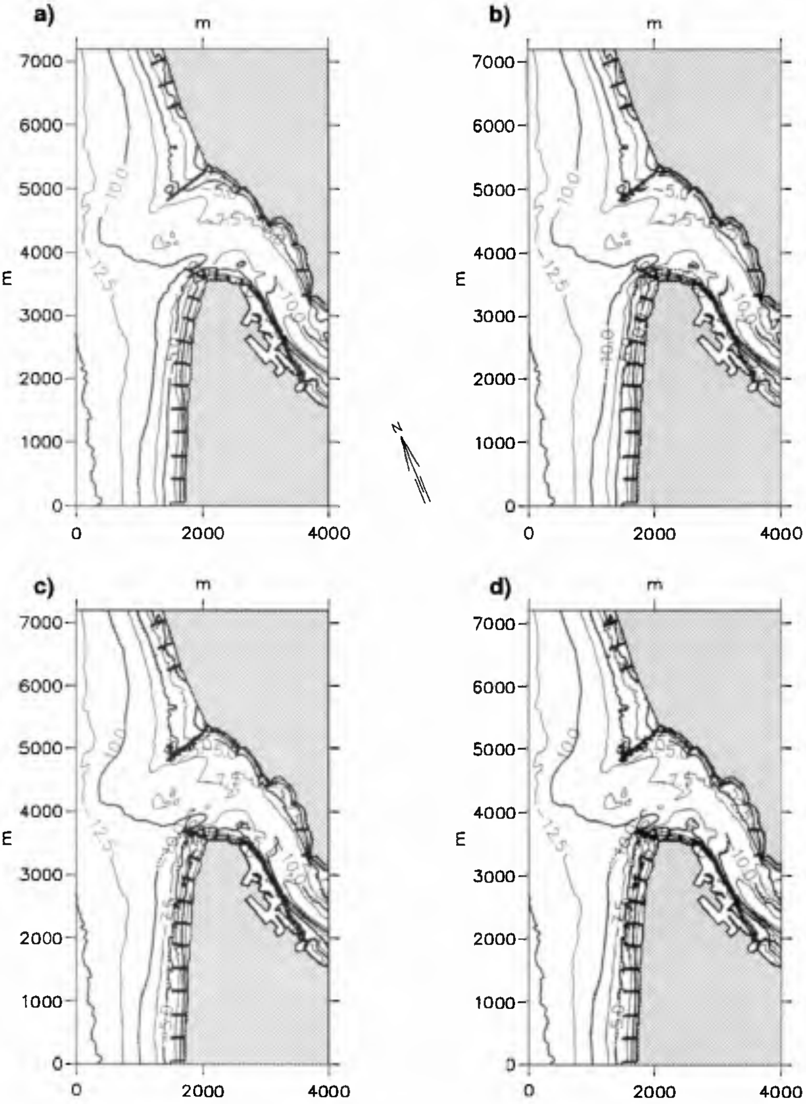

Figure 8 Calculated morphological evolution
a) From 20/1 1993 0:00 to 21/1 1993 0:00
b) From 20/1 1993 0:00 to 22/1 1993 0:00
c) From 20/1 1993 0:00 to 23/1 1993 0:00
d) From 20/1 1993 0:00 to 24/1 1993 0:00

New understanding of the complicated processes in the area was gained from the modelling work. Examples of details which were learned from the simulations are given below.

One example is the fact that the inlet over the last years has started to erode more severely on the opposite side, (the east side) to that where erosion previously occurred. It was clearly seen from the modelling that storms from southwest were responsible for this development, and over the last years the intensity of these storms has actually increased.

This effect becomes more clear if the model is run without any non-erodible clay layer. Figure 9 shows the comparison of the accumulated bed level changes over 4 days with and without the clay layer. It appears that a potential for erosion at the east side exists. (It should be mentioned that erosion does take place in the clay, just at a much slower pace than for sand. Erosion in the clay is therefore not included in the present model.) One effect of the clay layer on the sediment transport is seen from figure 10, where the accumulated transport across the western limit of Thyborøn channel, defined by the tips of the breakwaters, is compared for Storm 3 with and without the clay layer. It appears that the transport capacity is larger when the clay layer is included than when this is not the case. This is connected to the fact that the transport capacity decreases for increasing depth for constant flux.

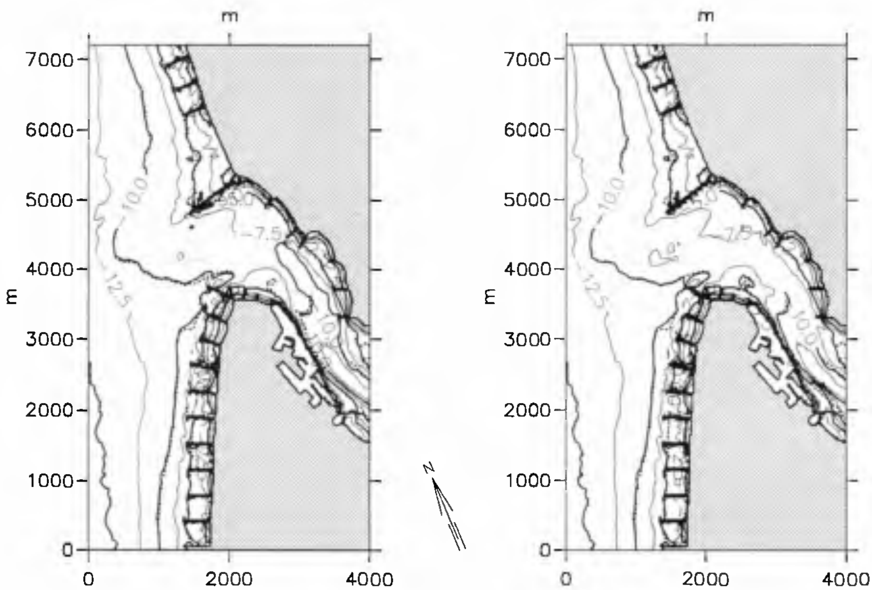

Figure 9 Comparison of accumulated bed level changes over 4 days.
Left: without clay layer
Right: with clay layer

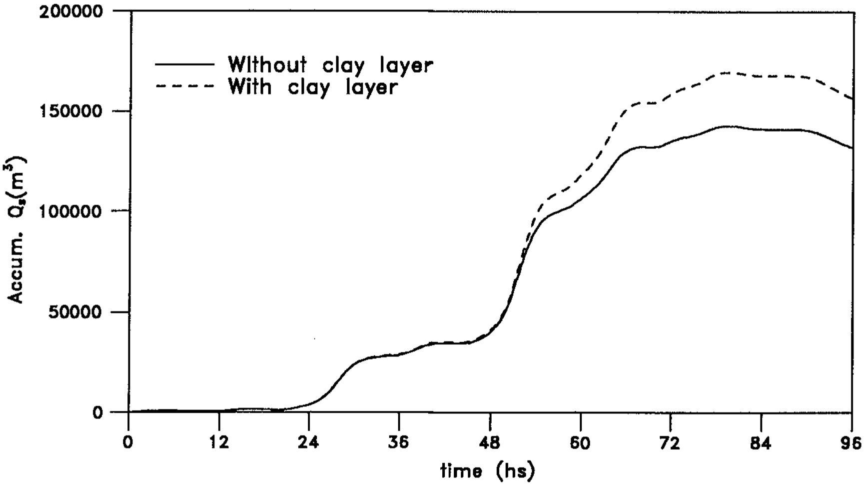

Figure 10 Comparison of sediment transport through the inlet with and without the clay layer

Another example was the observed tendency for more severe wave overtopping along the harbour protection works, which has moved further inside the channel than earlier observed. This could now be explained by the deposition and erosion patterns related to the predominant southwesterly storms which permitted the waves from northwesterly directions to penetrate further into the channel.

Sensitivity to the length of the groynes

The groyne system at Thyborøn was constructed about 100 years ago. Due to the ongoing erosion, the coastal profiles have steepened off the tips of the groynes with the result that the ends of the groynes have collapsed, and rocks from the old structures have been left at the sea bottom. The length of today's groyne system and the way in which its submerged part influences the littoral transport are therefore not known. The effect of the groynes on the morphological evolution has consequently been investigated for the two extremes: the original length of the groynes and today's length, as determined from the overwater part of the groynes.

Figure 11 shows the sediment transport on 22/1/1993 15:00 and the morphological response in the vicinity of some of the groynes in the two cases: original length of the groynes, and present length of the groynes. It appears that the flow and the sediment transport patterns and thereby the morphological response are very different for the two configurations. The example demonstrates the capability of the modelling complex to represent the interaction between the longshore current that is generated within the cells and forms a rip current along the updrift side of each groyne and the eddies generated in the lee of each groyne.

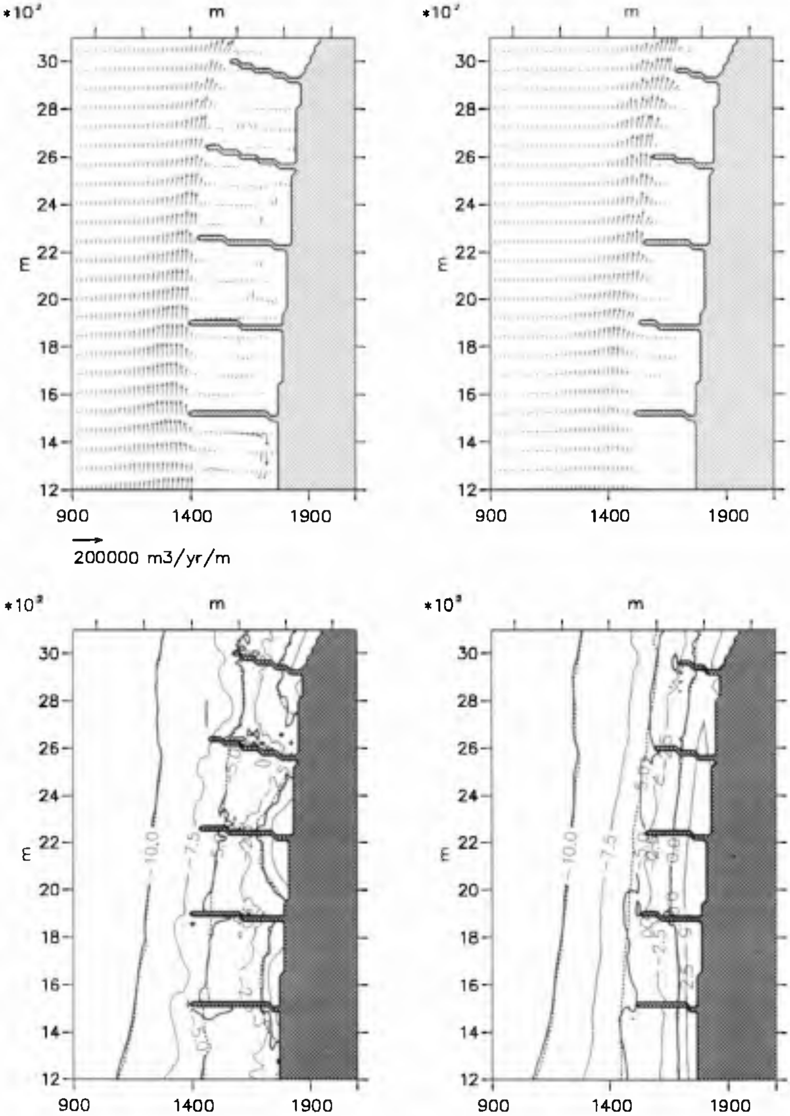

Figure 11 Sediment transport (instantaneous) and morphological response (20/1/1993 0:00 - 22/1/1993 15:00) in a groyne field during a storm. Two different lengths of the groynes are tested

CONCLUSIONS AND FUTURE PROSPECTS OF THE STUDY

Use of mathematical coastal models has cast new light on well-known coastal problems in the area and has allowed to quantify important parameters such as transport rates, spatial distributions of wave heights and current speeds, etc.

The results from the models have been useful in understanding some of the observed processes, cf. changes in erosion patterns in the channel and increased wave overtopping along the harbour structures.

Numerical models have proved to be an important tool for the analysis of different situations such as length of the groynes, existence of a non-erodible surface underlaying the sandy bottom, etc.

The work around Thyborøn is still in progress, November 1996.

More historical storms are planned to be modelled. The intention is to simulate a large enough number of different storms to reproduce both the observed sediment transport through the inlet and the development along the barrier beaches through a suitable combination of the storm events. At the present stage, only very scarce information is available on the current statistics in the inlet. A measuring campaign has been planned based on the model results, and this has now been initiated.

The model complex will be used to guide the design of possible coastal protection structures and to evaluate the effect of different nourishment schemes.

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