ANALYSIS OF THE MORPHODYNAMICS OF THE GERMAN NORTH SEA COAST ON THE BASIS OF A FUNCTIONAL SEABED MODEL

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ABSTRACT

The knowledge of the hydro- and morphodynamic realities and the resulting large and small scale shaping processes in marginal seas, coastal regions and in estuaries are the basis for planning of economic and ecologically compatible measures in the area of coastal protection, renewable energy and shipping. Research in recent years has contributed significantly to the morphology seen as a representation of hydrodynamic and meteorological forces.

A databased hindcast morphodynamic simulation model is presented to fill the gap between measured data and process based simulation models.

The so called functional Seabed Model is based on bathymetric and sedimentologic data sets in space and time. It builds the basis for morphodynamic analysis in the German Bight and provide data for process based numerical simulation models.

The structure and functionality of the essential components of the soil model are described. Special analysis and interpolation techniques are explained in more detail for the bathymetrical and sedimentological component.

1. INTRODUCTION

The morphology in the coastal area of the German Bight has a pronounced richness of forms. Especially in the field of amphibious coastal area and in the estuaries a large spatial variability of water depths can be observed. Flood plains, tidal flats, shallow water areas, many branched tidal creeks and channels are the basic elements in the German Bight. Also the mixture and the properties of the seabed are of very different natures.

The assessment of morphodynamic changes and associated shaping processes are the basis for sustainable coastal protection and development concepts. Numerical simulation models have become an important engineering tool. But just in setting up and operation of morphodynamic simulation models, there are many uncertainties in the parameters and boundary conditions. On the other hand, nature observations and measurements have always been the basis for the understanding of the morphodynamic processes. However, field measurements are also associated with uncertainties. The combination of data and process-based models leads to a reduction of the model uncertainties.

The development of a data based seabed model in combination with computational methods is presented below. The results presented are partly developed in the joint project “Development of

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integrated model systems to analyze the long-term morphodynamics in the German Bight – AufMod".

2. FUNCTIONAL SEABED MODEL

The functional seabed model is the computer-oriented implementation of a dynamic data-based model to describe the uppermost layer of the seabed. The model concept is space- and time-variant, to the extent permitted by the data availability.

2.1 Concept and Components

The generalized concept of a digital seabed model in time and space is based on the composition of measured data, interpolation and approximation methods in time and space in combination with morphodynamic interpretations. The functional seabed model consists of components for:

- bathymetry,
- bed-forms and
- sedimentology.

The functional seabed model is supplemented by a static model of consolidated horizon.

2.2 Functionality

The functional seabed model provides at any place in the German Bight and on any date (from 1950) the following quantities:

- altitude of the seabed,
- dune parameters,
- thickness of the mobility sand layer,
- sediment cumulative curve,
- proportion of the organic components and
- porosity.

This information is provided with appropriate confidence (fuzziness).

3. BATHYMETRIC MODEL COMPONENT

To describe the changes of the bathymetry we consider the digital terrain model as a continuous function z(x,y,t) in space and time. This digital bathymetric model in space and time is represented by discrete survey points and associated interpretation methods.

3.1 Bathymetric Database

The digital bathymetric model component currently consists of approximately 16.500 data sets with 1.75 thousand million survey points. The bathymetric data from different institutions are complemented by digitized maps and alternative models for hydraulic structures. The data sets in combination with appropriate metadata are stored in a database system. The selective access via the metadata allows an efficient management and maintenance of the database. The bathymetric data base covers large parts of the German Bight from 1950 until the present day.

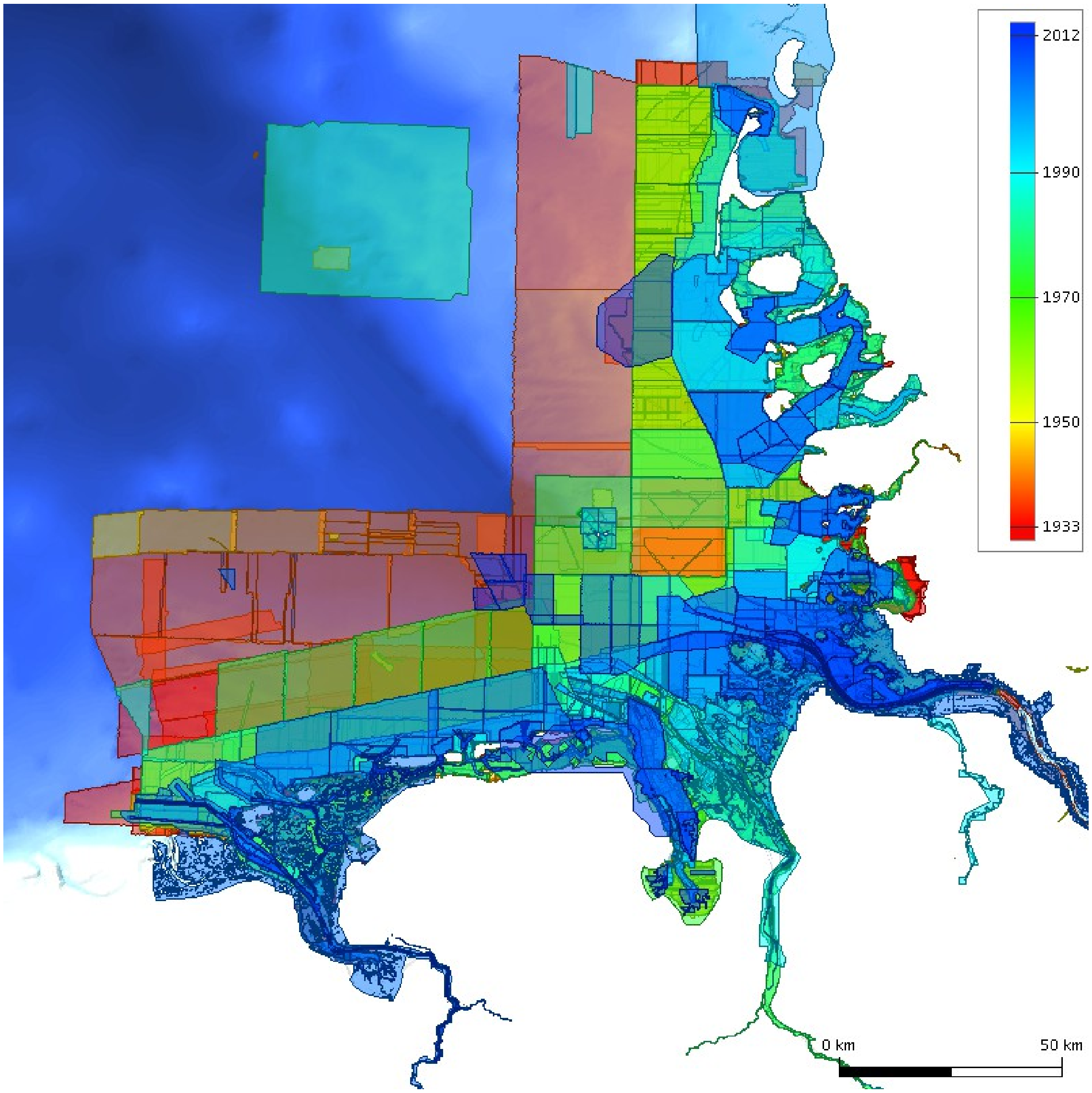

Figure 1 Metadata of the surveying data in the German Bight

For each data set the spatial confidence region, the temporal confidence interval, the accuracy of measurement and the recommended interpolation method are specified in the metadata.

3.2 Space-Time Interpolation

For the determination of a quasi-synoptic bathymetry at any time, temporal interpretation methods have to be additionally introduced, and temporal ranges of confidence have to be defined. A quasi-synoptic digital bathymetric model on a specific date can now be considered as a horizontal section in the spatial and temporal range of confidence (see figure 2).

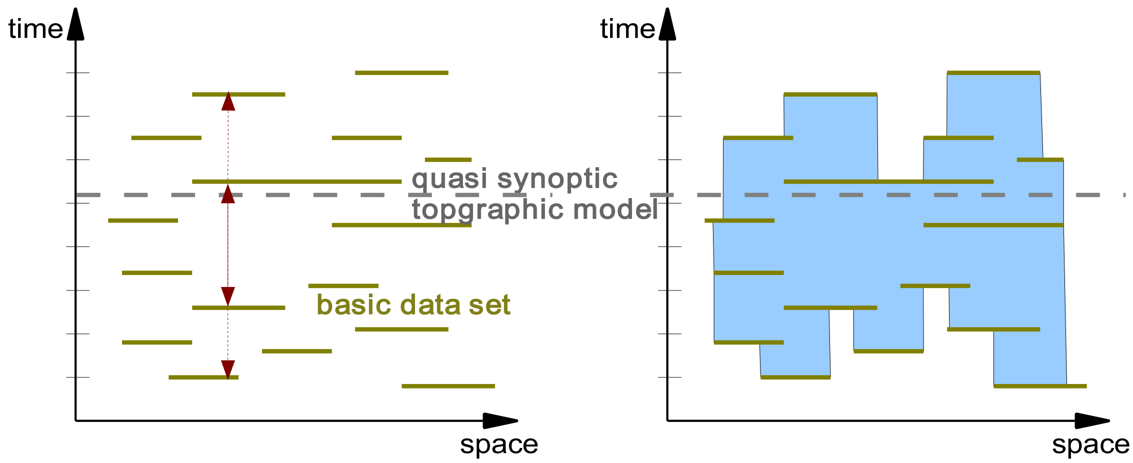

Figure 2 schematic space-time interpolation and temporary confidence region

To determine the depth at a specified sampling point on a date, first interpolations in space on temporally adjacent surveys are made and then these values used for interpolation in time. In Figure 3 on the left side the depth distribution in the German Bight on a 50m grid are shown on 01/01/2006. On the right side the associated absolute confidences are shown.

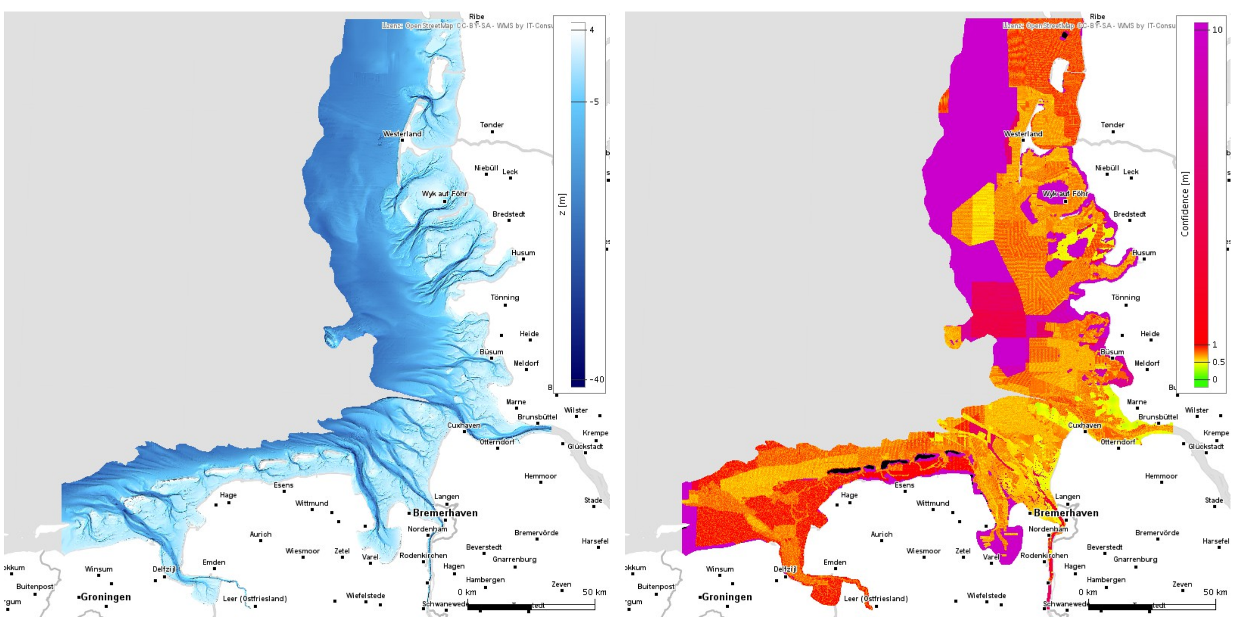

Figure 3 depth distribution for 01/01/2006 and associated absolute confidence

The determination of the absolute confidences is based on the combination of the relative confidences that are induced by the interpolation and the accuracy of the measurements.
Most of the spatial and temporal interpolation can be described in the following simple form:

$$z(x)=\sum_i \lambda_i(x)\cdot z^i$$

The basis functions λ can assume values from 0 to 1. A value of 1 is assumed by the basis function i, if the interpolated position x is exactly located at the grid point i. Thus, the largest λ is a good indicator for the relative confidence of the interpolated depth value. The relative space confidence can be determined in each measurement and then interpolated in time. This interpolated space confidence is then multiplied by the relative confidence in time, so that the spatial and temporal relative confidence arises. This parameter describes the uncertainty in determining the depth, which is exclusively induced by the interpolation. In a further step, the uncertainties of measurement are linked with the relative uncertainties.

For numerical simulation models, special requirements are made on the bathymetric approximation. The grid points in numerical simulation models usually do not describe the depths at the points themselves, but they represent the average depths for the corresponding regions. This requires complex integration processes on the associated Voronoi regions of the calculating points. The faithful representation of the volume in numerical grids leads to a better comparison of natural data and simulation results.

3.3 Bathymetric analysis and evaluations

Simple analyzes can arise from differences between the quasi-consistent bathymetries, for example maps of erosion- and sedimentation zones. In addition to any location within the study area, the time series of depths can be calculated. These time series can then perform statistical and functional analysis studies. Based on these time series, morphological parameters like changes in depth (dz/dt) or „morphological space" ($z_{max} - z_{min}$) can be derived or volumetric calculations can be performed. Figure 4 illustrates the morphological space and drive (the highest absolute value yearly changes in depth) for the coastal and near-shore area of the German Bight.

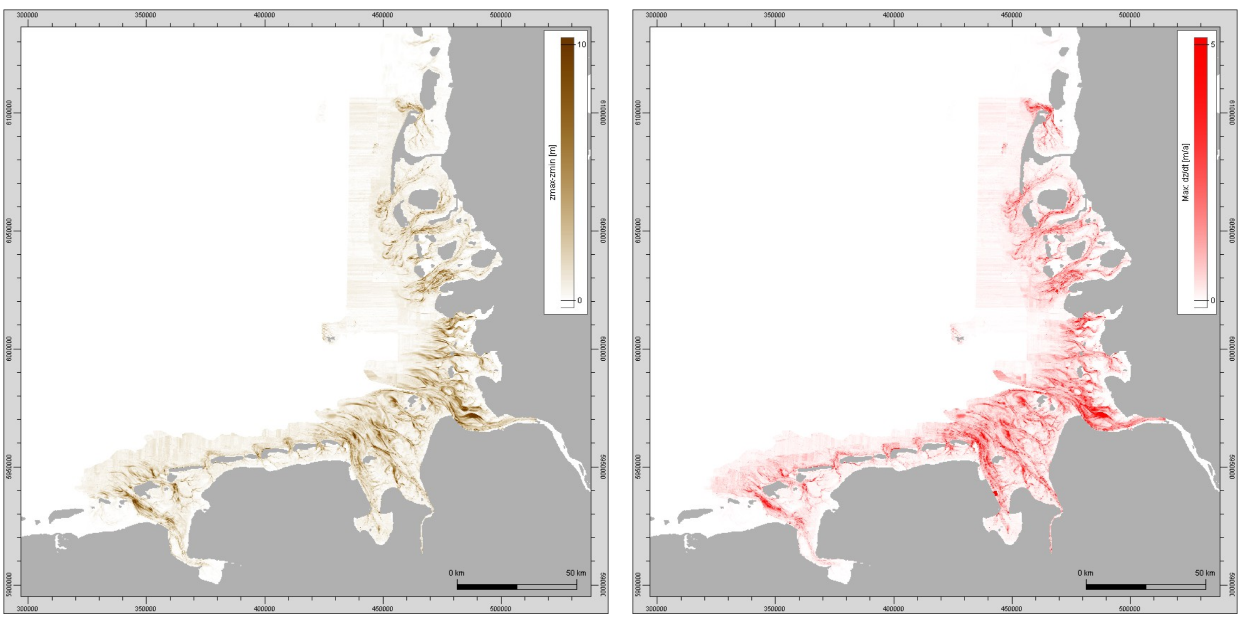

Figure 4 morphological space and drive of the German Bight

The information about the morphological activities, like erosion, sedimentation or the movement of morphological structures, e.g. of tidal channels, is important for the safety of waterways and shipping as well as for planning of sustainable routes for cables or gas pipelines.

The bathymetric database of functional seabed model, for example, can suggest that the tidal flats in the German Bight are volumetrically grown over the last decades. In detail, these changes vary spatially and temporally. Greater changes have occurred for example in the last 10 years in the area

of the Elbe estuary. In 2006/07 there was a big breakthrough for a Tidal channel named Medemrinne.
This breakthrough was a large-scale effect, which can be seen on the chart in figure 5.

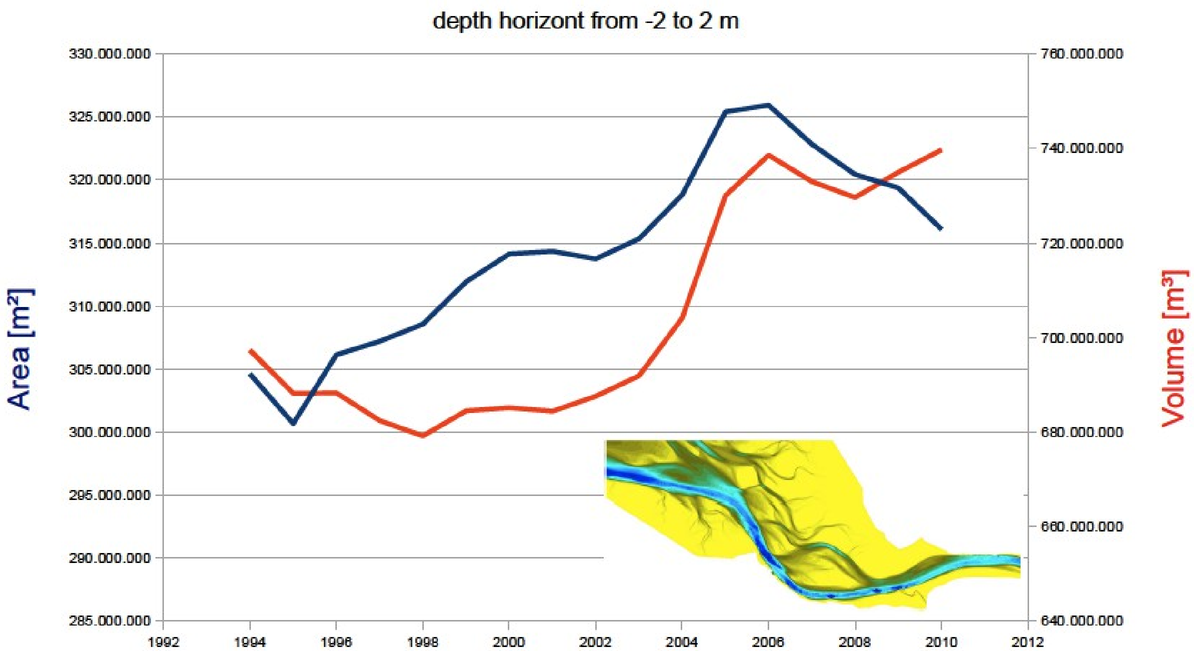

Figure 5 development of the tidal flat in the Elbe estuary (depth distribution 2010)

3.4 Morphological Velocities

If digital bathymetric models are understood as three-dimensional continuous interpolated functions $z(x,y,t)$ in space and time, it is easy to determine the gradients (dz/dx and dz/dy) within a measurement data set. The temporal gradient of the depth (dz/dt) can be determined by using finite differences on rays parallel to the time axis and thus areas of erosion and sedimentation can be identified.
To describe the transformation of local structures, such as the move of tidal channels or the fall of coastal lines, morphological velocities $\partial \vec{x} / \partial t$ are introduced. The morphological velocity is defined as the velocity of the movement of bathymetric characteristics. Such bathymetric or terrain characteristics are shorelines, tidal channels, transport bodies etc. that can be generally characterized by isolines or breaklines. The determination of morphological velocities can be based on the theorem of implicit functions. The isoline to the value k can be described implicitly by the function $R((x,y),t)=z((x,y),t)-k=0$. The theorem of implicit functions states, that if the equation $R((x,y),t) = 0$ (an implicit function) satisfies some mild conditions on its partial derivatives, then one can in principle solve this equation for $x(t)$ and $y(t)$, at least over some small time interval. Moreover, this theorem delivers the morphological velocities where the local space gradients are not zero:

$$\frac{\partial x(t)}{\partial t} = -\left(\frac{\partial z}{\partial x}\right)^{-1} \cdot \frac{\partial z}{\partial t} \quad \text{and} \quad \frac{\partial y(t)}{\partial t} = -\left(\frac{\partial z}{\partial y}\right)^{-1} \cdot \frac{\partial z}{\partial t}$$

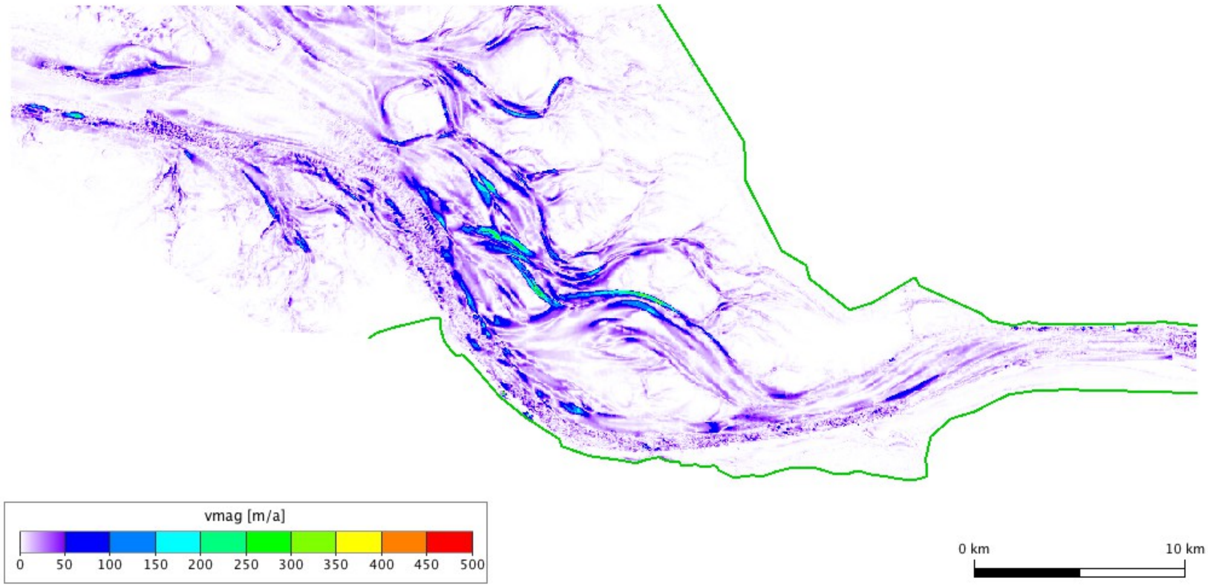

Figure 6 Magnitude of morphological velocities for the period 2009-2010

In Figure 6, the morphological velocities in the Elbe estuary is illustrated. The high speeds of up to 500 m/year at the channel edges are clearly visible.

3.5 Databased Morphodynamic Hindcast Simulation

The data-based hindcast simulation model is implemented in a similar way to classical process-based numerical simulation models. For the simulation, the nodes of a grid and time steps to export the result data are specified.

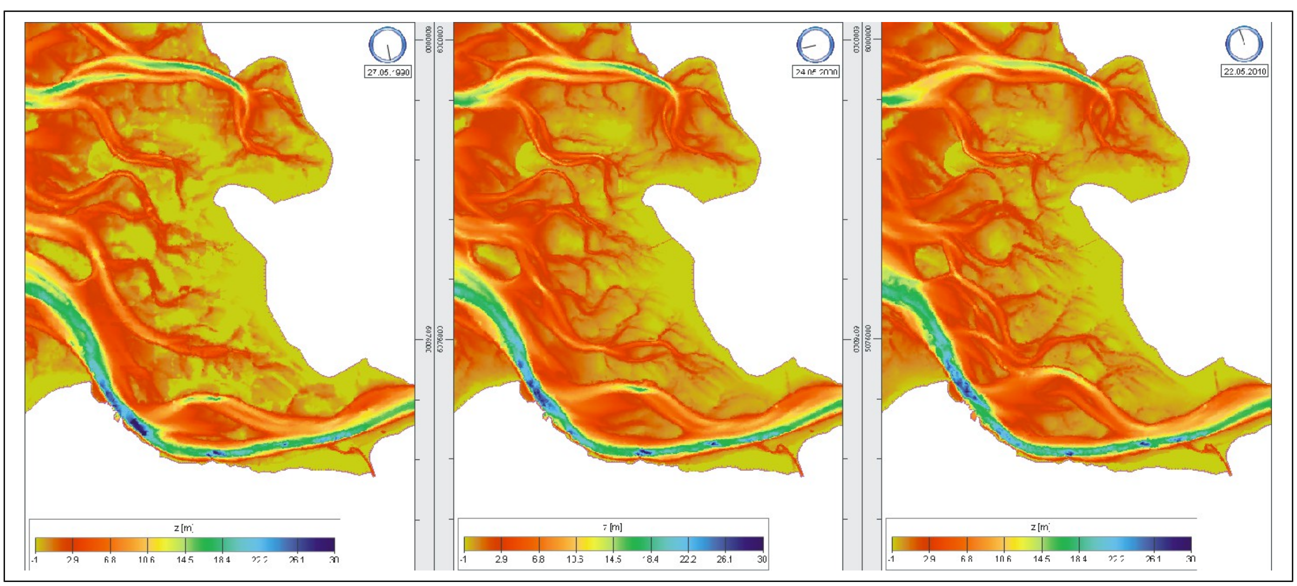

Figure 7 Hindcast bathymetry simulation for the elbe estuary (1990, 2000, 2010)

In the output file the depth, the erosion and sedimentation as well as morphological velocities are logged. The results of hindcast simulations are well suited for the plausibility of morphodynamic simulation models.

A direct link with the process-based hydrodynamic model is provided, and opens up the possibility that changes in ocean waves and currents, which are caused by the bathymetry, can be represented in the simulation model accurately.

4. SEDIMENTOLOGIC MODEL COMPONENT

The computer-oriented description of the composition and properties of the seabed is not as well developed as those of the bathymetry. The sedimentological model component describes the surface of the seabed, using particle size distributions, porosity and the organic portion. The particle size distributions are stored as a sum curve in a logarithmic scale, according to their resolution. The reference points of the sediment cumulative curve are interpolated using linear or constrained cubic spline interpolation (see Kruger CJC). Porosity and organic portion are described by scalar quantities. The sediment model component consists of 63-thousand sediment samples with different characters from various data collectors over the period 1941-2010 (see figure 8).

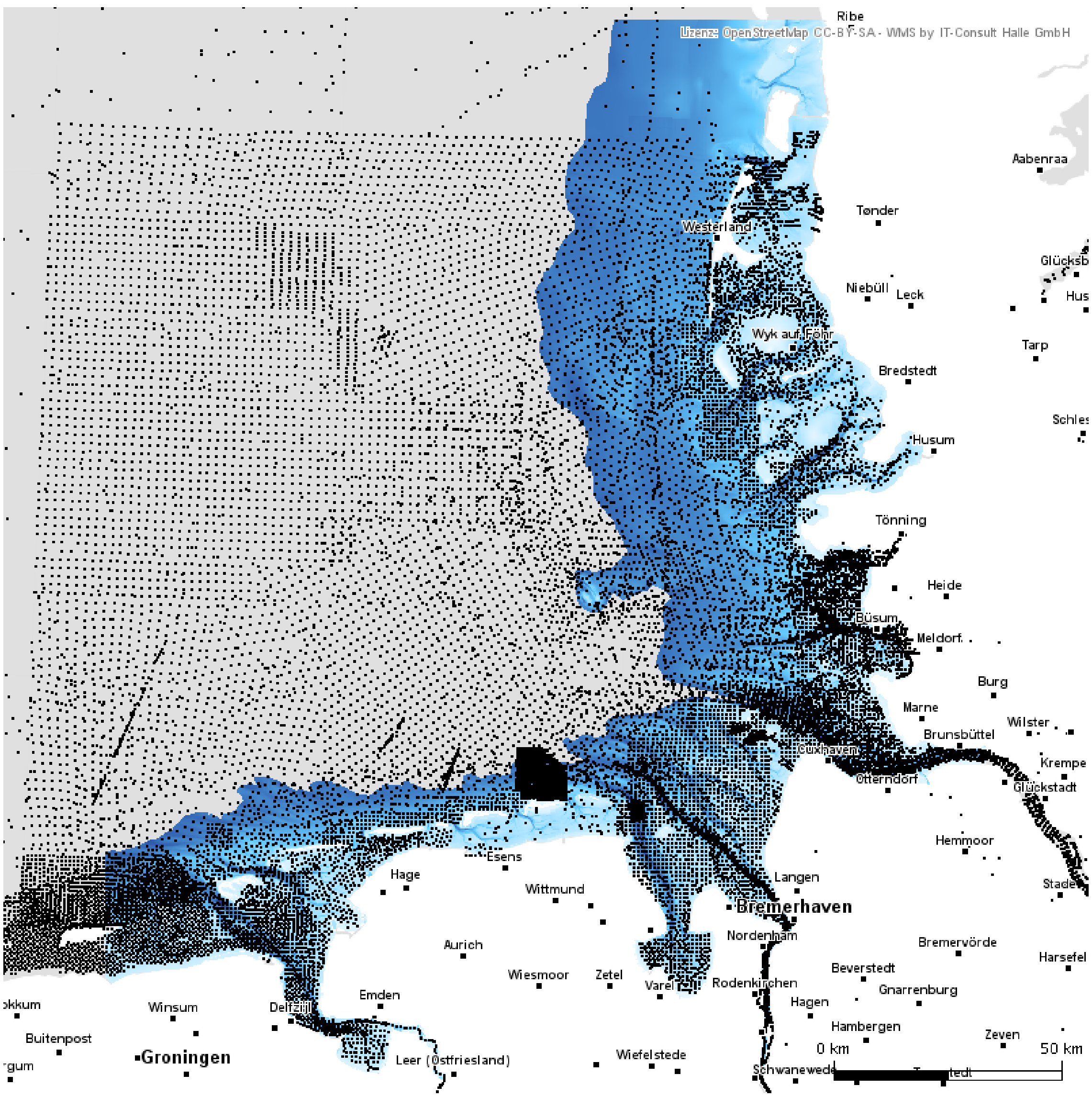

Figure 8 location of the sediment samples in the German Bight

The sedimentological data are much more sparsely distributed in space and even more so in time. Therefore special interpolation and approximation methods must be used.

4.1 Anisotropic Interpolation

The spatial interpolation on sparse data requires specially adapted interpolation. Traditional interpolation methods can be significantly improved by the addition of physics. An anisotropic shepard interpolation is used for spatial interpolation. The circular classical metric is deformated on the basis of a vector field to an ellipse. As an example, resulting flows over a tide can be used as the anistotropic vector field. The best results were obtained when the resultant sediment transport has been used over a year. Particularly in areas where the bathymetry changes greatly, the most differences can be seen in the interpolation. The result of this interpolation is always a complete sediment cumulative curve. In Figure 9 the derived d_{50} and particle sorting are seen.

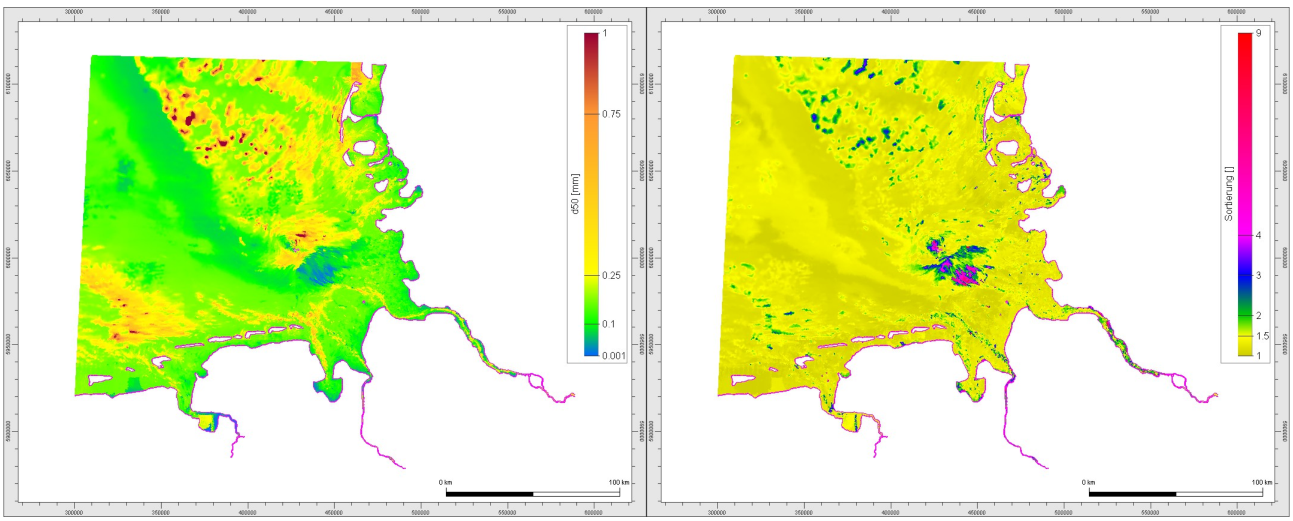

Figure 9 distribution of the mean grain diameter d_{50} and the sorting coeffizient in the German Bight

Based on the interpolated sediment cumulative curves different views can be derived, for example, maps for the fine sand fraction or sedimentological initial allocations for numerical simulation models.

ACKNOWLEDGEMENTS

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REFERENCES

Kruger CJC: Constrained Cubic Spline Interpolation for Chemical Engineering Applications. (http://www.korf.co.uk/spline.pdf)