Proceedings of 5th International Conference in Ocean Engineering (ICOE 2019)

28th July to 1st August 2019

DATABASED HINDCAST SIMULATION AND ANALYSIS OF THE MORPHODYNAMICS OF THE GERMAN BIGHT ON THE BASIS OF A FUNCTIONAL SEABED MODEL

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Abstract: The concept of a databased geomorphological hindcast simulation model as sets of basic data and corresponding interpretation rules in space and time provides new evaluation methods, e.g. to obtain new evaluation methods of large scale morphodynamic processes from measured data. This paper presents the basic concept of the so-called Functional Seabed Model (FSM), corresponding time-space interpolation methods and procedures for adequate geomorphological analysis.
Exemplary morphological analyses are presented for the German Bight with its morphologically active tidal flats and estuary systems.
The FSM can help to understand the effect of different morphologic features on dispersion and hydrodynamics in coastal Regions and estuaries.
Keywords: bathymetry; databased hindcast simulation; sedimentology; Functional Seabed Model.

INTRODUCTION

The German Bight, located in the southeastern part of the North Sea has a pronounced diversity of forms, e.g. offshore islands, estuaries and tidal flats. Changing environmental conditions through global climate change and the associated rise in the mean sea level as well as the different anthropogenic requirements for use need a better understanding of the hydro- and morphodynamic trends in the German Bight. This is crucial for coastal defense, cost-effective maintenance of shipping lanes and planning of coastal infrastructure (e.g. submarine cables) as well as, more recently, environmental assessment in the context of implementing EU directives. Historically bathymetric and sedimentological observation and survey data over a very long period of time are used to analyze and describe morphodynamic changes on the German North Sea coast. Alternative methods today are process-based numerical simulation models. Surveying and observation data are still of central importance for the calibration, validation and operation of such hydro- and morphodynamic simulation models.
In the joint project EasyGS-DB the Institute for River and Coastal Engineering at the Technical University Hamburg-Harburg (TUHH), Federal Waterways Engineering and Research Institute (BAW), the Federal Maritime and Hydrographic Agency (BSH) and the companies Küste&Raum and smile consult have collaborated to produce for 20 years (1996-2016) quality-assured hindcast data of the geomorphology and hydrodynamics of the German Bight and to make them available for free use.
This article focuses on the geomorphological products and the associated analyses.

THE FUNCTIONAL SEABED MODEL (FSM)

The Functional Seabed Model (FSB) based on observational data describing the surface of the seabed in their temporal and spatial context and linked with spatial and temporal interpolation methods to form a continuous hindcast simulation model of the seabed. It was designed for the

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entire North Sea with a focus on the German Bight. For this area, an enormous density of measurement data could be achieved, which made it possible to make use of the comprehensive possibilities provided by the FSM. Therefore, the following explanations are limited to the area of the German Bight.

At present, the FSM provides information on:

- topography (bathymetry),
- porosity,
- grain size distribution,
- organic matter content,
- thickness of the mobile sediment layer and
- bedforms as well as
- coastal engineering structures, e.g. dykes.

This functionality can be extended by other features of the seabed.

Functionality

All components of the Functional Seabed Model (FSM) are designed to be time-variant, so that at any location in the German Bight and at any date the above parameters can be calculated by spatial-temporal interpolation and approximation methods. The results of this data-based hindcast simulation depend on the spatial and temporal resolution of the measurement data stored in the FSM. Therefore, in addition to the actual modeled physical parameters, parameters for the assessment of the confidence value, the temporal distance to the next measurement and the relative and absolute uncertainty, are provided. In order to obtain information at every location in the German Bight, even if no repeat measurements are available and the spatial resolution of the natural data for the parameter under consideration is low, the measurement data are supplemented by a time-invariant background model (which is usually assigned the date 01.01.1900).

The bathymetric and sedimentological components are discussed in more detail in this paper.

The Bathymetric Component of the Functional Seabed Model

The digital bathymetric model component is based on measurements, associated metadata and interpolation methods in space and time. To describe the changes of the seabed, the model assumes a continuous function z(x,y,t) in space and time.

Bathymetric Database

Currently, the digital bathymetric model component of the German Bight consists of over 63 thousand data sets with over 43 billion data points covering a time span from 1946 to 2018. The survey data of different institutions are supplemented by digitized historical working maps of the sea survey as well as building and replacement models. Nearshore bathymetric data are available in an acceptable to relatively high spatial resolution from 1948 until today. Beyond a water depth of 15 m, bathymetric data in time are scarce. These digital bathymetric data are stored in a database. Each record is described by associated metadata. This metadata includes information about the data provider, the measurement procedure and, above all, the measurement period. According to the structure of the survey data, which depends on the respective measurement method (profile measurements, single or multi-beam echo sounder and LIDAR data), the metadata contains information on the validity region and the recommended local interpolation method.

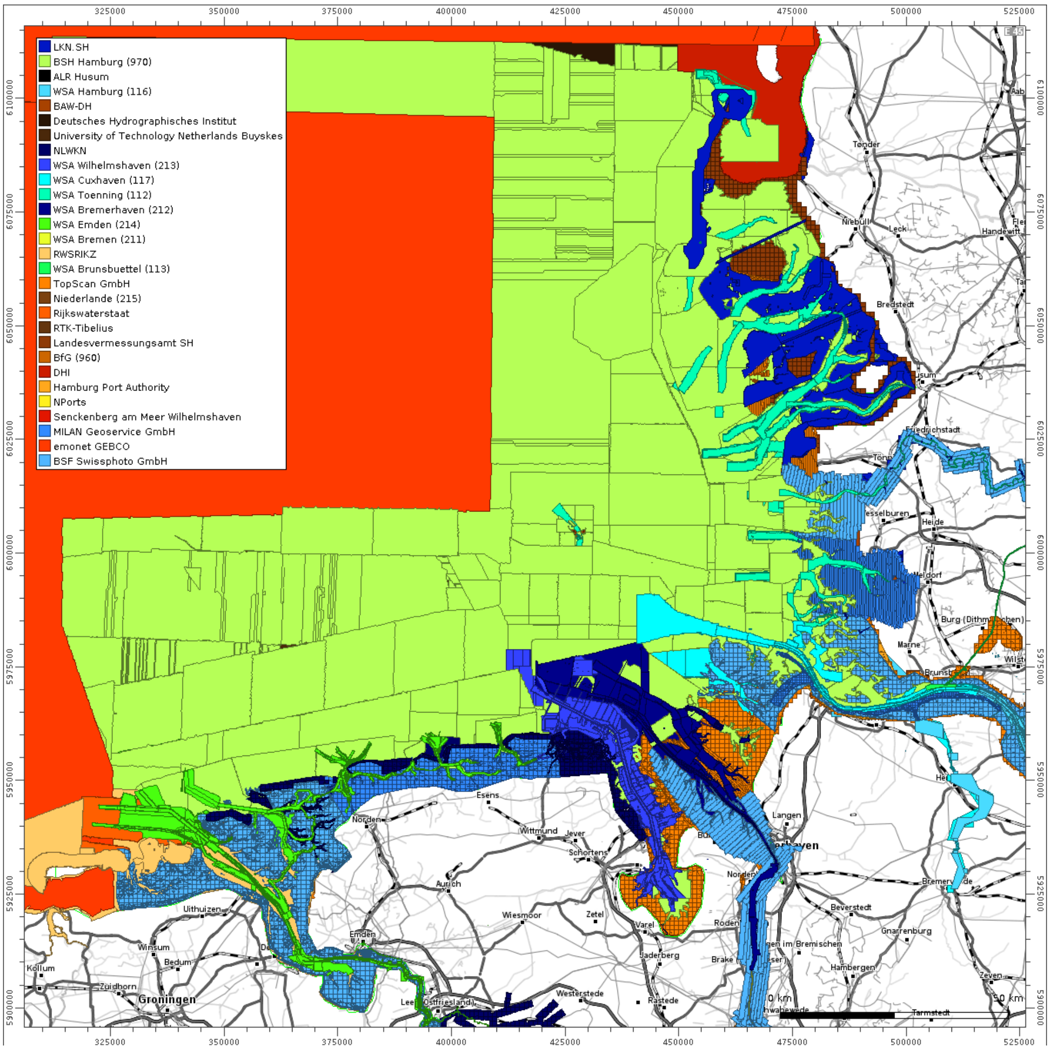

Fig. 1. Spatial extent of bathymetric surveys in the German Bight (colored by data provider) with OpenStreetMap.

Figure 1 shows the actual inventory of bathymetric data in the FSM for the area of the German Bight. In the highly dynamic coastal area the most recent data and most repetitive bathymetric and topographic measurements can be found.

Space-Time Interpolation

In areas where many measurements are available, the times of the earliest and latest surveying represent the limits of continuous space-time bathymetry (see Figure 2). Within this continuous space-time bathymetry, quasi-synoptic depth distributions can be calculated using the space-time interpolation methods implemented in the FSM. A quasi-synoptic bathymetry is the horizontal section through continuous space-time bathymetry (Milbradt 2011).

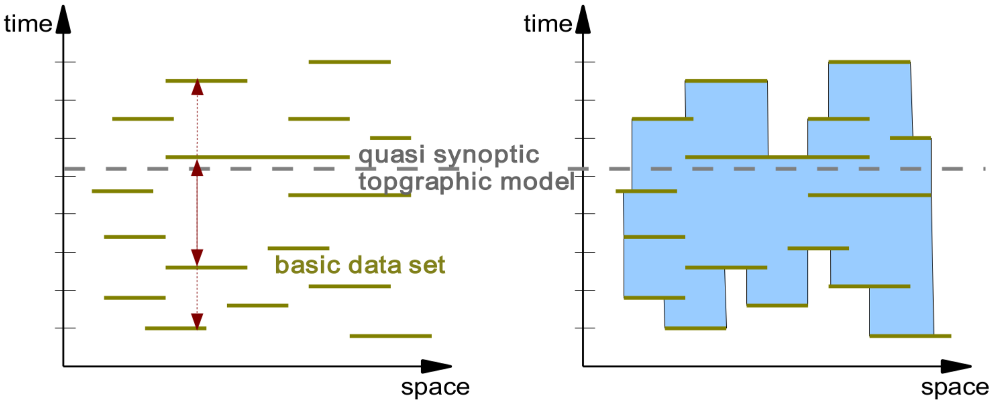

Fig. 2. Schematic space-time interpolation and temporary confidence region.

As products of such spatial temporal interpolations, consistent annual bathymetries and associated analyses are available for the period from 1996 to 2016. The bathymetric chart of 2016 and the erosion and sedimentation rate of the 5-year observation period (2011-2016) are shown as examples in Figure 3.

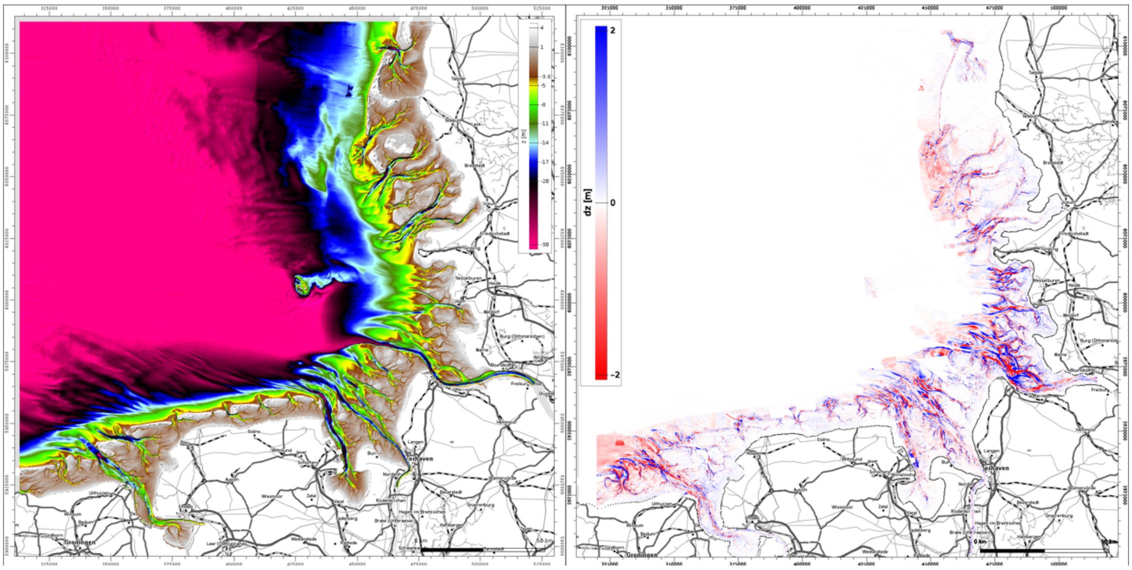

Fig. 3. Consistent Bathymetry 2016 and morphological alteration 2011 to 2016.

Further geomorphological evaluations are presented below.

The Sedimentological Component of the Functional Seabed Model

The sedimentological model component describes the properties of the surface sediment on the seafloor in terms of particle size distribution, porosity and organic content. The grain size distributions are stored in the FSM as sum curves in a logarithmic scale according to their resolution. The reference points of the cumulative grain size curves are interpolated based on a monotonic cubic spline (Kruger 2004), porosity and organic fraction are described as scalars.

Sedimentological Database

The collected sedimentological database is impressive for the German Bight and the estuaries, but cannot be compared with the bathymetric survey data in its spatial and temporal coverage. The sedimentological model component currently consists of approx. 63 thousand sediment samples in various resolutions and from various data collectors and suppliers from the period 1941 to 2012 (see Figure 4). About 44 thousand of those samples are from the area of the German Bight.

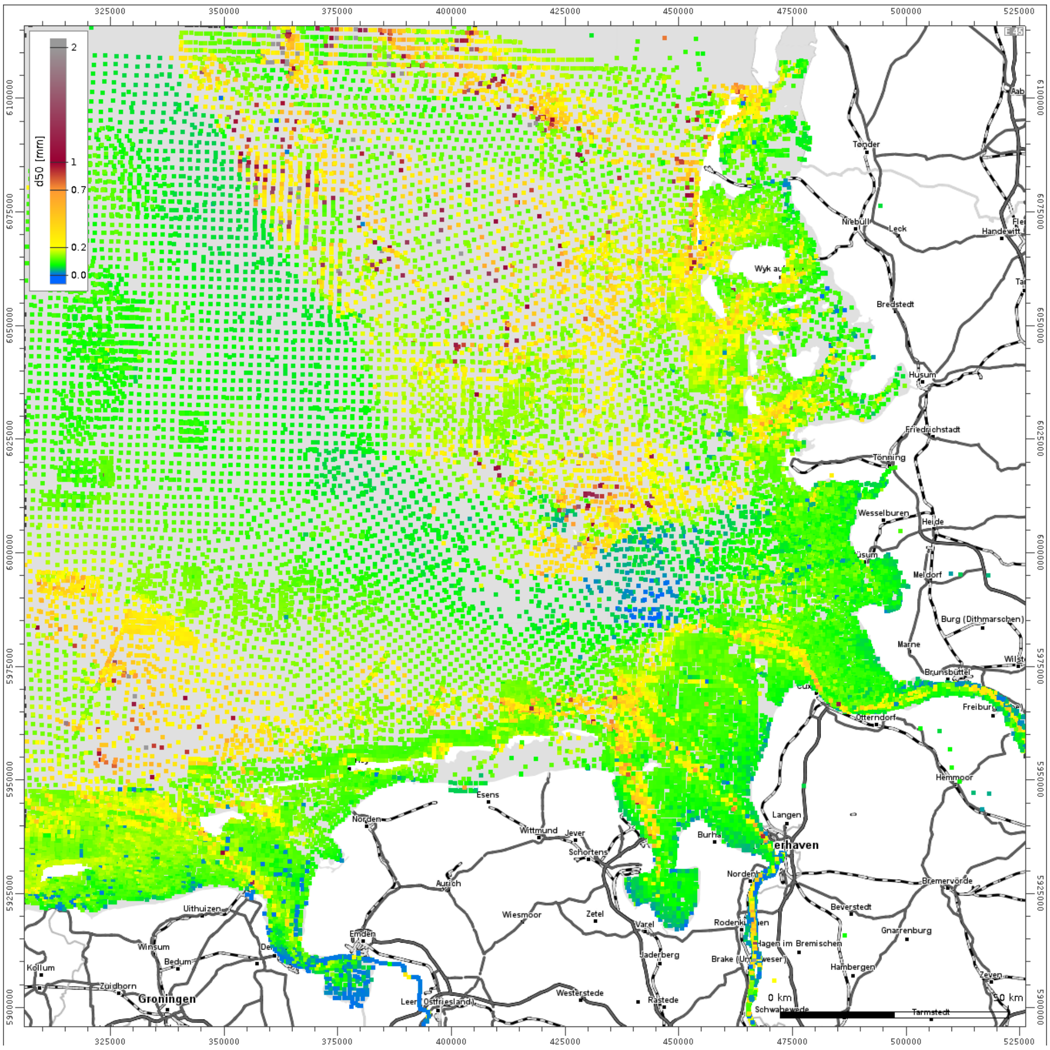

Fig. 4. Locations of the sediment samples in the German Bight (colored d_{50}) with OpenStreetMap.

Porosity and organic components have only been analyzed in very few of the available samples. However, particle size distributions are available for all stations shown in Figure 4. Thus, spatial interpolation methods can be applied. Time variant analyses are only possible to a very limited extent with this data.

Anisotropic Grainsize Sum Curve Interpolation

Spatial interpolation on sparsely distributed data requires specially adapted interpolation methods. Traditional geostatistical interpolation methods can be significantly improved by considering physical constraints. For the spatial interpolation of the whole cumulative grain size curve an anisotropic shepard-interpolation is used. The circular classical metric is distorted into an ellipse on the basis of the vector field of resulting bottom shear stresses. Anisotropic shepard-interpolation provides much better results, especially in areas where the morphology shows pronounced structures. Furthermore, this approach opens the development of time- and space-variant interpolations also for the sedimentological component. Based on the sedimentological component of the FSM, initial values and parameters for morphodynamic simulation models can now be derived. Both the spatial resolution and the resolution of the grain size distribution required for the simulation model can be selected arbitrarily. From the interpolated grain sum curves, statistical parameters such as median value, sorting or proportions of individual grainsize classes can also be derived (see Figure 5).

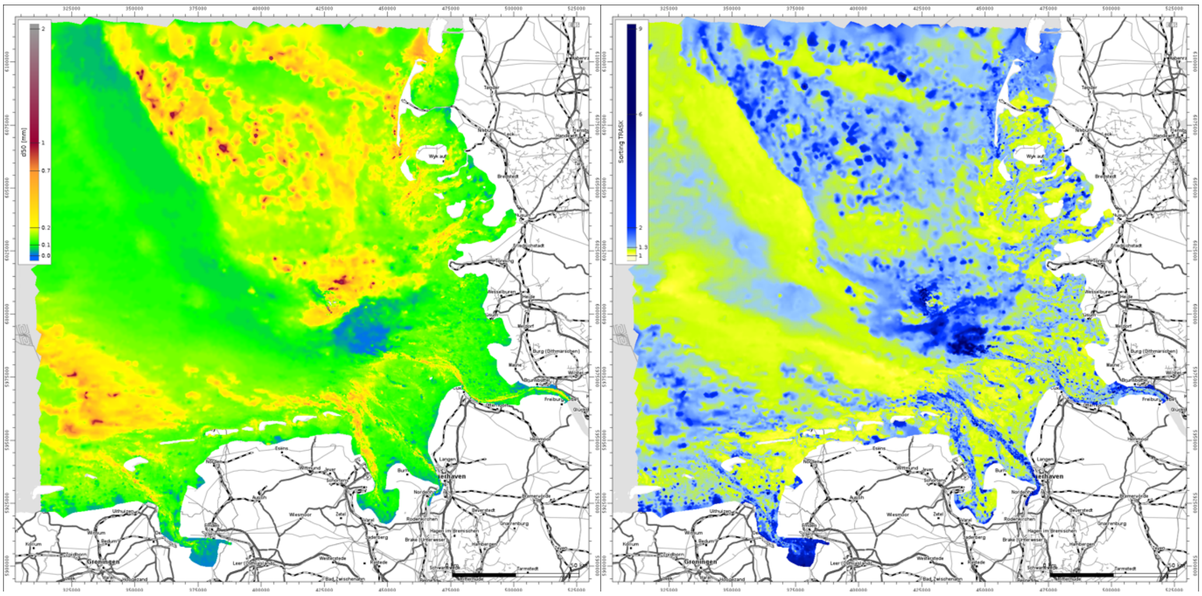

Fig. 5. Median grain size (d_{50}) and Sorting of surface sediments in the German Bight.

MORPHODYNAMIC OF THE GERMAN BIGHT

The FSM allows the simulation of consistent bathymetries and related analyses on them. In the next section analyses of geomorphological stability and sediment accumulation in the German Bight are presented.

Morphological Stability Map

If the maximum and minimum observed depths are subtracted, a map of the morphological space is produced (see Figure 6). This map can also be understood as a morphological stability map for questions concerning the routing of supply and disposal lines as well as connection lines for offshore wind turbines. The light green areas in the German Bight in Figure 6 can be interpreted as morphologically stable, whereas red areas are highly active.

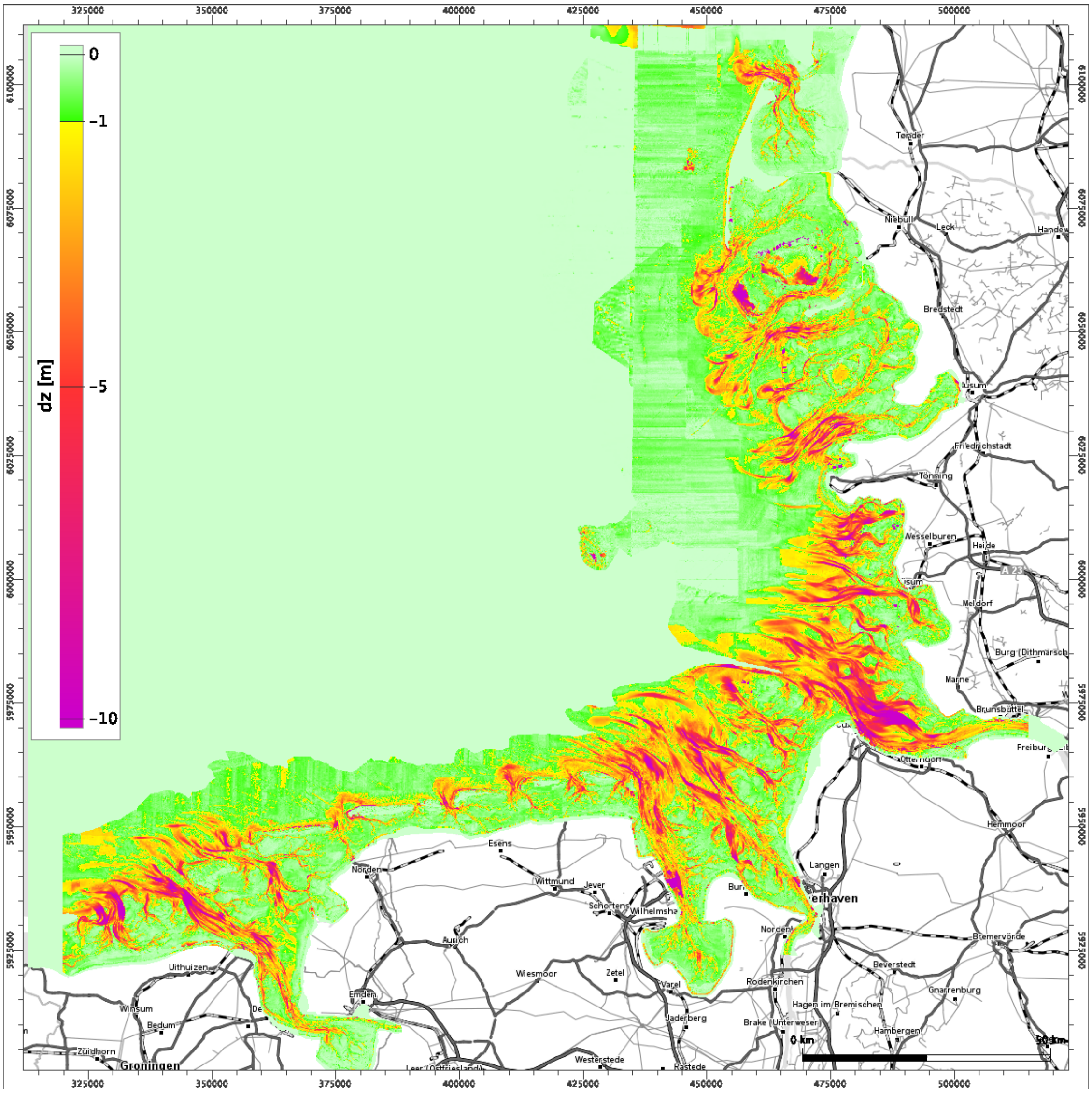

Fig. 6. Morphological Stability Map or Morphological space over the period 1996-2016.

Sediment Balance

Due to its location in the North Sea and the hydrodynamic conditions, the German Bight is an accumulation area. The sediment transport quantities are charged from different sources. Beneath the estuary discharges into the German Bight the exchange with adjacent regions of the North Sea are considerable. Several studies have been performed in the past to estimate wide area sediment transport within the North Sea and the German Bight. An overview of existing rather small-scale measurements and investigations is given, for example, in Gerritsen, et al. 2000 and Gerritsen, et al. 2001. Model-based investigations for the estimation of sediment transport quantities in the German Bight can be found in Puls et al. 1997 and Heyer u. Schrottke 2014.
The paths on which potential North Sea sediments move can be determined on the basis of hydro- and morphodynamic numerical simulation models. Hydrodynamic simulations can be used to determine, for example, vector fields of annual resulting bottom shear stresses and mean

currents. These vector fields can then be used to generate associated streamlines. The streamlines of the resulting bottom shear stresses, for example, provide good indicators for the transport paths of bedload sediment transport, whereas the streamlines of the mean current velocities characterize the suspended sediment transport (see Figure 7).

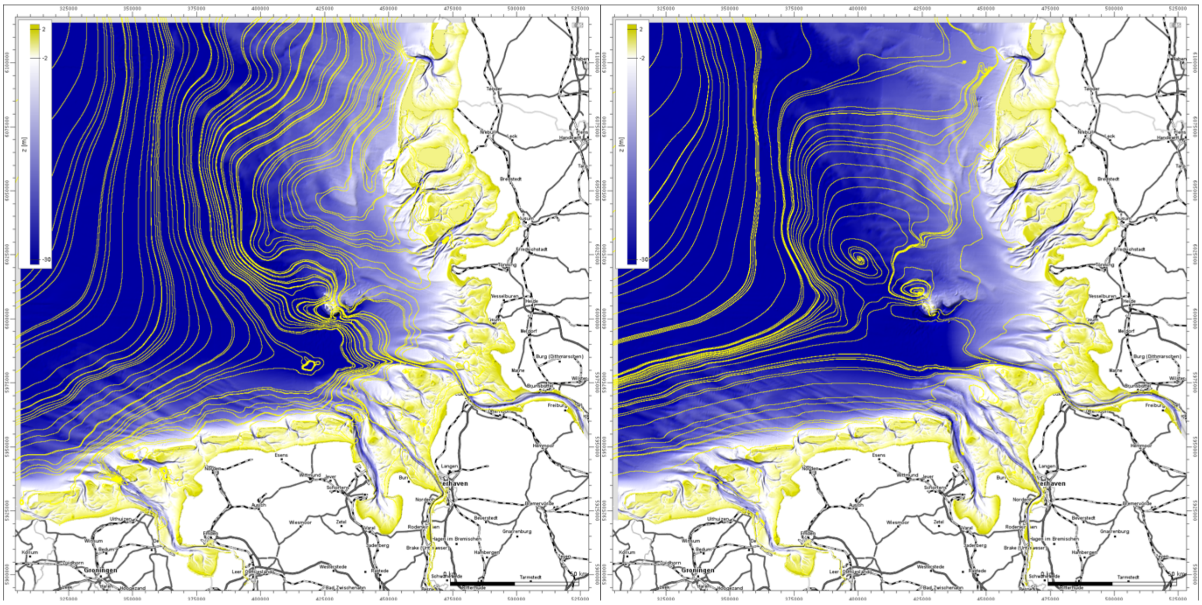

Fig. 6. Streamlines of mean current velocity and bottom shear stress of the year 2006.

In Figure 7 the basic trend of the transport regime from west to east seaward of the West and East Frisian coast is shown. On the western part of the North Frisian coast the vectors deviate widely seaward in a northerly direction. In the inner German Bight, the transport paths to the northwest bend into the old glacial valley of the Elbe river. The shape and position of the sediment transport pathways in the deeper regions of the German Bight are relatively stable over the various years, but are considerably higher in the outer regions of the German estuaries induced by the complex bathymetric situation and the river run off which has a distinct influence on the transport regime.

The quantitative estimation of the accumulated sediments can be carried out on basis of the FSM. The calculated accumulated sediment quantities on basis of the FSM fluctuate significantly, which is caused by the considerable measurement uncertainties of the underlying measurement data. The average accumulation rate of sediment in the German Bight over the last 20 years is approx. 232 Mt/year. By averaging over a long period of time, the uncertainty induced by the measurements can be reduced.

Development of the tidal flats in the German Bight

The coastal zone of the German Bight is characterized by the Wadden Sea, which developed during the Holocene due to the influence of tides and the large amount of sediment, and is subject to constant morphological changes. Additionally, fine sediment is deposited especially on the tidal flats nowadays. The collected survey data indicates an average tidal flat growth of 0.54 cm/a (based on the last 20 years). This tidal flat growth compensates on average for the rise of the mean sea level in the German Bight of approx. 0.21 cm/a (observed over the last 60 years at the gauge Helgoland). The growth of the tidal flats varies both temporally and locally. The growth is usually highest in the estuaries and decreases counterclockwise from the west, so that the North Sea coast of Schleswig-Holstein in particular has the least supply of sediment.

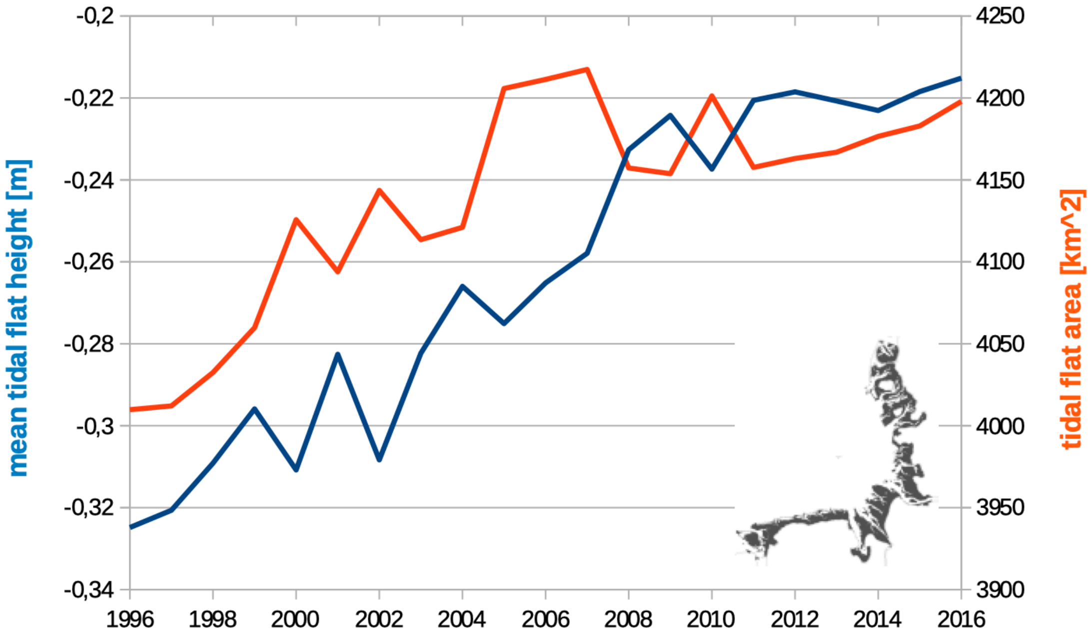

Fig. 6. Development of the tidal flats of the German Bight.

The resulting average accumulation rate of sediment in the tidal flats of the German Bight over the last 20 years is approx. 53 Mt/year. All evaluations presented here must always be seen in relation to the accuracy of the measuring instruments used. The best height accuracy to be achieved for a single measuring point is currently more than one decimeter.

CONCLUSIONS

The presented concept of the Functional Seabed Model (FSM), as a holistic time and space variant hindcast simulation model of the seabed surface, opens a multitude of geomorphological analyses in the German Bight. On the one hand the FSM forms an essential basis for the construction of process-based numerical simulation models in coastal engineering and, on the other hand, the FSM makes it possible to establish links between different parameters of the seabed. In this paper, it was possible to show, despite the considerable uncertainties in the survey data, that the current height growth of the Wadden Sea is even higher than the mean sea-level rise in the German Bight. Morphological stability maps in different spatial resolutions and yearly consistent bathymetries are already in demand by different stakeholders and are used for practical engineering tasks.

The profound linkage of sedimentological data with bathymetric products as well as with simulation results from process-based simulation models could only be outlined.

The products developed within the framework of the joint project EasyGSH-DB, such as yearly bathymetries or consistent sedimentological data sets, can be downloaded via the open data portal (www.mcloud.de) of the Federal Ministry of Transport and Infrastructure. The continuous further development, expansion and maintenance of the database can guarantee sustainable use for interdisciplinary questions and contribute to a better understanding of geomorphological systems.

ACKNOWLEDGEMENTS
The author would like to thank the Federal Ministry of Transport and Infrastructure for the financial support of the mFund joint research project EasyGSH-DB as well as all colleagues who have actively participated in the joint project. Last but not least, on behalf of the project, we would like to thank all data providers in Germany and Europe who have contributed significantly to the success of the project by providing data and information.

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