Modelling the Morphological Sensitivity of Large Nontidal Coastal Areas to Climatological Changes

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Abstract

This paper deals with two–dimensional hydrodynamical and morphological modelling of a large nontidal coastal area located at the German coast of the Baltic Sea. This work has been carried out in order to consider the morphological response of this region caused by climatological changes. The morphological processes in this region are mainly wave–dominated, hence a shallow water wave model was coupled with a vertical integrated flow model. Stationary simulations for waves, currents and sediment transport are carried out for a large range of meteorological situations, which were defined due to a statistical analysis of the output fields of a coupled ocean – atmosphere global circulation model. The wave parameters of this surface wave model are used as input to coastal area models.

The calculated morphological trends obtained for different meteorological situations show good agreement with the morphological changes observed in this area. By combining and weighting the individual situations the resulting flow field and sediment transport for known meteorological events can be found. The morphological sensitivity to climatological changes of the coastal area is investigated by applying this methodology to different climate scenarios.

Introduction

The prediction of the morphological behaviour of a coastal zone, for present or future environmental conditions, is a task for a coastal area morphodynamic modelling system. A system of this kind consists of coupled wave, flow and sediment transport components, which are able to describe the dynamical behaviour of the simulated area due to the feedback of morphological changes to the hydrodynamical conditions (de Vriend et al., 1993a, Nicholson et al. 1997).

In the coastal area presented in this paper, a quantification of sediment transport and of the morphological behaviour under changed environmental conditions is carried out. The

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investigated domain covers an area of about 90 km by 60 km, and is located at the German coast of the Baltic Sea (Figure 1). Attention is concentrated on the morphological behaviour of the outer coast formed by the peninsula Fischland, Darß and Zingst. Observations have shown that the Western coast of Fischland and the Northern coast of Zingst are erosion zones. At Darßer Ort, which is found between these erosion zones, accretion is observed. It is important to note that this area is located at a coast nearly without any tidal movements. Thus the definition of boundary conditions for the hydrodynamical models is very difficult due to the absence of periodical water level oscillations.

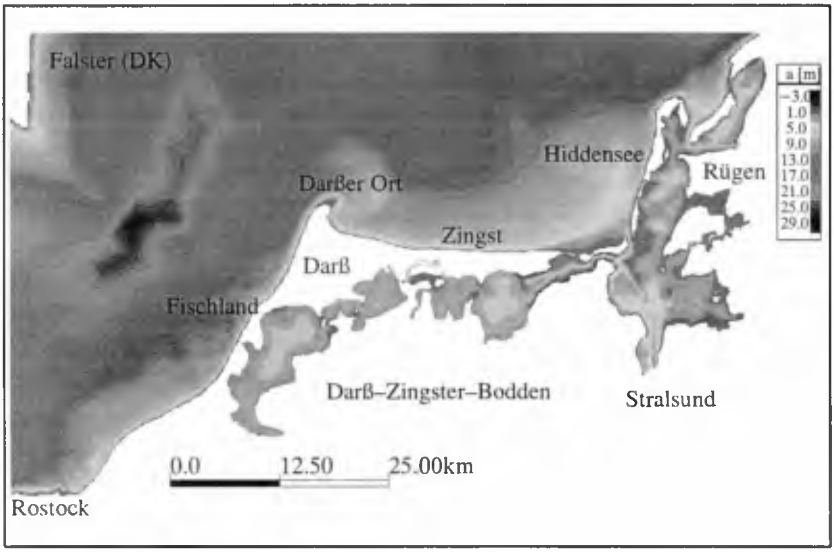

Figure 1: Domain of investigation

Waves and wave–driven currents are highly important for the sediment transport processes in this region, so emphasis was laid on the simulation of the hydrodynamical conditions in the coastal area, especially in the nearshore zone. For that purpose, a coupling of the free surface model *TELEMAC–2D* (Hervouet, 1993) and the wave model *HISWA* (Holthuijsen and Booij, 1989, 1995) due to wave–induced forces has been carried out.

The idea is to discern the effect of hydrodynamical forces on various coast sections for specific wind situations by wave and flow modelling on a large scale. The results calculated by the wave and the flow model are suitable for sediment transport calculations with regard to erosion as well as accretion zones. By combining calculated typical situations it is intended to develop scenarios which are to show the morphological sensitivity of any particular coast section to changing conditions.

In the following text, hydrodynamical simulations and sediment transport calculations will be described and scenario results will be presented and discussed with regard to their sensitivity to climatological changes.

Hydrodynamical Simulations

Flow and wave conditions in the area under research must be thoroughly understood, since the results will be decisive for the qualitative and quantitative representation of the sediment transport results, which in turn are required for the morphological findings. In order to obtain experience in the use of coupled models and in the spatial resolution required in the models, initial studies for a schematic test case have been carried out (Weilbeer, 1998).

2D–Momentum–Equation:

$$\frac{\partial v}{\partial t} + \vec{u} grad(v) + g \cdot \frac{\partial h}{\partial y} - h \cdot div\left(\nu_T \cdot grad(\vec{u})\right) = \boxed{S_y} - g \cdot \frac{\partial Z_f}{\partial y}$$

$$\frac{\partial u}{\partial t} + \vec{u} grad(u) + g \cdot \frac{\partial h}{\partial x} - h \cdot div\left(\nu_T \cdot grad(\vec{u})\right) = \boxed{S_x} - g \cdot \frac{\partial Z_f}{\partial x}$$

Source Terms:

Waves ⟶ $S_i = \frac{1}{\rho \cdot h} \cdot \frac{D \cdot T}{L} \cdot k_i$

Bottom Friction (WCI) ⟶ $S_i = \frac{1}{\rho \cdot h} \cdot Y \cdot (\tau_c + \tau_w)$

Wind ⟶ $S_i = \frac{1}{\rho \cdot h} \cdot \rho_{air} \cdot c_D \cdot u_i|\vec{u}|$

Eddy Viscosity: ⟶ $\nu_T = M \cdot h \cdot \left(\frac{D}{\rho}\right)^{\frac{1}{3}}$

Figure 2: Coupling of Models

A significant influence of grid–scale on the diversity of the hydrodynamic results was evident in these coupled wave and flow computations. The flow model as well as the wave model requires a spatial resolution of at least 10 m in order to reproduce satisfactory results. This resolution is vital since the waves, particularly in nearshore regions, undergo a number of transformations and have a high spatial variability. Furthermore, it was evident that more reliable results were obtained, if the wave–driving forces were calculated using the dissipation formulation (Dingemans et al., 1987). Wave–Current–Interaction is also considered due to an enhanced bottom friction using the parameterization of Soulsby et al. (1993), the wind stress is considered due to a coupling with an atmospheric model (Hinneburg et al., 1998) and the eddy viscosity is expressed in terms of the dissipation rate D (Battjes, 1975) (Figure 2). The most relevant processes for a wave–driven coastal area model are considered (Johnson et al., 1994, Péchon et al., 1997).

These findings were the basis for the developement of the model of the outer coast. For the wave model, high resolution is necessary in the nearshore region and demands a nesting of the area. Consequently, an elaborate nested grid system for the wave model has been developed (Figure 3) and also the FE–mesh of the flow model has been highly resolved along the shoreline in order to meet all requirements.

First the wave model is run for the entire area with a spatial resolution of approximately $\Delta x/\Delta y$ = 125/250. The boundary conditions for the eight nested grids defined in advance are retrieved from the model. Next the nested grids are calculated with a spatial resolution of approximately $\Delta x/\Delta y$ =10/25. The wave parameters (wave height, period, wave length, dissipation etc.) required for the successive models are interpolated onto the nodes of the FE–mesh.

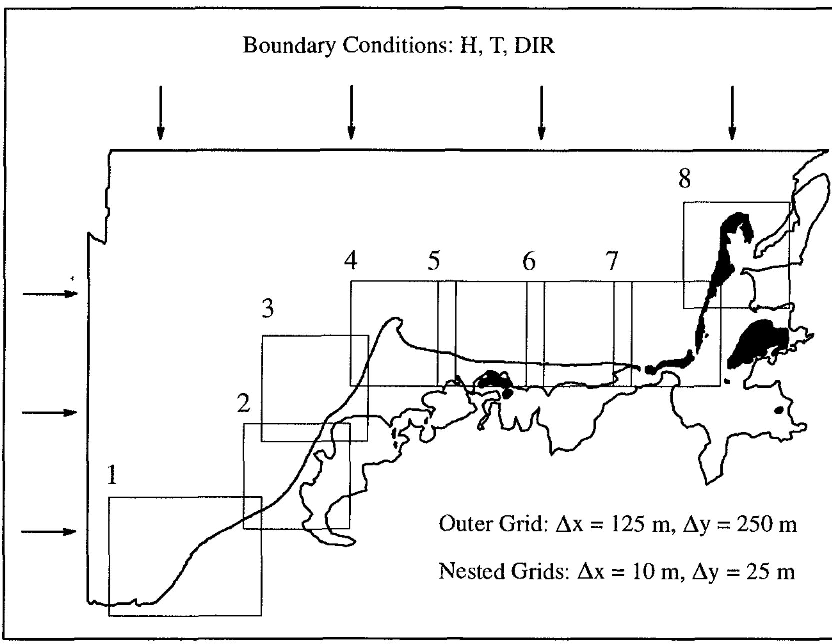

Figure 3: Nested grid system used for wave modelling

Defining the boundary conditions for the wave and the flow model presented a considerable problem for the region under consideration. The flow model requires boundary conditions at two open boundaries. It has been mentioned above that there is no periodicity as in tidal areas. Consequently, the boundary conditions have to be interpolated either by water levels measured in the area, or from a larger scale hydrodynamic model of the Baltic Sea.

However in this particular application the free surface elevation at the open boundaries in the flow model were kept constant, since noticeable water level elevations will only occur during an extreme storm event. It is true that such events will affect the bottom morphology of the area, but they cannot be completely represented by applying a method like the one used here. Instead, attention was paid to the definition of boundary conditions, i.e. wave heights H, wave periods T and incident wave direction DIR along the open boundary of the wave model.

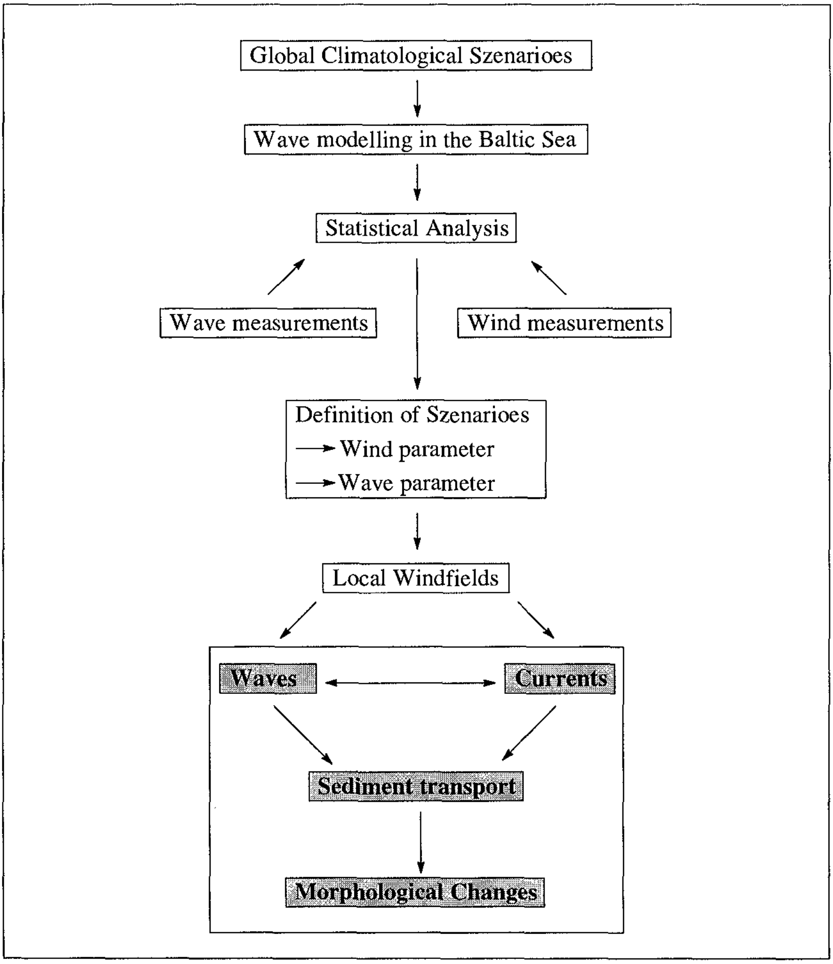

Figure 4: Modelling concept to assess the climatological impact on local coastal zones

Figure 4 presents the procedure for the compled model application. The climate input comes from global climate computations carried out at the German Climate Computation Centre (DKRZ). Wind fields calculated for a span of 13 years (1981 – 1994) were extracted and taken as input data for a sea motion model of the Baltic Sea (*HYPAS*, Günther et al., 1979, Kolax, 1998). The wave data output from this model are used as basis for defining typical situations.

First, the events were classified into 8 wind velocity classes and 12 wind velocity direc-tions. A reduction of the input data is required in order to simplify the hydrodynamic input conditions (Steijn, 1992, de Vriend, 1991, 1993b). For the required values H/T/DIR the above hindcast results, considering regional wave measurements, were used as boundary conditions for the wave model (*HISWA*). In addition, variable wind fields were used corresponding to the direction and the velocity classes.

As a consequence of the geometry, the waves can be included only in half the number of direction classes, reaching from the Southwest to the Northeast section. Since, however, the predominant wind direction in the region is West, the main directions are accounted for. The other flow fields are generated exclusively by wind-induced forces.

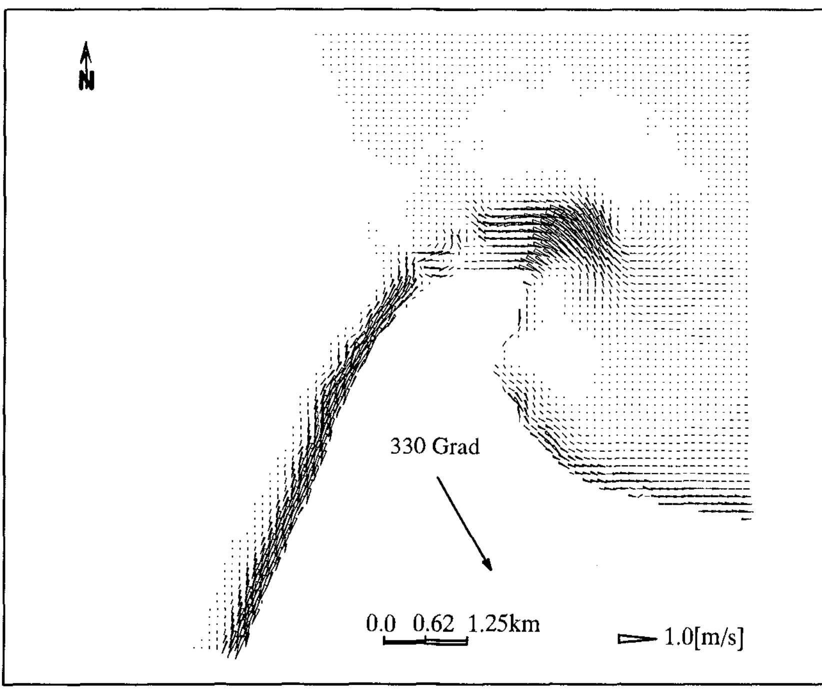

Figure 5: Current pattern near Darßer Ort (Northwest)

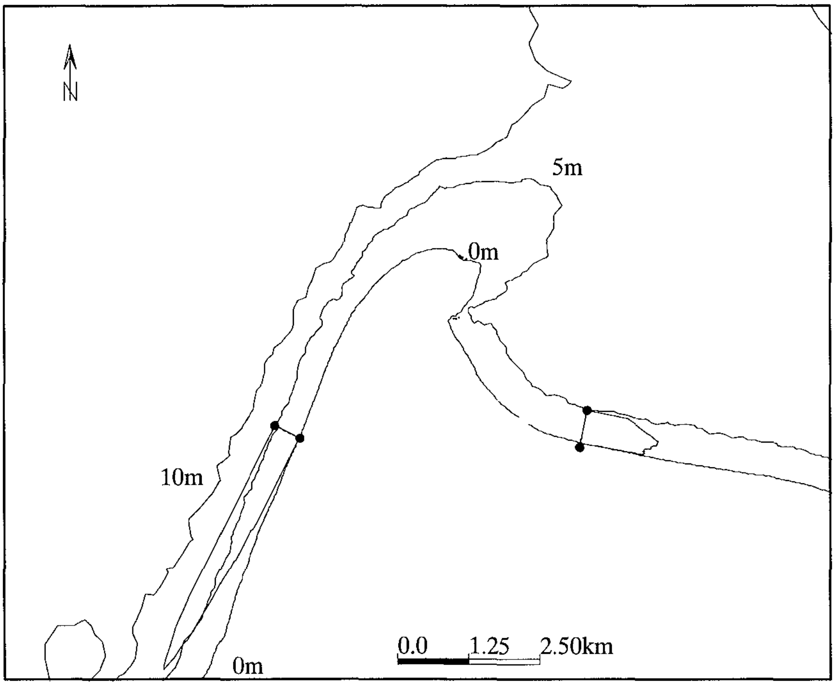

Figure 6: Typical sediment transport pattern near Darßer Ort (Northwest)

The computation times necessary for the high–resolution models limit their applicability. Continuous simulations cannot be carried out with these coupled models. A recoupling of calculated water levels and current velocities – and so a real interaction between currents and waves – is equally difficult to realize. Instead, boundary conditions and driving forces were kept constant for each situation, until stationary flow conditions had been established.

Figures 5 and 6 show as an example the current and sediment transport patterns near Darßer Ort, which are created when the wind and wave direction is from Northwest at a wind velocity of 12.3 m/s and a wave height of approximately 1.5 m. The strong longshore currents in front of Fischland as well as the protecting effect of Darßer Ort are clearly visible.

Measured time series of wind data or data obtained from climate models can be used to form statistical wind distributions in accordance with the above classification. The number of occurences (described by a Weibull distribution) leads to calculations of factors for the weighting of typical meteorological situations. As long as no changes of bathymetry are taken into account, the individual results can be combined, thus helping to find the resulting flow and sediment transport.

This procedure was carried out with a wind data series gathered over 20 years (Beckmann, 1998). Figure 7 shows the weighting factors for the average distribution of the time range 1970 – 1990. Climate scenarioes are represented by such a wind distribution, for example by a distribution for one year with extremely much Western wind, or a contrasting year (1976) with extremely little Western wind (Weilbeer, 1998). Other wind distributions could be found from measured wind data series, or else extracted from model calculations for different climate scenarios (e.g. doubling or tripling the carbone dioxide (CO_2) content in the atmosphere).

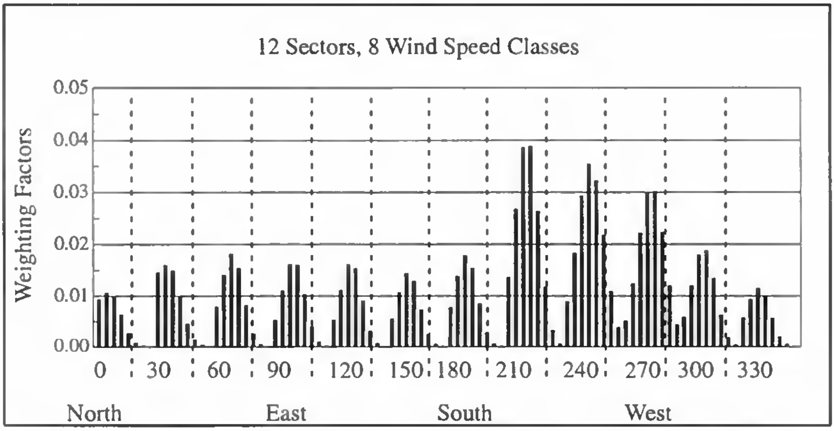

Figure 7: Weighting factors for a mean wind distribution

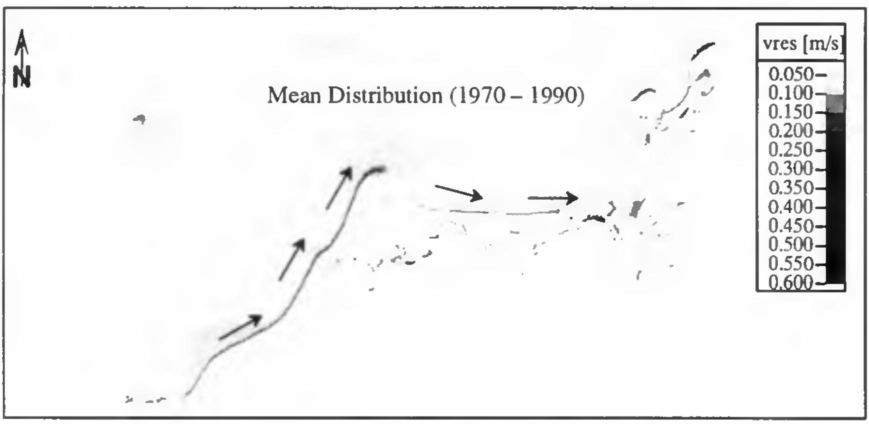

Figure 8: Resulting current pattern for a mean wind distribution

The flow resulting from this distribution is shown in Figure 8. The flow direction (represented by the arrows) is always East, as can be observed in nature. The varying flow velocities are clearly recognizable. It is particularly satisfying that the highest velocities, and consequently the probably highest hydrodynamical forces are found in those regions which are known to be erosion zones. This is due to the location of the coast line of Fischland, which is oriented nearly perpendicular to the main wind direction (West) and to the steep slope of the bathymetrie in front of Fischland. The dissipation of the wave energy offshore this coast section is rather small.

This interpretation regarding the hydrodynamical forces is a rather positive evidence. Further analyses of the hydrodynamic results, e.g. regarding bottom shear stresses, could be carried out.

Sediment transport:

This method was used for the calculation of the net potential sediment transport as well. It is practicable, in this case, to use a so-called ISE-Model (*Initial-Sedimentation-Erosion*) (de Vriend et al., 1993b). Starting from the wave and flow conditions already found, the sediment transport can be calculated in a separate run completely decoupled from the hydrodynamics. The formulations of Bijker and Van Rijn (van Rijn, 1989) on potential sediment transport due to currents and waves are used for the calculations. Then, by weighting the individual events in the way already described above, the possible resulting sediment transport is calculated.

The calculations led to annually averaged rates of sediment transport which are distinctively different. If the rates of sediment transport which arise from average conditions are taken as reference values, the rate of transport in front of Fischland is reduced up to 40% at the scenario with a weaker west wind and amplified up to 40% at the scenario with a strong west wind. The differences are not as big at the locations Westdarß and Darßer Ort. A bigger rate of sediment transport already at the medium wind conditions led to smaller differences (+-25%) at the other scenarios.

Another system behavior can be recognized east of Darßer Ort. The resulting capacities of sediment transport are growing towards the east in front of Zingst, but the differences between the scenarios are not as clear as on the west coast.

It is noteworthy that if one compares the different formulations of transport then the fuzziness in the quantitative description of sediment transport only effects the absolute rates. The percentage changes of different wind scenarioes are in general very small, although comparisons of certain events lead to bigger differences in the rates of transport. It follows that this technique can produce realistic statements on the sensitivity of this coastal area for climatic fluctuations if the present conditions are modeled accurately.

Unfortunately there are hardly any clues about how to asses the reliability of the model results at this time. Therefore they could only be checked for plausibility up to now. The growth of area at Darßer Ort suggests the order of magnitude, but can not directly be used for a model validation.

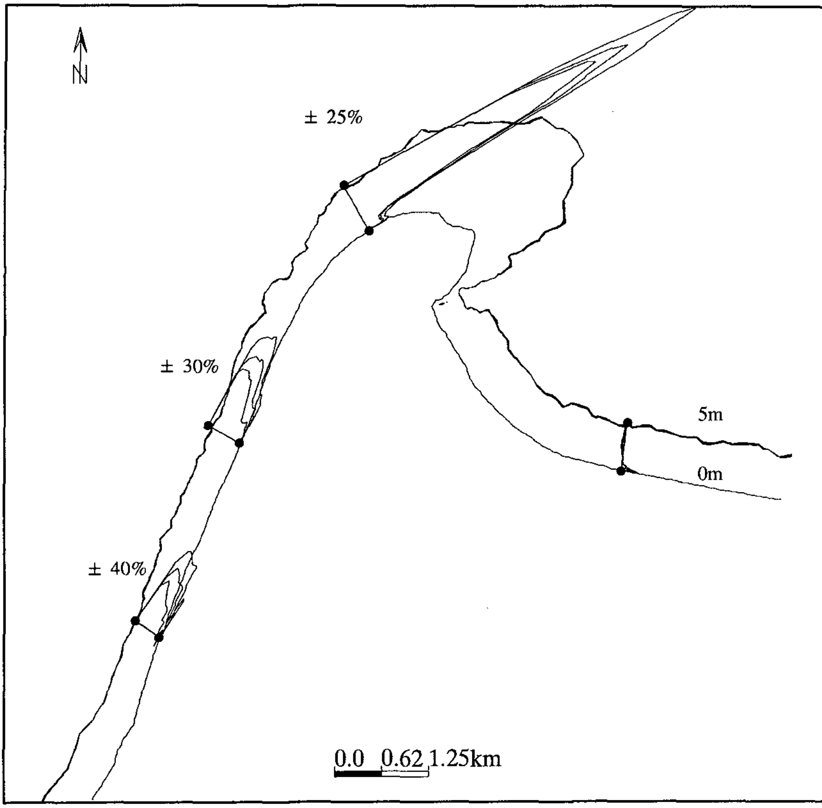

Figure 9: Resulting sediment transport for three different climate scenarioes. Potential sediment transport is calculated using the formula of van Rijn (1989)

It would, generally speaking, be possible to carry out morphodynamic calculations, but in reality they would not be feasible due to the size of the area. Application of models of this kind is limited regarding time scale and spatial scale. Succesfull calculations have been carried out in small coastal areas only, in order to find out, for example, about the changes in the bathymetry, due to constructions, such as breakwaters or groynes (Nicholson et al., 1997). The boundary conditions again are to be considered, since the effect of wave chronology, e.g. the succession of events may be decisive for a morphological development (Southgate, 1995).

Therefore, the described way was used to show the sensitivity of this coastal area to changing environmental conditions. The techniques presented here have potentials which are not at all exploited yet. Further principle and sensitivity studies can be conducted easily by using different transport formulations with more detailed approaches concerning for example suspended sediment or total load formulas.

Conclusions

A method for carrying out two–dimensional hydrodynamical numerical simulations in a large non–tidal area has been presented, with the intention to give forecasts on possible morphological trends due to changed environmental conditions. By coupling a wave model with a flow model with (wave–) boundary conditions coming from a larger numerical model, the hydrodynamical situation and the resulting sediment transport for single events can be calculated. By combining such situations, scenarioes can be developed which can be used for investigating the morphological sensitivity of this particular section of the coast.

Acknowledgements

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