A Morphodynamic Model for River and Estuary Management

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1. INTRODUCTION

The Elbe estuary as part of the German Bight of the North Sea provides the waters for the worlds most frequented waterway to the City and Port of Hamburg in Northern Germany (Fig.1). At semi-diurnal tides with a range of approx. 3.5 m, alternating tidal currents and sediments ranging from fine cohesive material such as clay or silt to fine and coarser sands signify the estuary. Maintenance of approximately 100 kilometers of navigational channel with widths ranging from 250 to 450 m and minimum depths of

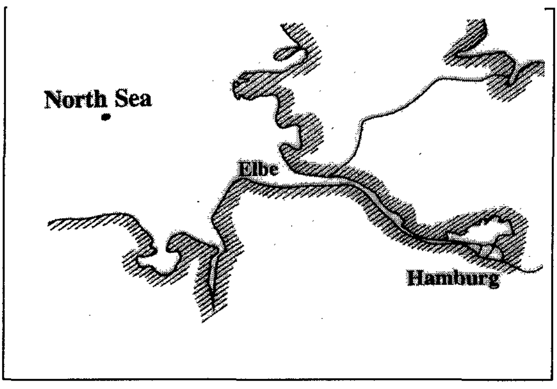


Fig.1 Elbe Estuary

13,5 m below chart datum is mostly done by dredging. Some stretches are holding natural depths of more than the required depth; in other parts the necessary flushing force of the current is achieved by concentration of flow through the arrangement of groynes and training walls.
Dredging quantities are dependent on the hydrological conditions and vary between

12 and 20 Mio. m^3 / year. In the early eighties, dredging strategies permitted material to be pumped directly ashore for deposition. However, decreasing space and increasing prices for dump sites required a change of strategy. Nowadays, most dredged spoils stay within the system. Consequently, it is dumped in deeper parts of the estuary and even of the naviagational channel. In either case, the sediment dynamics of the system will replace the dredged material and erode the dump sites and, therefore, lead to a continuous change between accumulation and erosion. Sediment which has been dredged at point A and deposited at point B can easily be transported back to A by tidal currents in no time. Therefore, the choice of dumpsites and the right time when to dump the material is of major importance.

The immediate effect of dredging operations and river training measures can easily be monitored through surveying and bathymetric comparisons. The complex nature of the estuary system and the multitude of factors of influence, however, prevent a direct correlation between bathymetric changes and the abiotic changes. This, and an effective prognosis can only be done by applying sophisticated engineering prognosis tools.

2. MORPHODYNAMIC MODELLING

The development of numerical models as engineering tools has made an enormous leap from simple 1-D-models for the simulation of hydrodynamic processes to 3D-models including the simulation of the most complicated turbulence structures in currents and waves, the transport of matter etc. Limitations are more or less set by the available computing power. While the 'real-time' inclusion of sediment transport in hydraulic modelling had found its way fairly early into physical models where scaled bed-material such as sand, coal, bakelite, ground walnut shells etc. was used to simulate the real world, the consideration of sediment transport in numerical models went through various steps of development. From a sole estimate of sediment transport on the basis of the computed hydrodynamic conditions various methods of computing sediment transport capacities were used. The hydrodynamic computation, however, was always based on a non-modified bathymetry. The step to the morphodynamic model has finally closed another gap in the suite of prediction tools by including in real time the bathymetric changes in a model (Fig.2).

The continuous calculation of the sediment transport and the sediment balance in a single grid point leads to upgrading the bathymetry at every time step. The immediate reaction of the bottom to waves and currents and, vice versa, the reaction of the hydrodynamic conditions to the changing bathymetry guarantees a much more realistic simulation of the processes than could be done with only a hydrodynamic model.

A very detailed study of morphodynamic modelling has been undertaken under the auspices of the MAST project of the European Community (Ref. Ref. To KÜSTE-paper in prep.). While the inclusion of the very details of the physical processes involved in the transport of sediment under currents and waves can be included in the simulation process, the necessity to introduce filtering procedures [3] and/or

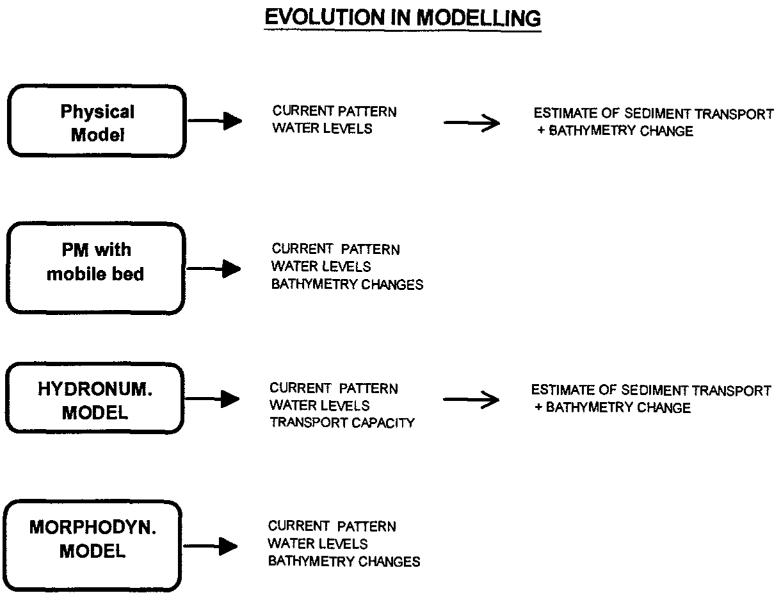


Fig. 2 Modelling Evolution

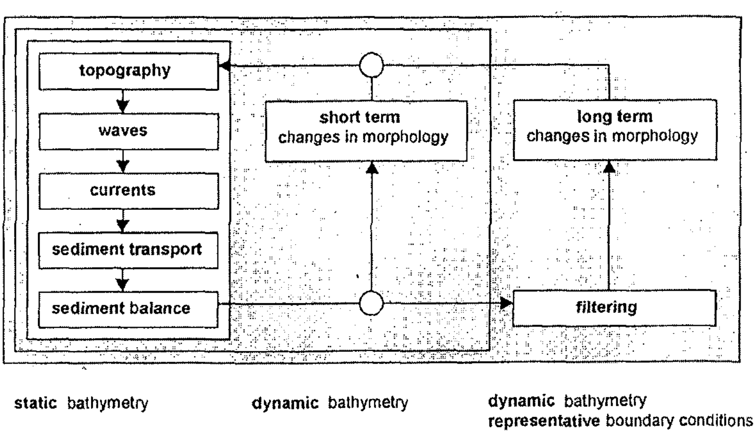


Fig . 3 Morphodynamic Modelling Concept

eliminate the influence parameters of lesser importance due to the enormous requirements of computational capacity became apparent from the beginning.

3. THE MODELLING CONCEPT

This paper describes the application of the well proven code TICAD [2] for the solution of the shallow water equations on the basis of a finite element system. The subsequently developed code TIMOR3 [7] includes the sediment transport. Basis of the morphodynamic processes is the evolution equation for the bottom:

$$\frac{\partial z}{\partial t} = \frac{\partial q_{tx}}{\partial x} + \frac{\partial q_{ty}}{\partial y} + E - S$$

with:
z = bottom elevation
q = transported quantity in x-direction
q = " " " y –direction
E = source term for erosion due to re-suspension
S = sink term for deposition

The equation is being solved numerically in time steps $\Delta t_S < \Delta t$ by an upwinding scheme. For the computation of the transported volume several sediment formulae were included in the model:

a) Integrated transport equation by Vollmers/Pernecker [8], without transition between immobility and mobility:

$$G^* = 25 \cdot Fr^* - 1$$

with

G* = dimensionless transport parameter
Fr * = Froude number of the grain

Zanke [9] expands this equation by adding a likelihood function for the incipient motion:

$$G^* = 25 \cdot Fr^* \cdot R$$

with

R = risk of motion acc. to equ. 4 in Zanke [8]

$$R = (10\,(Fr^* / Fr^*_{crit})^{-9} + 1)^{-1}$$

with

Fr^*_{crit} = Froude number of the grain at beginning of motion

The dimensionless transport parameter G* can be expressed in terms of the transported volume to be

$$G^* = \frac{q_{tx,ty}\,\rho' g}{u^{*3}}$$

with

qtx = transported sediment volume per unit of time and x-direction

qty = transported sediment volume per unit of time and y-direction
ρ' = relative density $(\rho_s - \rho_w) \backslash \rho_w$
ρs = sediment density
ρw = water density
g = acceleration of gravity
u* = shear stress velocity

This equation is set equal to the integrated transport equation to be solved for the transported volume per unit time and length:

$$q_{tx} = \frac{u_x^{*3}}{\rho' q} (25 \cdot Fr^* \cdot R)$$

$$q_{ty} = \frac{u_y^{*3}}{\rho' q} (25 \cdot Fr^* \cdot R)$$

with:

G* = dimension less transport = $q_t \rho' g/u^{*3}$
q_t = transported sediment volume per unit of time and width relative density
ρ' = relative density = $(\rho_s-\rho_w)/\rho_w$
ρ_s = sediment density
ρ_w = density of water
g = acceleration of gravity
u* = shear stress velocity

In the case of the total load based equation E and S are implicitly included in the transport formula. The simulation of erosion, suspended transport and sedimentation is solved in TIMOR3 by using entrainment-settlement-terms. The basic principle is demonstrated in Figs. 4 and 5 . Dependent on the net sediment flux of bed-load and suspended load in the bottom evolution equation the nodes of the topographic mesh change their level.

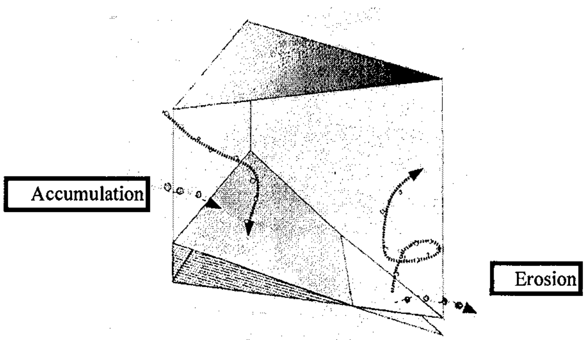


Fig. 4 Movable bed

This concept permits to continuously lift sediment from the bottom, carry it in the water column under concentration control and dump it depending on the hydrodynamic conditions. By doing this, the concentration of the suspension is not handled deterministically but simulates nature in a dynamic equilibrium. The entrainment rate for non-cohesive sediment can be taken from van Rijn [7], while the terms given by Partheniades [5] are best suited for cohesive material.

A major advantage of TIMOR3 against its predecessors is the ability to handle layered material where at every node in each layer an individual grain distribution can be defined. More than 1000 layers at each node and 10 grain size classes in each layers are possible dependent on computer capacity. Investigations with more than 100 layers have been carried out. These layers were static layers of constant thickness.

The thickness of the top layer, however, is related to the processes in the bed. As a mixing layer , which is dependent on the height of bottom ripples or dunes and follows the bed evolution, it can include one or more of the static layers. In case of accumulation active layers in the mixing zone switch from active to static one after the other. The main difference of this TIMOR3 concept to other mixing layer concepts , based only on two or three active layers [6] is the memory effect of the sediment distribution of the bottom in case of alternative and repeated accumulation and erosion. Fig. 5 demonstrates the multi-layer concept.

During the calculation the grain distribution within the active surface layers can change according to the hydrodynamic activity. As an example for the validation of the implemented sediment mixing procedure, all laboratory tests on armouring carried out by Günther [1], were re-run numerically. A main result was, that the resulting size distributions of the armour layer found by TIMOR3 were independent of the used transport formula. Only the computational time differed.

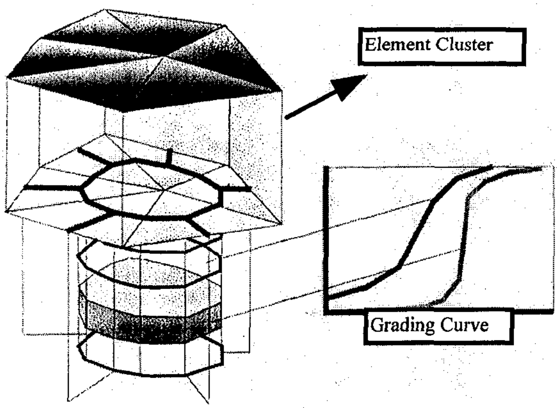


Fig. 5 The Multi-Layer Concept for an Element Cluster

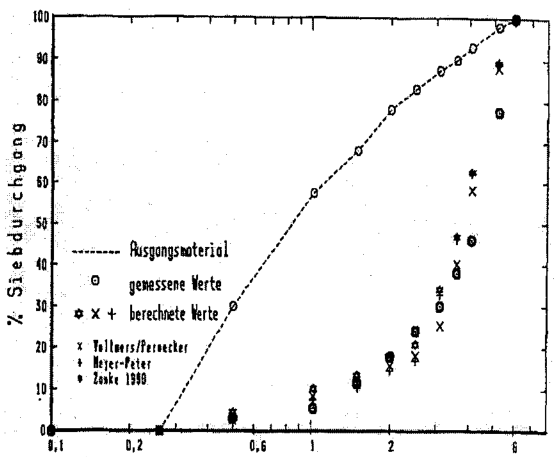


Fig. 6: Comparison between measured and calculated sediment transport

dashed line: initial cond. - o : measured values + x ✡ : calculated values

Considering the possibilities of the numerical code as mentioned before and the problems to be solved through the model application the steps in the various simulation runs, as indicated in Fig. 7 had to be followed.

The simulation of long term processes such as the evolution of an estuary under currents and waves considering the variability of the tide can be a time consuming operation. For short term simulations such a neap-spring cycle reproducing the actual tidal signal may be still feasible. However, if the development of the bathymetry and the long-term effect of construction measures is to be investigated the computational costs can become excessive. Therefore, methods needed to be developed which

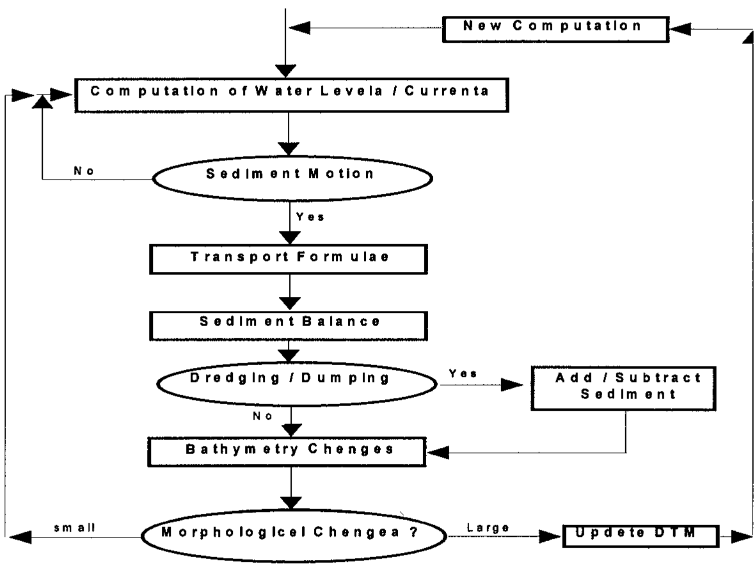


Fig. 7 Computational Steps for the Morphodynamic Model

reduce or simplify the number of events driving the model and increase the bathymetrical time step, i.e. reduce the number of updates of the bathymetry during the process.

Latteux [3] has described in detail the methods which can be applied to achieve this goal. For the simulation, e.g. of the tidal climate of one year, a limited set of natural events has to be found which forms the bathymetry as an actual set of tides would do. This could, e.g., be a weighed combination of mean and storm tides. The upgrade of the bathymetry is done at every 'tidal phase' where the definition of the "tidal phase' is not quite clear. Within this study we have achieved good results by integrating the sediment transport and bathymetric changes every x minutes with x ranging from 0.5 to 2 minutes. After extended research on the effect of mean and storm tides on the bed of the Elbe a weighted combination of mean and storm tides was used to control the model.

4. THE STUDY

The investigation area had to be selected carefully on the basis of the availability of permanent recording stations for water levels and field investigations of currents in the area. Boundaries were also chosen such as not to cut across side branches and tributaries of the river. Moreover, the area was limited by economic considerations of available computer power. Thus, a 25 km stretch of the Elbe estuary which is prone to high sedimentation and/or sediment drift, was chosen. Included in this reach of the estuary is a shallow water region where tidal flats frame the access channel to a small craft harbour, a tidal barrage and a ferry terminal. The stability of this channel is very much threatened by continuous drift and deposition of silt and clay the removal of which approaches the limits of economical maintenance. The drift and deposition of very fine sands and silt at the southern tip of the island 'Rhinplatte' triggers frequent dredger deployment and has caused several navigational restrictions in the past. Quantities to be dredged in this area can amount to several million cubicmetres if the hydrodynamic conditions show low tides combined with a frequently low or average fresh water discharge. Fig. 8 shows a map of the Elbe estuary, the main navigation channel and the investigation area.

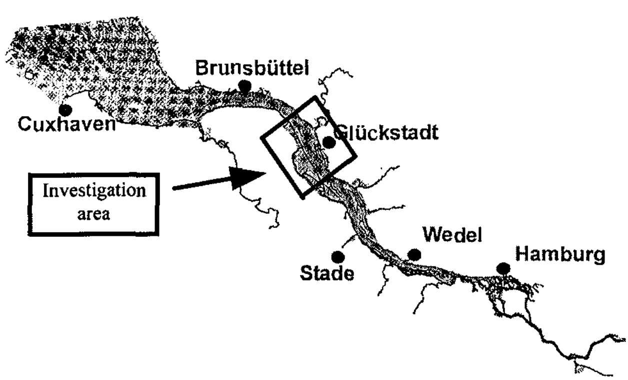


Fig. 8 Elbe Estuary With Investigation Area

Boundary conditions for the model for the calibration/ verification phase as well as for short term simulations were provided through tidal records at the lower boundary and by discharge at the upper boundary. The results of the calibration show that the match between computed and actual water elevations is not perfect. Considering, however, that prognostic runs to be carried out are based on a system comparison and 'artificial' tides are being used for model control the estuary is simulated with a satisfactory similitude. The same applies to the comparison of tidal currents as shown in Fig. 9 .

The strongly structured bathymetry of the investigation area required a high resolution in various parts. Particularly well known deposition and erosion areas, more important small tidal gullies and side branches were to be overlaid by a finite element grid with element lengths down to 15 m. The diversity of the grid is demonstrated in Fig. 10.

Generally, this pilot study for the deployment of a morphodynamic model was initiated to determine its capability to simulate short-term and long-term sediment processes as a result of man-made changes to the system. This would include

- the effects of dredging operations on the channel
- the selection of dump sites for dredged spoil to prevent backdrift into the channel
- the design of access channels in areas of heavy sedimentation, and

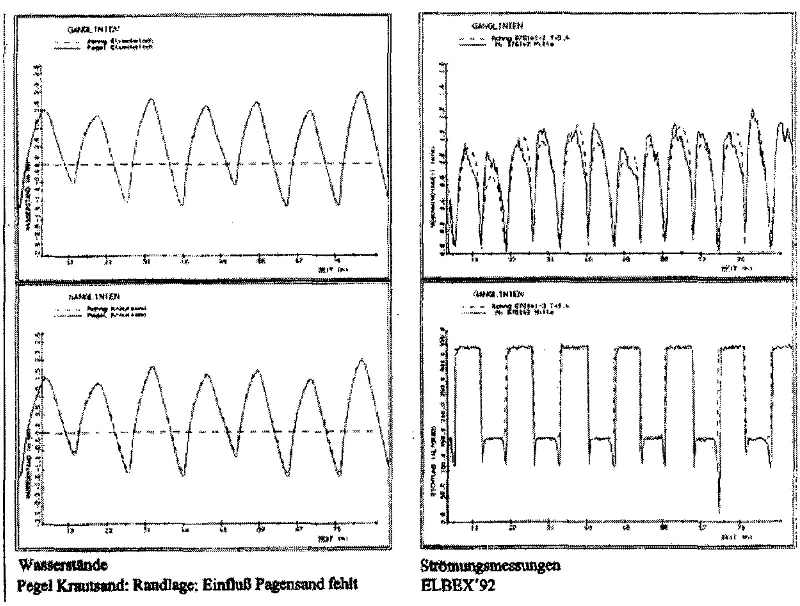


Fig. 9 Water Levels and Current Velocities - Verification Runs

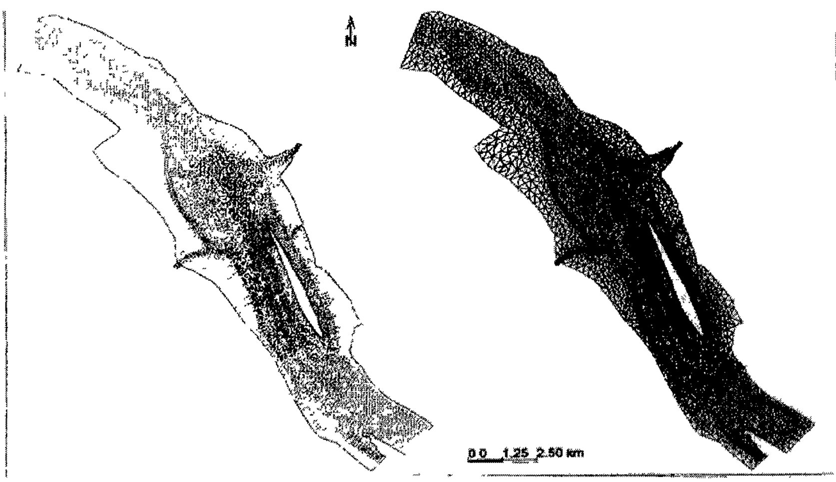


Fig. 10 FEM - Grid of 7,000 Grid Points and 14,000 Elements

- the design of river training measures for channel stability and economic maintenance

To achieve this, the evolution of the investigated stretch of the estuary was simulated for a period of **twelve and twentytwo** years with and without the usual maintenance by dredging In a pre-run and to generate an initial situation a period of two years was simulated to allow for the necessary morphodynamic adjustment of the bathymetry created from echo soundings Fig 11 shows the intial bathymetry and the changes after these two years without and with man-made changes (dredging) The difference after 12 years would give an indication of the trend in the natural development of the system. The difference after 22 years gives clues as to where the changes occur and at what order of magnitude they will occur Hence, the given time frames cannot be taken as absolute A more accurate information can be given only after intensive calibration of the model with historical developments or long-term morphological comparisons. The difficulties of obtaining continuous environmental data for the same period is well known Fig 12 finally shows the difference of 22 years of morphodynamic development with and without maintenance dredging.

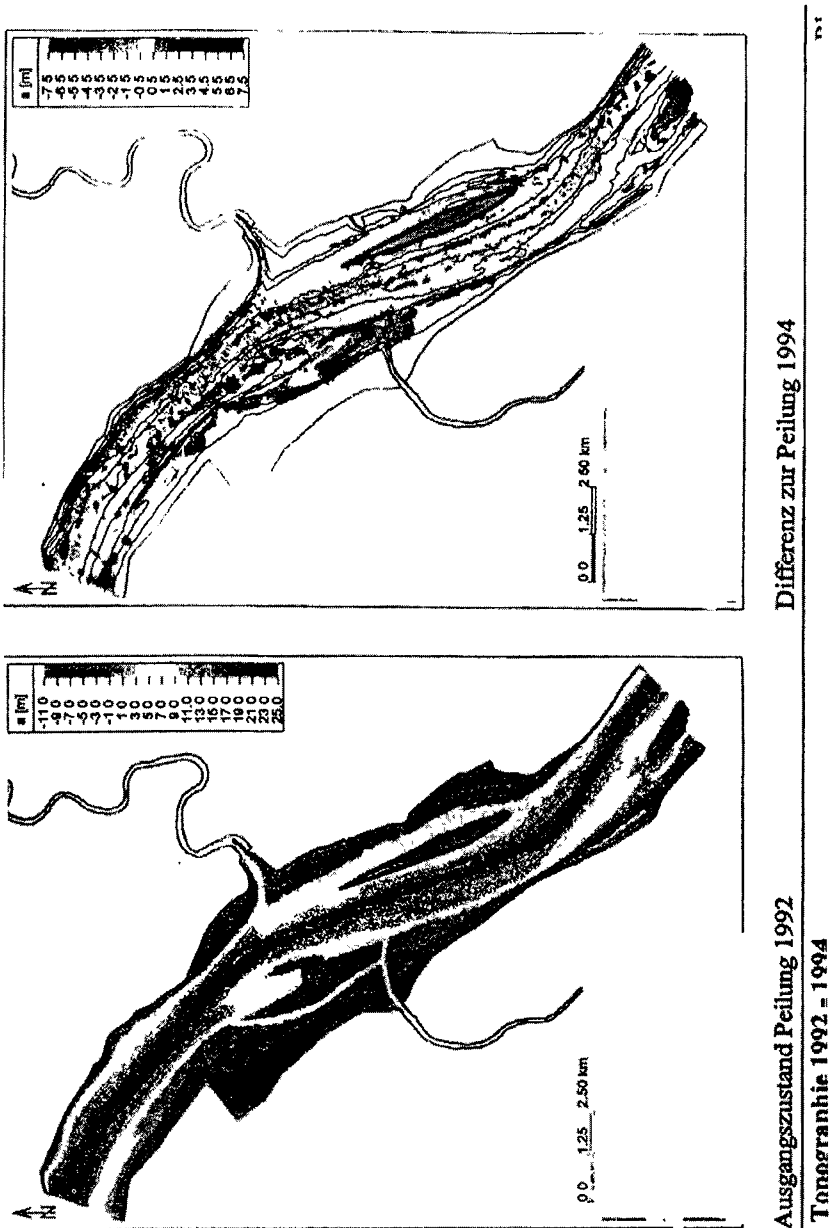
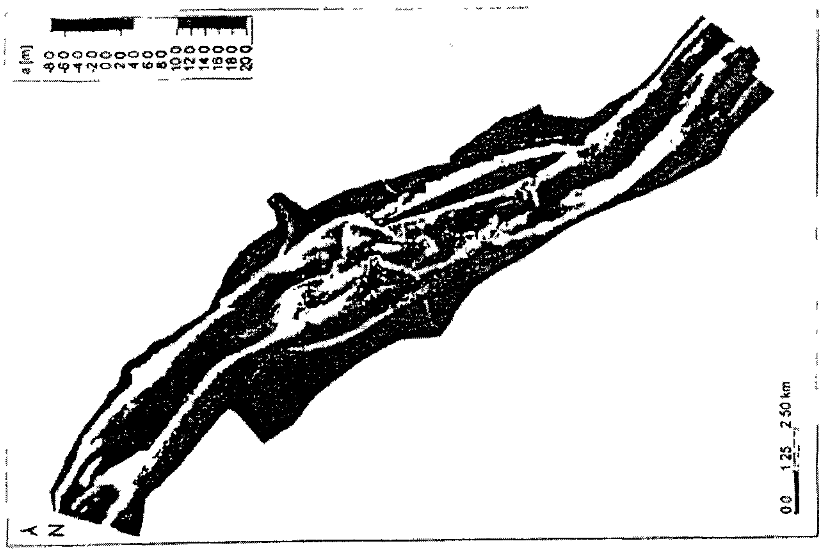


Fig. 11 Evolution of Bathymetry After 2 Years



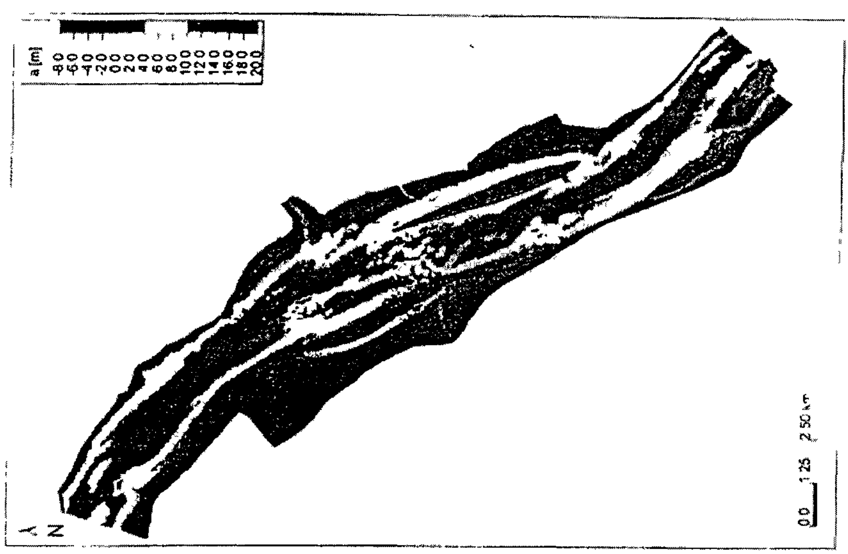


Fig. 12 Development of the Investigation Area in 22 Years Without (Top Graph) and With Maintenance Dredging

Even though the grey shading in the graph cannot well reproduce the differences between the two stages of development as the original coloured graph could the effect of maintenance can well be detected. Without going into detail here one can interpret the results of the
investigation in a way to show

- the effects of dredging activities for the channel and adjacent areas,
- the effect of dumping operations on the bathymetry,
- possibilities to change dredging strategies, and
- the imminent danger of meandering of the system if maintenance is not carried out on a regular basis.

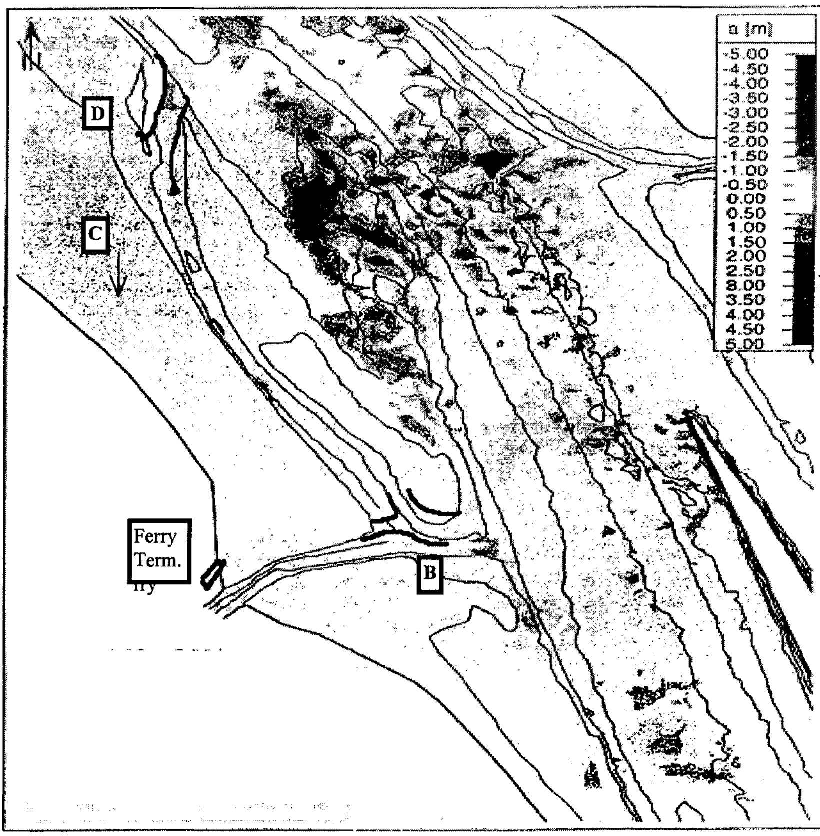


Fig. 13 Investigation Area of the Ferry Access Channel - Alternatives

In a more detailed analysis of short term changes for the ferry access channel a morphodynamic development period of one year was simulated. This included the existing situation and various alternatives which theoretically should improve the situation (Fig. 13).

The investigation showed clearly that none of the proposed alternatives would improve the existing set-up. This is demontsrated through the graph in Fig. 13 showing the quantities to be dredged annually according to the numerical simulation. These quantities are in accord with the acctually dredged material.

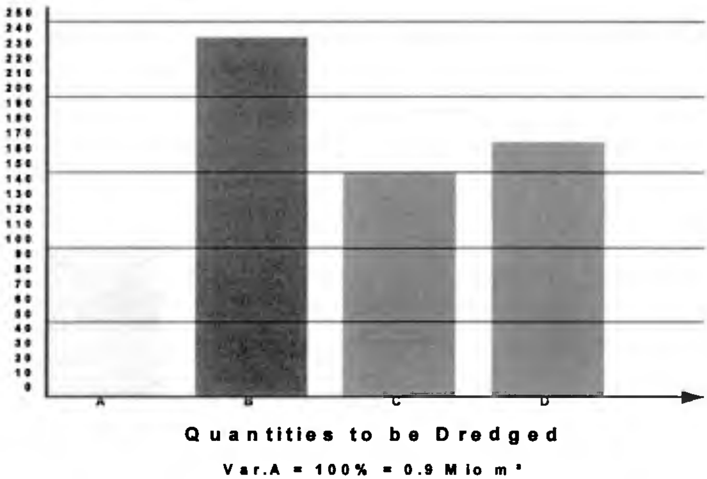


Fig. 14 Quantities of Dredged Spoil for Alternatives A - D

5. CONCLUSIONS

The investigations with a morphodynamic model set up to simulate the short-term and long-term sediment processes in an estuarine environment revealed that

- the model can be used as an economical engineering tool to plan and/or optimize dredging operations and river training measures,
- with a suitable hardware basis the calibrated model can even be deployed as a case-to-case- tool for maintenance dredging when changing tidal patterns required an immediate decision for dump sites,
- the comparison between the one-grain-model and the multi-layered system clearly

points towards the latter. However, for cheap and fast analysis, the simple model may be sufficient.

A major conclusion from this model study is, that the set-up, calibration, verification and running of a morphdynamic model requires the cooperation and functioning-as-a-team of experts from various disciplines. The interaction of these experts who seldom can be united at the same location is a major basis for the economic and successful conclusion of studies of larger extent. Therefore, a project has been intitiated which combines the expertise from various fields in a 'virtual institute'. Utilizing modern information and communication technology on the basis of the INTERNET these experts collaborate form various locations in the same project. Further information about the MORWIN-project and a copy of the first milestone report can be obtained through

hhtp://morwin.bauin.uni-hannover.de

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