Modelling large scale sediment transport in the German Bight (North Sea)

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Zusammenfassung

Der Aufbau von integrierten Modellsystemen (AufMod) zur Analyse der langfristigen Morphodynamik in der Deutschen Bucht war Ziel des KFKI-Verbundforschungsvorhabens (Laufzeit: 2009-2012). Auslöser hierfür war eine im Jahr 2008 durchgeführte Ausschreibung des KFKI mit einer detaillierten Anforderungsliste.

Im Projekt wurde sehr frühzeitig die Entscheidung getroffen, ein umfassendes softwaregestütztes Bodenmodell zu generieren, das die Daten zur Bathymetrie und Sedimentbeschaffenheit gemeinsam verwaltet und funktional, d. h. nach spezifischen Vorgaben, verarbeiten und dem Anwender anforderungsgerecht zur Verfügung stellen kann (Funktionales Bodenmodell).

Die Betrachtung der Sedimentprozesse in der Deutschen Bucht kann nicht ohne die Berücksichtigung der Prozesse in der gesamten Nordsee erfolgen. Deshalb wurden auch umfangreiche Daten der Anrainerstaaten akquiriert und in das Funktionale Bodenmodell übernommen. Die großräumigen und langfristigen Sedimentbewegungen sind auch von lokalen, teilweise zeitlich beschränkten Prozessen beeinflusst. Deshalb fokussierte sich das Funktionale Bodenmodell auf bestimmte Gebiete: das Schelf bzw. das Küstenvorfeld, den Vorstrandbereich, die Bereiche von Inseln und im Wattenmeer.

Im Rahmen der Anwendung deterministischer Prozessmodelle wurde ein konsequenter Multi-Modell-Ansatz mit Simulationsmodellen unterschiedlicher Prozessauflösung verwendet, um die Streubreite der Ergebnisse abschätzen zu können. Für die Modelle, welche auf unstrukturierten Modellverfahren basieren, wurden überwiegend identische Gitternetze und Randwerte verwendet. Soweit möglich, wurde auch ein einheitliches Post-Processing durchgeführt, um den Vergleich der Modellergebnisse mit einheitlichen Methoden zu gewährleisten.

Abschließend wurde eine gemeinsame Synthese erarbeitet, die alle relevanten Ergebnisse der Teilprojekte einbezieht und eine übergreifende, gemeinsame Bewertung zur Beantwortung der in der KFKI-Ausschreibung formulierten Ziele erstellt.

Schlagwörter

Nordsee, Deutsche Bucht, Sedimentverteilung, Sedimentzusammensetzung, Porosität, Bathymetrie, Topographie, Sedimenttransport, Morphodynamik, Numerische Modellierung, Meeresspiegelanstieg

Summary

The main objective of the multidisciplinary research project "AufMod" (2009 – 2012) was the development of model-based tools for analyzing long-term sediment transport and morphodynamic (MD) processes in the German Bight. AufMod aimed at bringing together marine geoscientists and coastal engineers to build up consistent bathymetric and sedimentological databases and to compare different numerical models using the same data input and model grid with respect to uncertainties in their results.
AufMod provides a suite of consistent annual bathymetries as well as initial sediment parameters which can be used by numerical MD models for further analyses. Different patchy datasets from bathymetric survey campaigns since 1948 have been compiled and have undergone a sophisticated postprocessing procedure to overcome inconsistencies arising from the use of different echosounding techniques, vessels, tidal correction and so on. For the first time, data on grain size distribution have been composed for the entire North Sea including the German Bight in order to analyze geomorphological processes and to calculate sediment input parameters for morphodynamic modelling. By establishing a so-called "Functional Seabed-Model" consistent annual bathymetries and initial sediment distribution and composition (grain size distribution) have been made available together with their spatial and temporal uncertainties.
The morphodynamic numerical model simulations cover a time span from 1996 to 2008. They are based on natural processes and take account of the whole variability of tides, external surge, river run-off, wind and waves. "AufMod" provides a suite of consistent annual bathymetries as well as initial sediment parameters which can be used by numerical MD models for further analyses. By using the same model grids the strength and weakness of the different numeric models can be evaluated and their uncertainties can be assessed. The morphodynamic model results provide a first comprehensive impression of the resulting sediment transport pathways in the German Bight.
Further model runs have focused on the sensitivity of sediment transport and the morphological response due to wind forcing, mean sea level rise and variation in porosity.

Keywords

North Sea, German Bight, sediment mixture, sediment distribution, porosity, bathymetry, sediment transport, morphodynamic, numerical modelling, mean sea level rise

Contents

1 Introduction

A better understanding of the morphodynamic processes along the German North Sea coast 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. The German Coastal Engineering Research Council (**KFKI**) consequently published a call for proposals in 2008 focusing on enhanced numeric modelling of relevant large-scale and long-term sediment transport pathways, including their directions and mass budgets. The AufMod R&D project was conducted by a multi-disciplinary research group under the leadership of the Federal Waterways Engineering and Research Institute (BAW) from 2009 until 2012. Its purpose was to develop an integrated model system for analyzing the long-term morphodynamics in the German Bight (North Sea).

The multidisciplinary research project **AufMod** (German acronym for "Model-based analysis of long-term morphodynamic processes in the German Bight") was funded by the Federal Ministry of Education and Research (**BMBF**) to investigate long-term sediment transport and morphodynamic processes. The project focuses on the German Bight, located in the southeastern part of the North Sea. AufMod takes a combined data-based and process-based modelling approach to investigate long-term sediment transport.

The research group comprised the Federal Waterways Engineering and Research Institute (**BAW**), the Federal Maritime and Hydrographic Agency (**BSH**), the Christian-Albrechts-University of Kiel, the University of Bremen, the University of the Federal Armed Forces Munich, Senckenberg Institute Wilhelmshaven and smile consult GmbH, Hannover.

The principal goals of **AufMod** were

- to establish to the greatest extent possible a consistent and plausible database with respect to bathymetries and physical sediment properties and to provide these for third parties beyond the lifetime of the project;
- to build up and develop a morphodynamic modelling toolbox including tides, waves, and wind-induced currents;
- to analyze different scenarios of sea level rise with respect to climate change; and
- to share the treated data for online publishing in cooperation with the R&D-project Marine Infrastructure in Germany (**MDI-DE**) in an information model.

One main scientific objective of **AufMod** is to identify processes and effects which are relevant to long-term sediment transport and the morphodynamic reaction of the sea bed. The concept of the **AufMod** project implied the observation of the compartments air, water, and seabed (e. g., meteorological, hydrodynamic and sediment data), the analysis of morpho- and sediment dynamic processes using data-based and process-based models and the allocation of the results (products) via an integrated spatial data infrastructure (Figure 1).

The "Functional Seabed Model" **FSM** was initially set up to build a consistent bathymetric and sediment database, to test the suite of numeric morphodynamic models which are used in AufMod, including aspects of validation, and to facilitate critical discussion of first results, namely sediment transport pathways in the German Bight from different model runs. AufMod takes a combined data-based and process-based modelling approach to the investigation of long-term sediment transport.

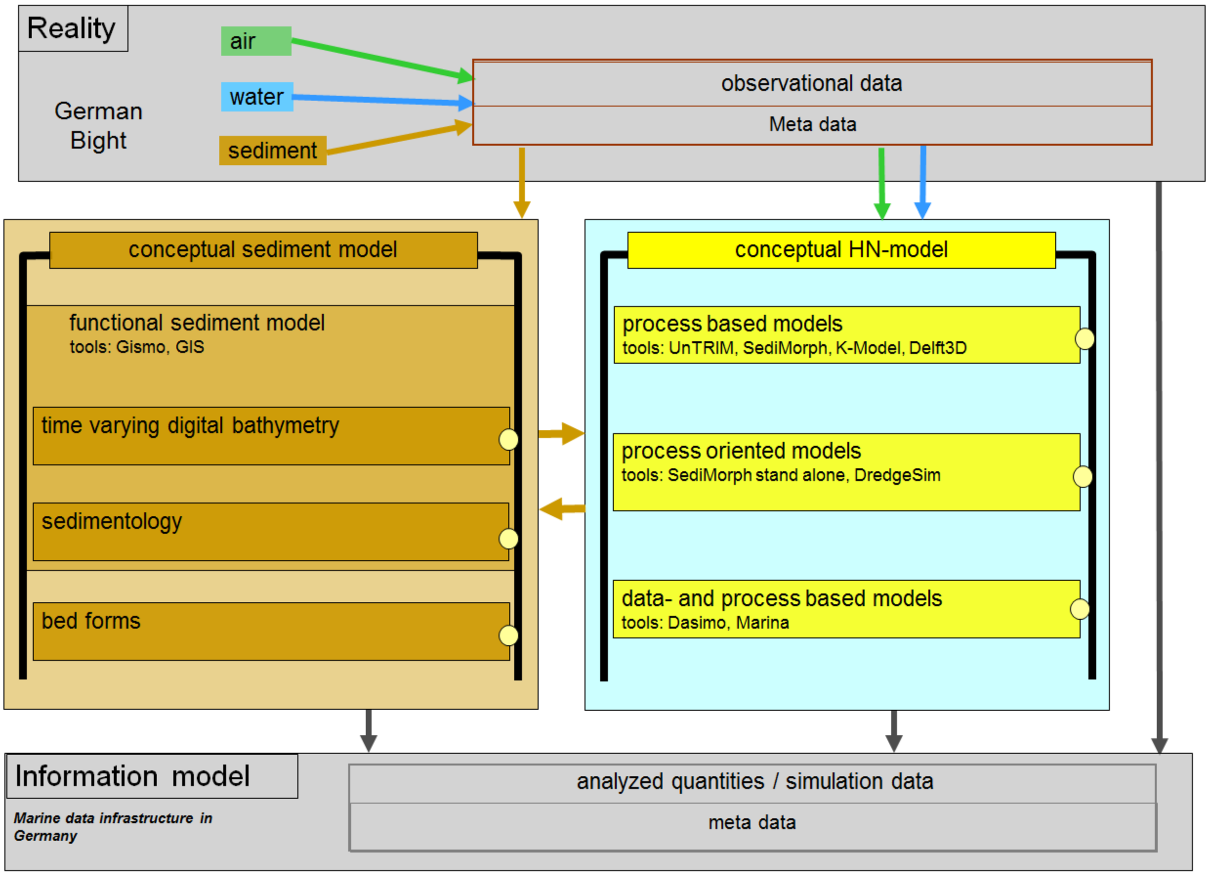

Figure 1: Conceptional model of **AufMod.**

2 Study site

The project focuses on the German Bight, which is located in the southeastern part of the North Sea where semidiurnal tides enter from the west (The Netherlands) and propagate counter clockwise along the coastline of the German Bight towards the Danish waters under the influence of Coriolis accelerations. The tidal range varies from app. 1.5 m (Islands Borkum and Sylt) to app. 3.5 m (in the Elbe river mouth).

The seabed is dominated by different sand deposits which are prone to sedimentation and erosion under the recent hydrodynamic regime. Coarser sediments occur in the tidal channels, where current speed reaches up to 1.5 m s^{-1}. Coarse sands and gravels also occur in some parts of the shelf, where they represent relict sediments of the Saalian glaciation and/or fluvio-glacial sediments from the Weichselian.

3 Data base

The database for all investigations can be characterized using the data from the seabed which is needed to describe physical sediment properties (e. g., grain size distribution, porosity, …), bathymetry over several years and bed forms. Different datasets were therefore compiled and assessed in **AufMod**:

1. sedimentological data,
2. bathymetry data,
3. hydrodynamic and meteorological data and
4. model results after model set-up, running and interpolation as well as interpretation.

2.1 Sediment data

The following parameters were relevant for morphodynamic modelling:

1. grain size analyses of surface sediments,
2. porosity,
3. thickness of the mobile sand layer and
4. content of organic matter in muddy sediments.

Table 1: Sources of sedimentological datasets.

Data	Source	#	Spatial Extent	Temporal Extent
MUDAB - grain size distributions	BSH	25.309	North Sea	1924-2008
WADABA - grain size distributions	Helmholtzzentrum Geesthacht	1.449	German Wadden sea	1987-2003
Grain size distributions Spiekeroog	Research institute Senckenberg am Meer, Wilhelmshaven	941	Shore face Spiekeroog	1986-1989, 2005
Grain size distributions Great Britain	British Geological Survey (BGS), Nottingham, Great Britain	15.946	North Sea sector Great Britain	
Grain size distributions Netherlands	Geological Survey of the Netherlands (TNO), Utrecht, The Netherlands	6.619	North Sea sector Netherlands	1969-2006
Grain size distributions Norway	Norges geologiske undersøkelse (NGU), Trondheim, Norway	129	Skagerrak	1992-1994
Interpolated medians of grain size distributions Belgium	Royal Belgian Institute of Natural Sciences, Brussels, Belgium	250m-Grid	North Sea sector Belgium	
Grain size distributions Belgium	Royal Belgian Institute of Natural Sciences, Brussels, Belgium	3.468	North Sea sector Belgium	1984-2009
Grain size distributions Denmark	GEUS, Copenhagen, Denmark	215	North Sea	2000-2008
Grain size distributions Denmark	Danish Coastal Authority, Ministry of Transport and Energy, Denmark	215	North Sea sector Denmark	2010
GPDN - grain size distributions	Geopotential Deutsche Nordsee (BSH, BGR, LBEG), Germany	1.363	North Sea sector Germany	2008-2011
SedDB (Küste) – grain size distributions	BfG, Koblenz, Germany	4.949	Elbe-, Jade-, Weser-, Ems-estuary	1982-2009
Grain size distributions Sedimentatlas Waddenzee	Waterdienst (Rikswaterstaat, Ministerie van Infrastructuur en Milieu), Lelystadt, Netherlands	7.502	Wadden sea of the Netherlands	1989-1997
Grain size distributions Offshore Windfarms licensing procedures	BSH (confidential) , Germany	4.383	North Sea sector Deutschland	2000-2008
FeDaBa - grain size distributions	BfG, Koblenz, Germany	3.163	Elbe-, Jade-, Weser-, Ems-estuary	1980-2012
GROBEKART - grain size distributions	AWI, Germany	4.373	Shelf of Schleswig-Holstein	2004-2011

The grain size analyses cover the German Bight in a quite high spatial resolution of one half to one nautical mile. In contrast to the bathymetric database, hardly any time series are available (Table 1). The grab samples were collected over a time span of app. 90 years; most of them between 1960 und 1970. Figure 2 depicts the sample locations together with the individual data sources. Grain size data were made available for the whole North Sea area. The particle size distributions are stored as a sum curve in a logarithmic scale, according to their resolution. The individual grain size fractions of the cumulative particle distribution are interpolated using linear or constrained cubic spline interpolation (Kruger, 2004).

Hardly any porosity data is available for the German North Sea, especially for sandy sediments. Porosity of marine sands in the tidal flats of the inner German Bight ranges by about 40% (Füchtbauer and Reineck, 1963). Porosity measurements were carried out for fine-grained sediments in the Elbe-Weser estuary during the AufMod project.

Figure 3 illustrates data points on the thickness of the mobile sand cover, which is used as a proxy for the available sediment budget. These data result from previous R&D projects and geological mapping programs.

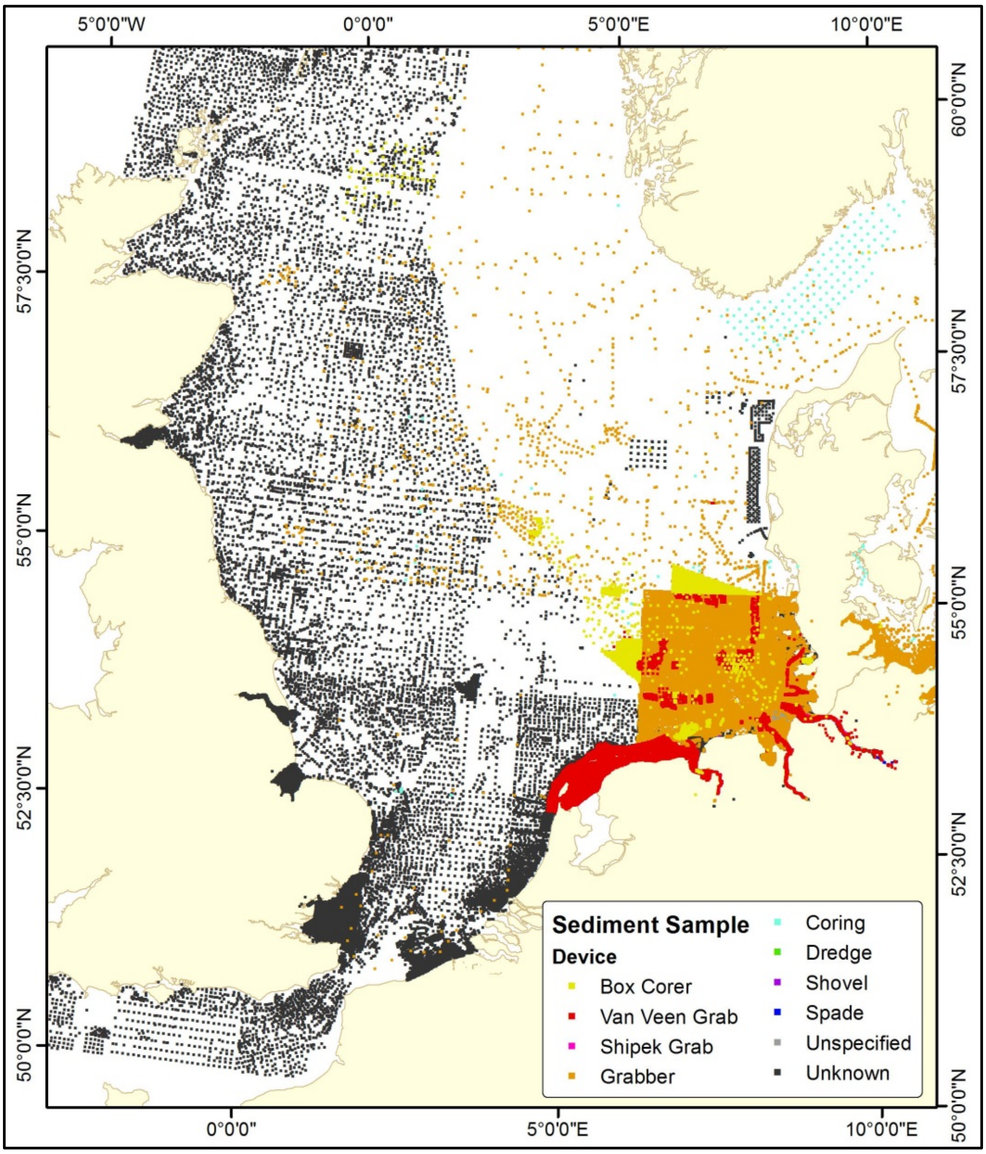

Figure 2: Locations of grain size data in the North Sea.

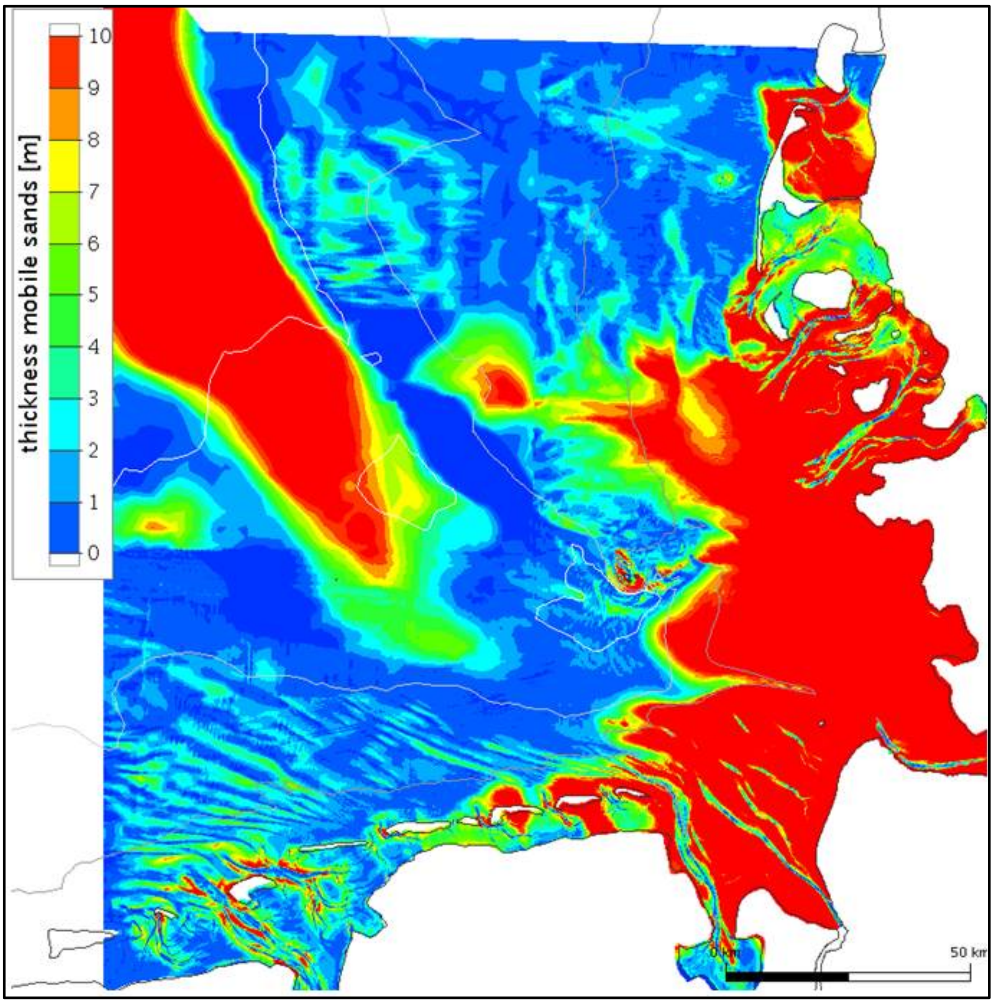

Figure 3: Thickness of the uppermost sediments (mobile sand cover and Holocene sediments) in the German Bight.

2.2 Bathymetric data

To describe the changes of the bathymetry we considered 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.

The first step was to compile bathymetric data from the different data sources (Table 2). Figure 4 illustrates the spatial and temporal distribution of the different bathymetric surveys which have been subject to the quality assessment of the hydrographic survey requirements; most of them have been performed in the Elbe, Weser and Ems estuaries and, subsequently, within the shallow waters down to 20 m of water depths in different time intervals.

In the next step the bathymetric database was enhanced with relevant metadata in order to describe the survey data in a comprehensive manner. The spatial confidence region, the temporal confidence interval, the accuracy of measurement and the recommended interpolation method are specified in the metadata for each data set, for example.

In total, 1.7 billion data from more than 16,000 bathymetric surveys have been compiled in this way covering a time span from 1948 to 2012.

Table 2: Suppliers of bathymetric data.

Source	Spatial Extent	Temporal Extent
BSH	German North Sea	1983-2012
BSH	Digitized operating sheets of hydrographic surveys for different subareas of the German North Sea	1974-1979
KFKI-Project 03KIS308	Digitized operating sheets of hydrographic surveys for different subareas of the German North Sea	1948-1982
WSA Bremen	Weser	2008-2009
WSA Bremerhaven	Weser estuary, Jade Bight	1996-2009
WSA Cuxhaven	Elbe estuary up to the north west of Helgoland	1990-2012
WSA Emden	Ems estuary	1990-2011
WSA Tönning	Channels of the North Frisian Wadden Sea	1990-2010
WSA Wilhelmshaven	Shipping channel of the Jade, area around Spiekeroog and Wangerooge	1996-2012
NLWKN	Northern beach area of Juist and Langeoog	1983-2007
LKN-SH	Base map of the Wadden Sea	1935-2012
Landesvermessungsamt Schleswig-Holstein	ALS - data for the Wadden Sea (Schleswig-Holstein)	2005/06
British Oceanographic Data Centre	Digital Elevation Models of the North Sea	1998, 2008
Danish Hydraulic Institute	Digital Elevation Models of the North Sea	2003, 2009
Kystdirektoratet/The Danish Coastal Authority	Danish Wadden Sea, Blavandshuk to Hindenburgdamm	2008
Senckenberg am Meer, Wilhelmshaven	Shore face of Spiekeroog	2003, 2007
JadeWeserPort Logistics Zone GmbH & Co.KG	Jade	2010

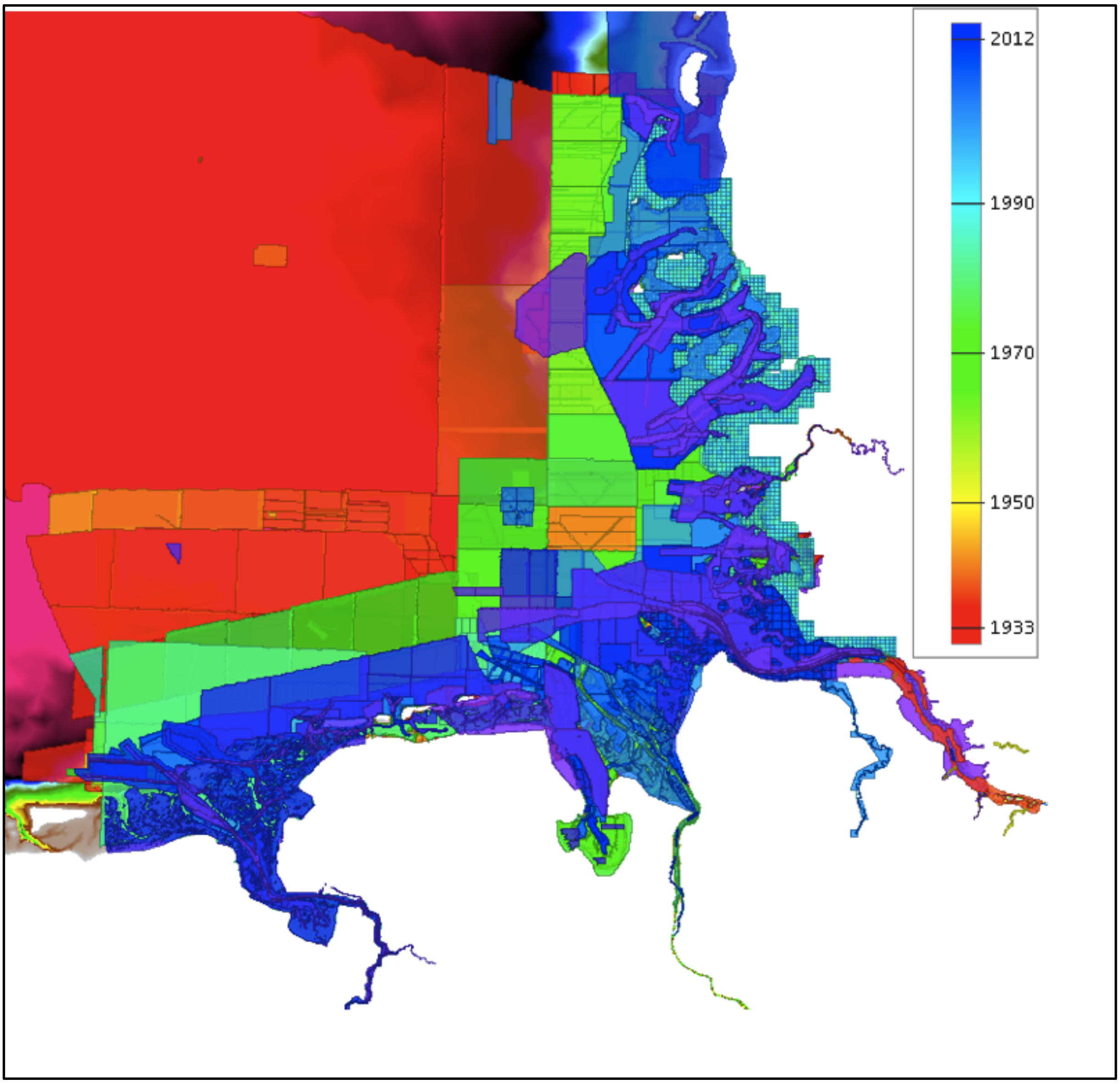

Figure 4: Spatial and temporal extent of bathymetric surveys in the German Bight (North Sea) used for morphodynamic analyses.

3.3 Hydrodynamic and meteorological data

Meteorology and hydrodynamics are the driving forces of the morphodynamic in the German Bight. Hydrodynamic and morphodynamic models as well as morphodynamic analysis require information about the time varying water levels along the open (seaward) boundary, river discharge quantities and wind velocities in time and space in addition to bathymetry and sediment data:.

- Water levels: The tidal signal was derived from the global tide model FES2004.
- Run off from measurements in the German Bight and long-time means for the other river discharges from analysis.
- Wind fields are taken from forecast weather model runs by the German Weather Forecast Service (**DWD**).

4 Functional seabed model

The term "Functional Seabed Model (**FSM**)" is introduced to describe a database for morphodynamic analyzes which include data-based models of annual bathymetries and sediment properties for any location and time within the study site. Moreover, the **FSM** also depicts the temporal evolution of the seabed. The two-dimensional models of the annual bathymetries and sediment properties were generated by appropriate interpolation and approximation methods (Milbradt 2011).

At present, the **FSM** provides information on:

- topography (bathymetry),
- thickness of the mobile sediment layer,
- porosity,
- grain size distribution,
- organic matter content,
- resistance of consolidated sediments and
- bedforms.

Firstly, the Functional Seabed Model consists of a time-invariant model (so-called "background layer") which comes into operation for interpolation or approximation when survey data are missing for a specific site. The topographic background layer includes the model grid of **BAW** for the North Sea and summarizes bathymetric data up to 1989. The background layer of the sediment thickness dates back to 1985 and has been estimated, via the depth of erosion between the years 1985 and 2009, to be at least 1 m. Porosity was set to 25%, organic matter to 5%. The **FSM** suggests that consolidated sediment underlies the mobile sand cover which itself cannot be mobilized.

Cumulative grain size distributions are typically used in the **FSM**. A representative distribution of d50 (median) based on the combination of grain size data from **BSH** and model runs was modelled for the background layer. This resulted in a consistent d50 layer, especially in the estuaries and in the tidal flats for which grab samples are not available in a sufficient spatial resolution.

Secondly, the **FSM** embodies a time-variant module which was developed using a multi database system. It produces annual digital terrain models (Figure 5) to provide the user with quasi-synoptic topographies from the coastline down to a water depth of app. 20m. Moreover, each annual bathymetry is linked with layers for spatial uncertainty, e. g. spatial confidence (Figure 6) and minimum distance with respect to the dataset in time.

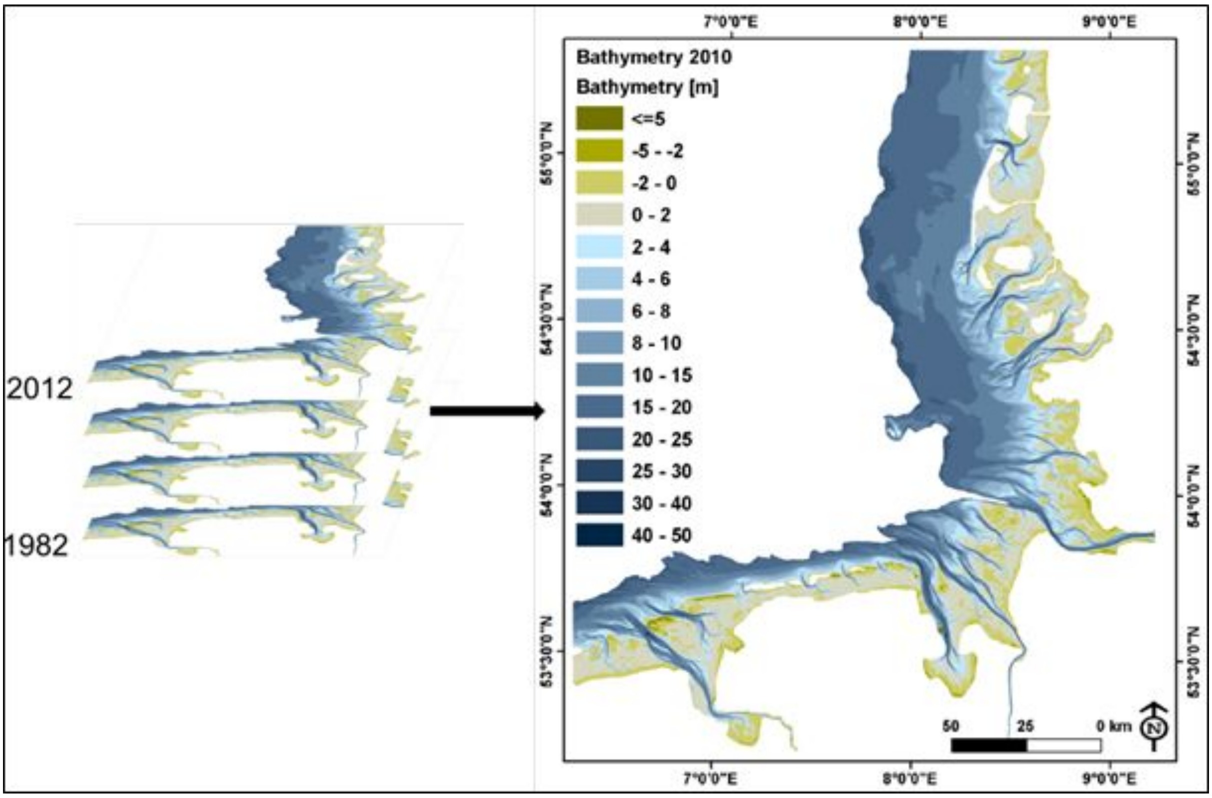

Figure 5: Example for an annual bathymetry (digital terrain model) and layers for spatial and temporal uncertainty.

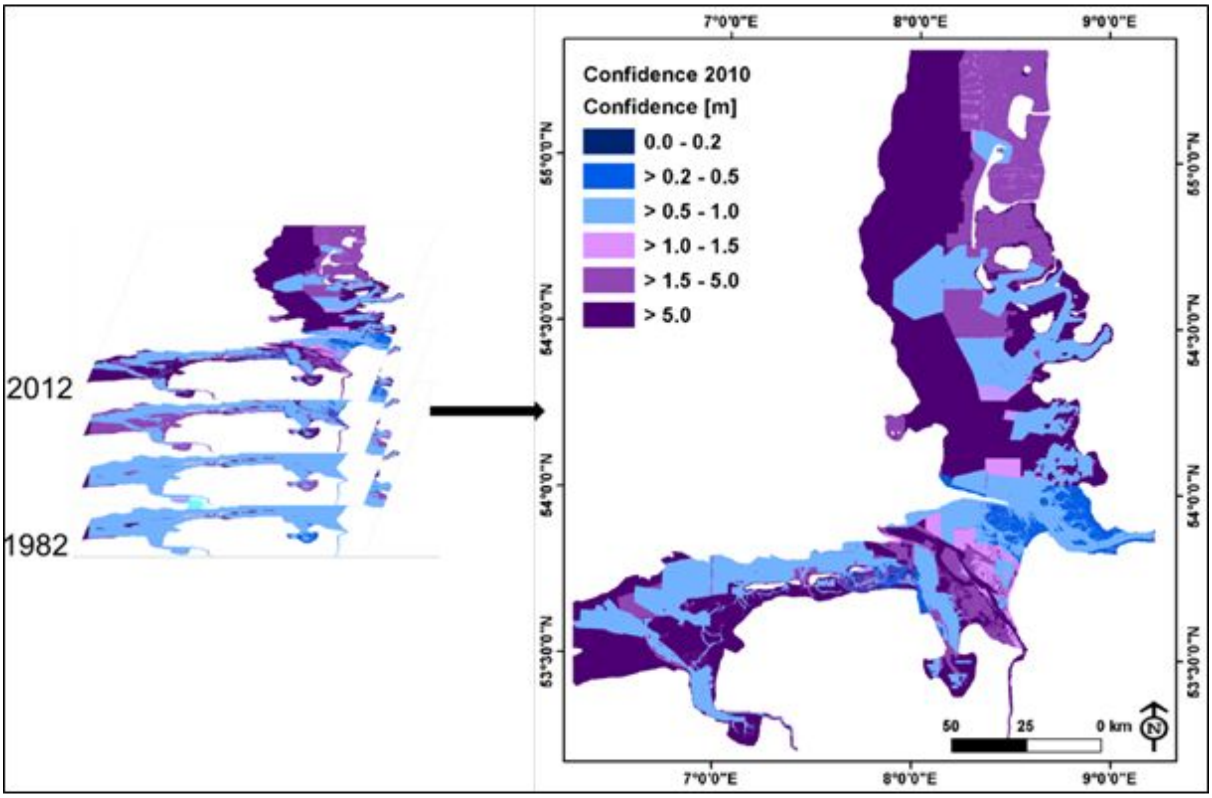

Figure 6: Spatial confidence for annual bathymetry shown in Figure 5

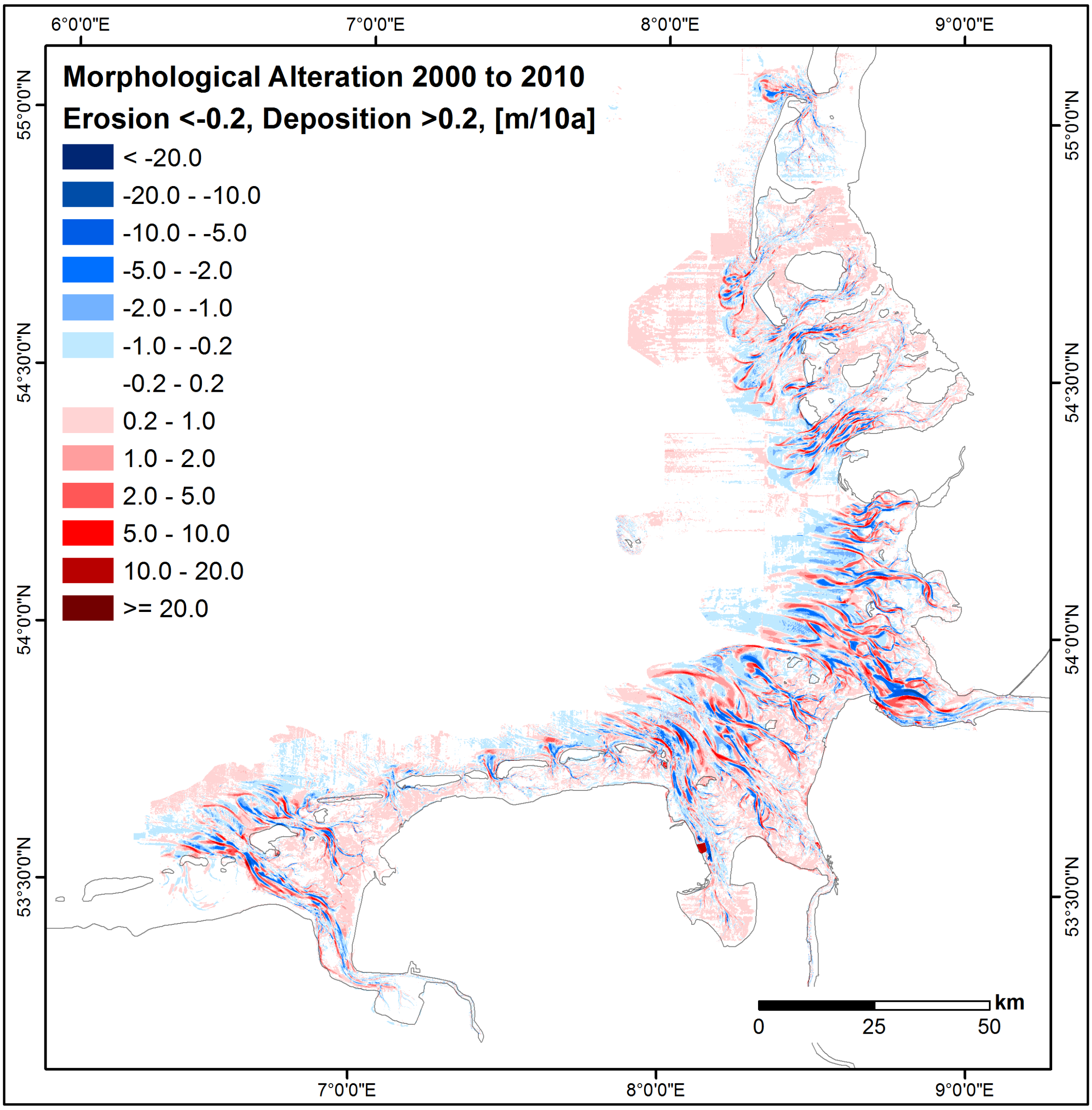

Figure 7: Example for morphologic alteration based on annual bathymetries.

The annual topographies are the prerequisite for modelling further datasets on the temporal evolution of the seabed:

- morphologic alteration (Figure 7), e. g. topographic differences for 1, 5, 10, 30 years,
- morphologic space (Figure 9), e. g. difference of the historically highest and lowest water depth at each location over distinct time intervals (5, 10, 30 years) and
- morphologic drive (Figure 8), e. g. difference of maximum and minimum annual depth change for distinct time intervals (5, 10, 30 years).

The distribution of statistical parameters, derived from the cumulative grain size distribution, was modelled for sediment properties, e. g. median (Figure 11) or sorting (Figure 10) as well as different grain size classes. These parameters are helpful in at least analyzing sediment dynamics on the shelf beyond 20 m of water depth, where bathymetric time series are scarce and even morphological changes are with the range of uncertainty of the survey data.

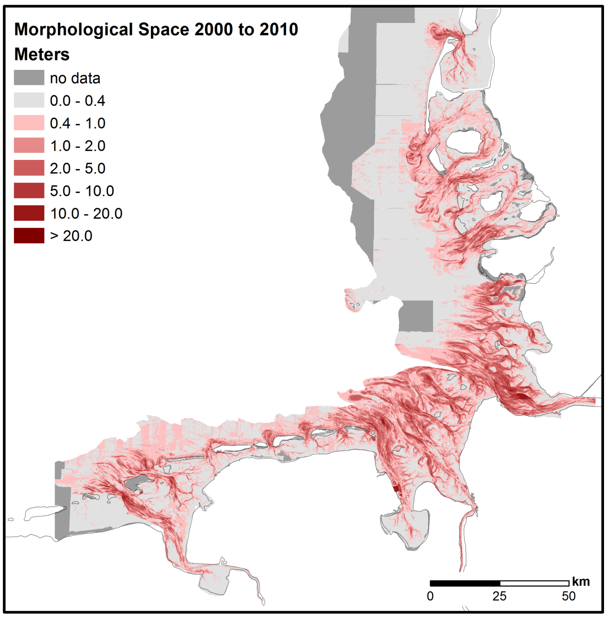

Figure 9: Example for morphologic space based on annual bathymetries.

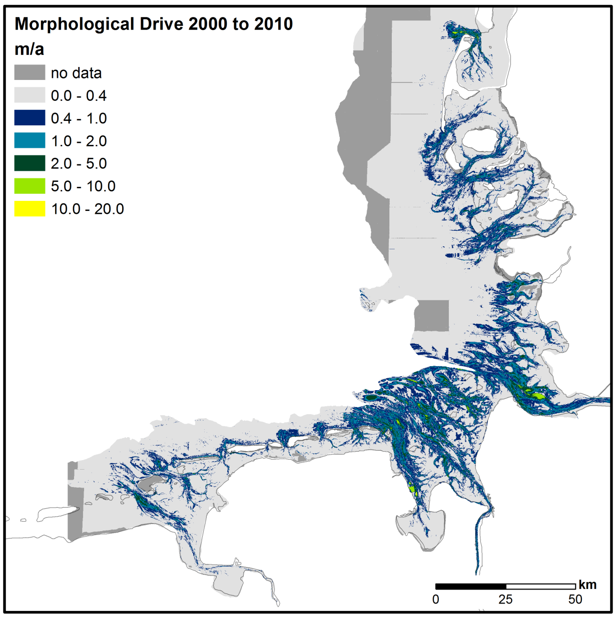

Figure 8: Example for morphologic drive based on annual bathymetries.

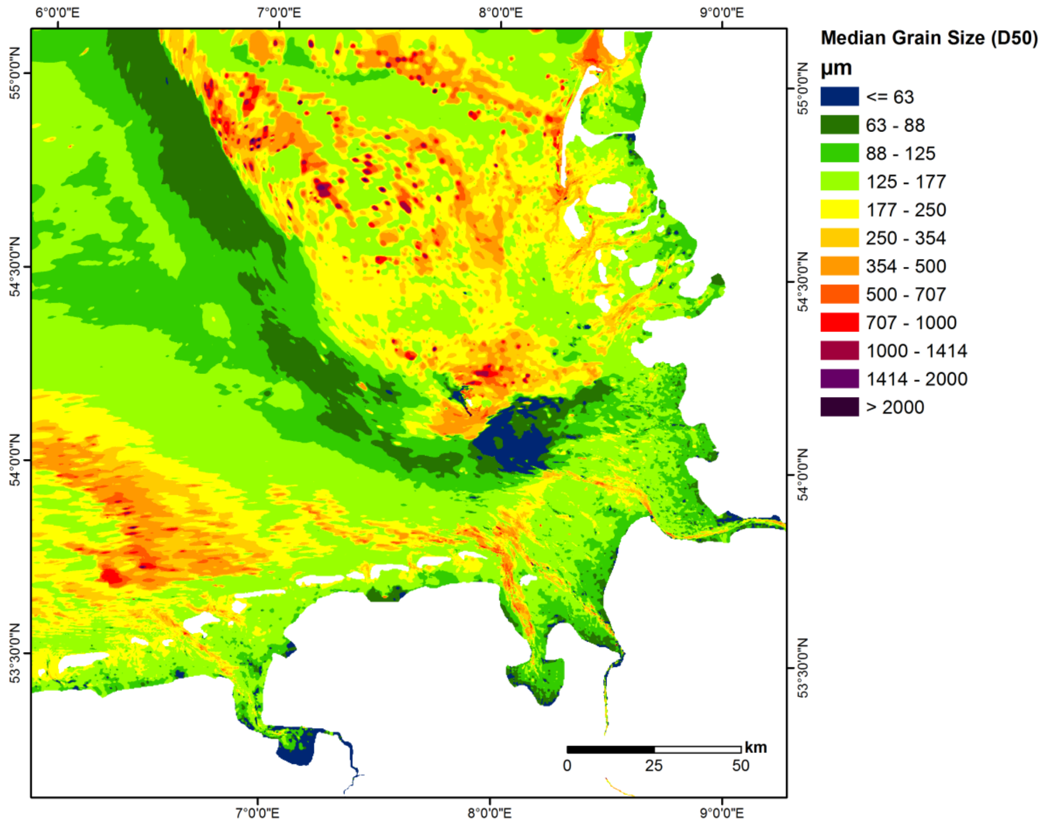

Figure 11: Median grain size (D50) of surface sediments in the German Bight (North Sea).

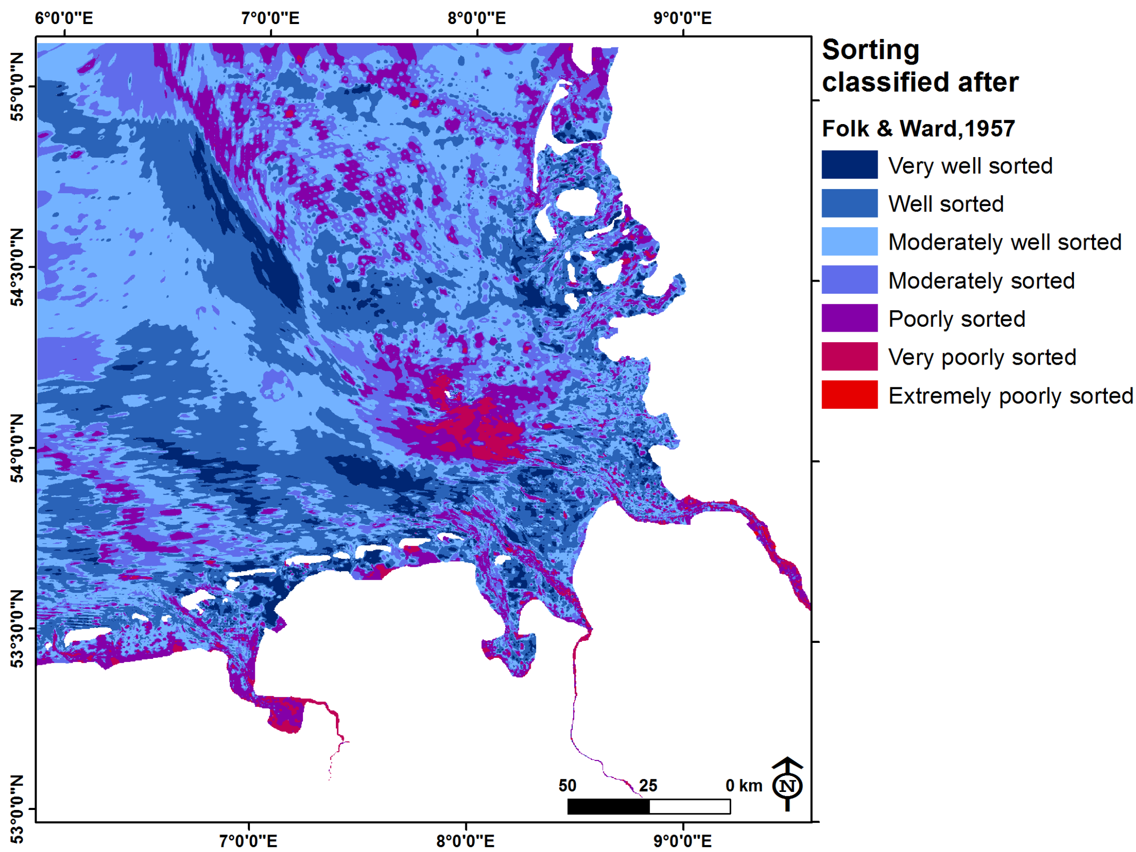

Figure 10: Sorting of surface sediments in the German Bight (North Sea).

5 Numeric modelling toolbox

Numerical simulation models have been established in recent decades as a prognostic engineering tool for the evaluation of large-scale sediment transport conditions in the German Bight, with a focus on the effects of:

- pending climate change,
- offshore renewable energy systems and their connection to the mainland and, last but not least,
- the safety and efficiency of navigation

It is important to bear in mind that the operation of morphodynamic simulation models is still subject to considerable uncertainty and that development work is still ongoing on both models and field measurement methods.

In the context of using deterministic numerical models within **AufMod** a consistent multi-model approach was established as a numerical toolbox (Table 3). These models apply different process resolutions in order to estimate the spread of the results. All models were set up to cover the entire North Sea, including a finer grid resolution for the German Bight. Sediment transport due to tidal currents, wind-driven circulation and waves were taken into account.

Table 3: Modeling systems used in **AufMod**.

Time scale	Hydrodynamics	Waves	Morphodynamics
Short-term Day – 12 month Medium-term 1 – 10 years	MARINA UnTRIM DELFT3D-FLOW	MARINA UnK SWAN	MARINA SediMorph DELFT3D-MOR
Medium-term 1 – 10 years Long-term 10 – 100 years	TELEMAC	TOMAWAC	SISYPHE

5.1 Model domain (grid)

The numerical toolbox encompassed the hydrodynamic and sediment transport modeling systems applying one domain (grid): UnTRIM2007 (Casulli and Zanolli, 2002), TELEMAC (Hervouet, 2000) and MARINA (Milbradt, smile consult) (Figure 12 left) and a two model domain concept operated by DELFT3D (Lesser et al., 2004; Figure 12, right). In order to represent well determined meteorological and tidal conditions, all models were forced with the same boundary conditions for water level, river discharges and wind.

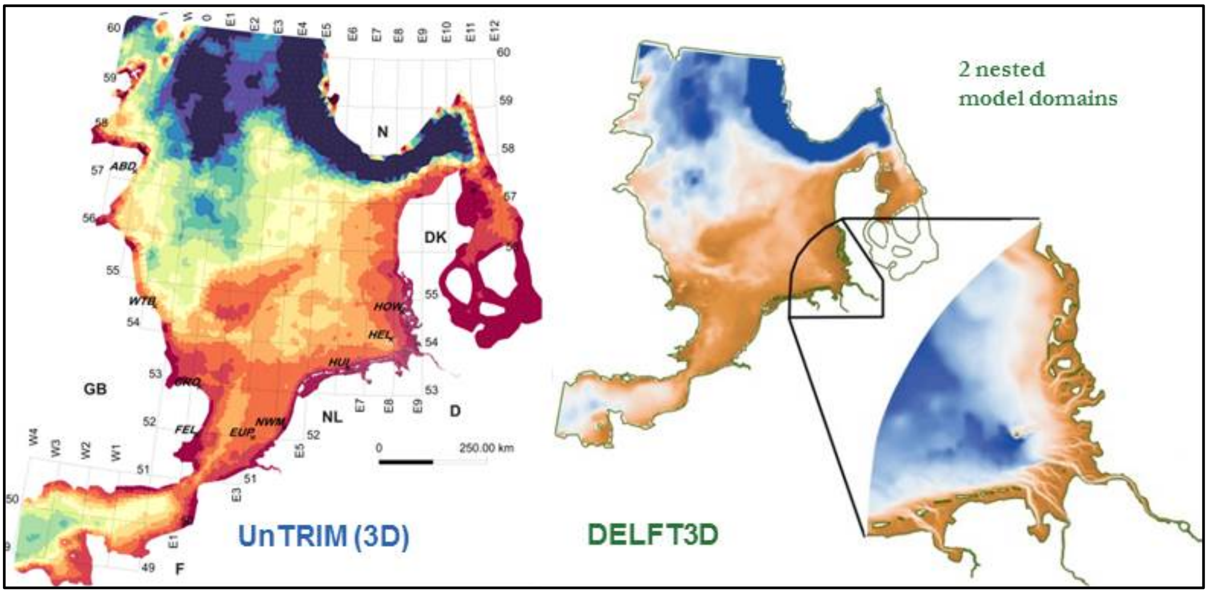

Figure 12: Model domain of the North Sea: UnTRIM, TELEMAC and MARINA (left) and a nested model of the North Sea and German Bight for DELFT3D (right).

5.2 Boundary conditions

The boundary conditions applied for all model runs are the same for all model systems in **AufMod**. An overview for this is given in Figure 13.

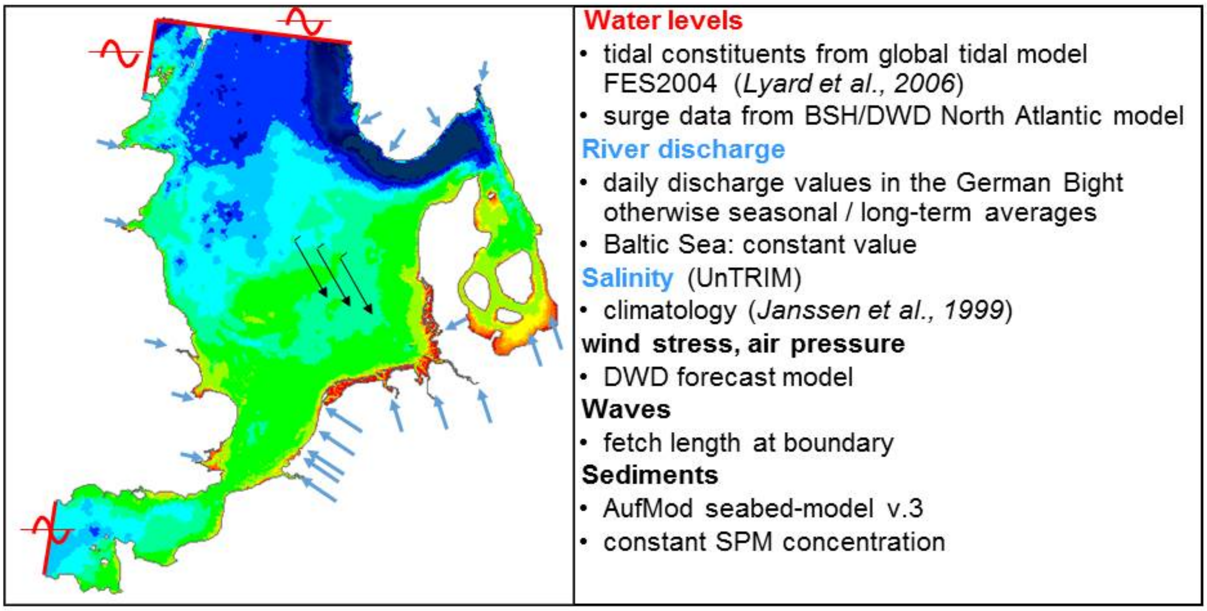

Figure 13: Boundary conditions for all model runs used in **AufMod**.

5.3 Model calibration and validation

The process of calibration and subsequent validation of morphodynamic simulation models has been operated in several steps.

An analysis of the uncertainties of the measured basis data was developed before initiating a basic model calibration. This was also the case for the measured data used for validation purposes. The inaccuracy of data throughout the whole data flow (measurements and modelling) provided the range and variation of the model parameterization for the model calibration. The model results must fall within the scope of uncertainty in the destination parameters of the calibration and validation.

The plausibility of the morphodynamic model components was checked using regular measurements of the seabed in connection with adequate spatial and temporal interpolation methods. Besides volumetric analysis of seabed evolution, bed forms and changes in the sediment mixture are also relevant.

An example of the validation of hydrodynamic model components is the documented comparison of measurements with simulation results for waves and water levels (M2-components). Given that there was a large number of a different model results available, only two comparisons were documented for waves and water level (harmonic analysis: M2-tide) Figure 14.

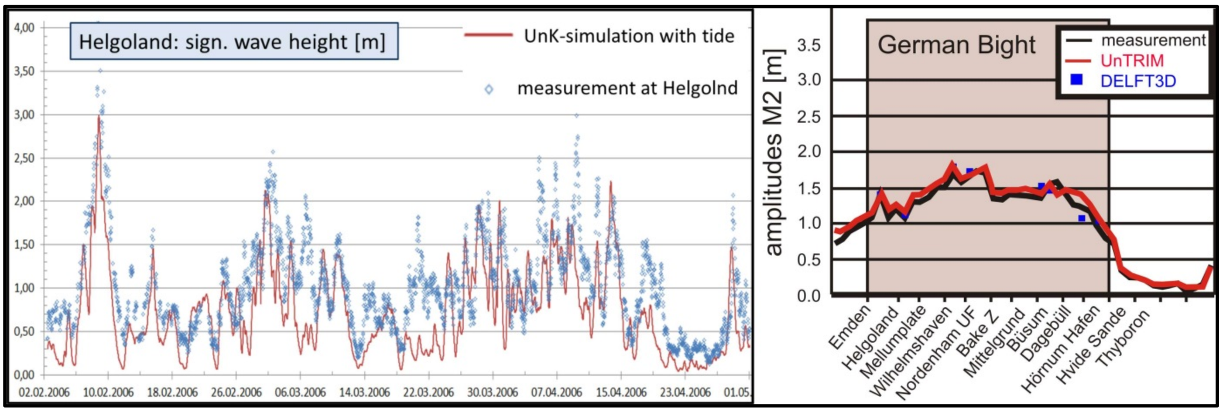

Figure 14: Comparison measurements / calculation (left: waves / right: water level).

Sediment transport cannot be acceptably validated simply by comparing measured data at certain locations. The measurement methods and uncertainties concerning the interpretation of the data, as well as the scarce availability of spatiotemporal data, cannot be directly compared with the model results themselves.

To ensure the plausibility of the morphodynamic model constituents three main parameters are taken into account:

1. morphologic space,
2. volumetric changes of the bathymetry and
3. histograms of sediment volume / mass transport.

5.4 Sensitivity studies

Miscellaneous sensitivity studies were set up to investigate the influence of sediment transport and morphodynamic relating to the

- influence of wind / wave action (Kösters and Winter 2014),
- porosity (Plüß and Kösters, 2014),
- sediment mixture (Valerius, Kösters and Zeiler 2014),
- long term simulations (Putzar and Malcherek, 2012; Putzar and Malcherek, 2014; Milbradt, 2011), and
- mean sea level rise (Plüß and Kösters, 2014).

6 Sediment transport in the German Bight

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. Figure 15 shows the basic results.

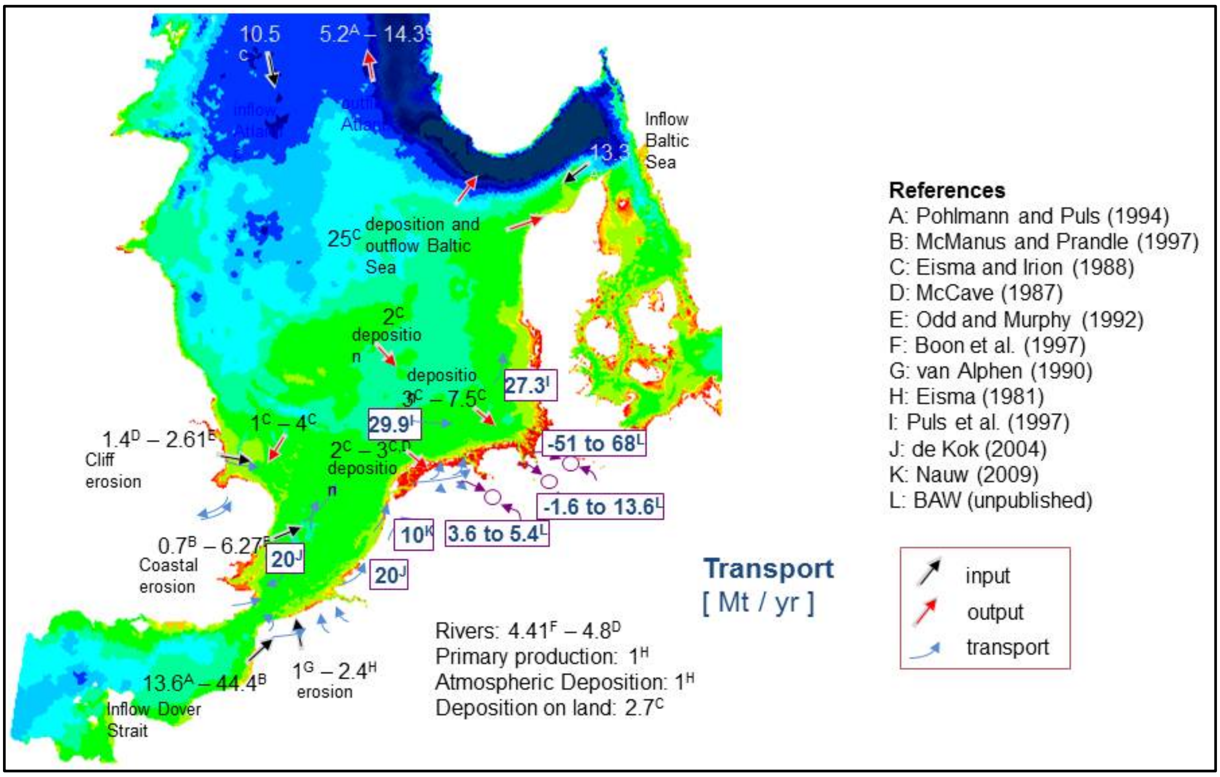

Figure 15: Estimation of sediment transport budgets in the literature.

6.1 Sediment transport paths

Identifying sediment transport paths in the German Bight was one of the main targets in AufMod. The sediment transport paths were calculated from the vectors of the resulting total transport (suspended and bed-load sediment transport) for the year 2006, including the wave effect. Figure 16 shows the sediment transport paths in the southern North Sea calculated by TELEMAC (A), MARINA (B) and UnTRIM (C), as well as the mean value resulting from these different simulation runs (D).

The basic trend of the movement of sediment from west to east seaward of the West- and East Frisian coast is shown. Mixed inconsistent transports predominate within the inner German Bight (Jade, Weser, Elbe estuary up to approximately Helgoland). On the western part of the North Frisian coast the vectors deviate widely seaward in a northerly direction. A left-turning circulation arises in the area between Wash and Doggerbank.

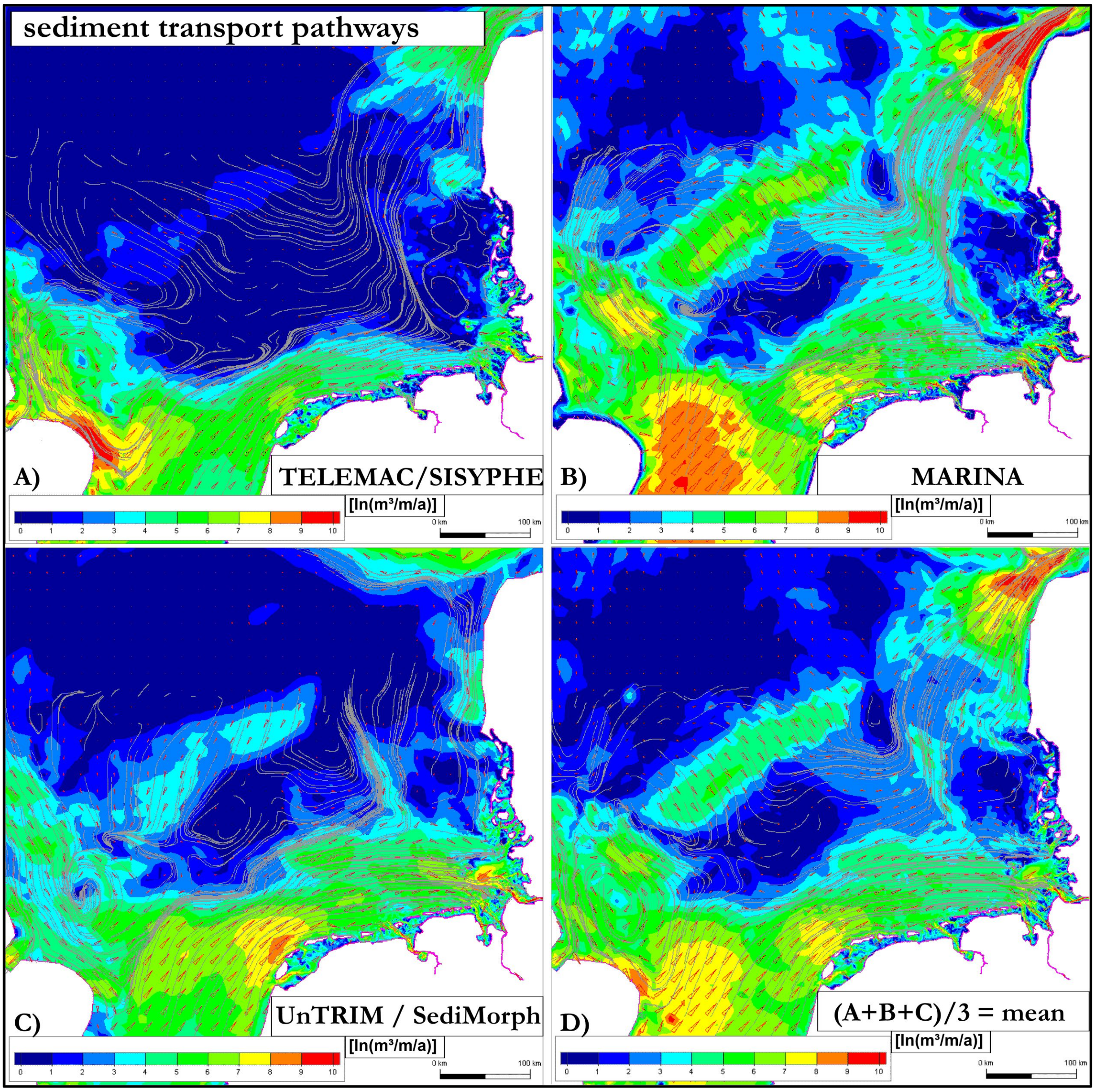

Figure 16: Sediment transport pathways from different model systems and mean value of them.

The shape and position of the sediment transport pathways proved relatively stable over the various years of simulation. The deficiency of sediment in the region of the North Frisian Islands (northern part of the German Bight) is especially apparent in all model results.

The variability of the sediment transport pathways is considerably higher in the outlet regions of the German estuaries owing to the complex bathymetric situation and the river run off which has a marked influence on sediment transport. Figure 17 documents the mean sediment transport pathways for the mouth of the Elbe estuary for the year 2000 (top panel) and for 2010 (lower panel).

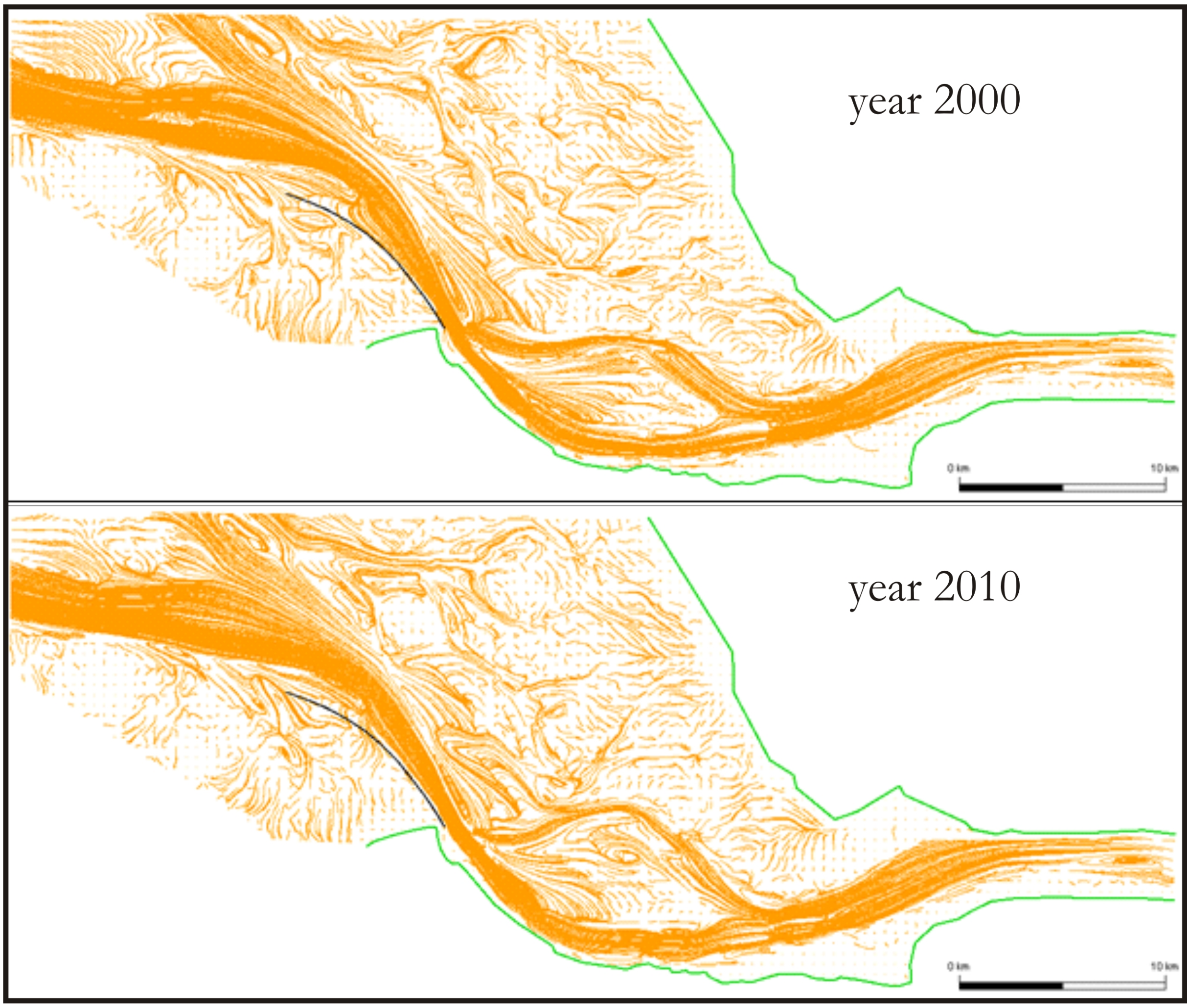

Figure 17: Characteristic sediment transport pathways in the mouth of the Elbe estuary for the year 2000 and 2010.

6.2 Sediment balance

The net sediment transport quantity entering and leaving the German Bight was estimated by defining analysis profiles to integrate the sediment mass over one year as a balance.

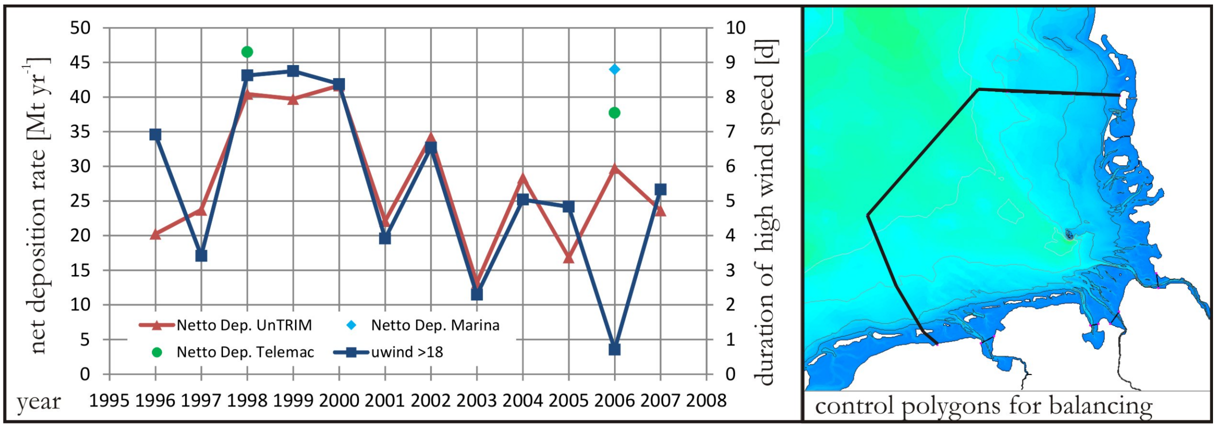

Figure 18: Net sediment deposition integrated over the boundary of the German Bight derived from UnTRIM (red), TELEMAC (green) and MARINA (light blue) and duration of high wind (> 18 m/s) at Helgoland – control sections for balancing are marked in the right panel.

Figure 18 shows these results for three different model investigations: Un-TRIM (red: 1996 - 2007), TELEMAC (green: 1998 and 2006) and MARINA (light blue: 2006). Compared with the duration [d] of high wind (> 18 m/s) at Helgoland, there is a remarkably clear correlation between transport and wind.

The export of sediment mass from the German Bight is one order of magnitude smaller than the input. No results for the exchange with the estuaries are available due to the relatively coarse spatial grid resolution of the numeric models. These exchange quantities are consequently not well incorporated to the mass balance.

Net deposition in the German Bight is calculated as the difference between the residual in and out-going sediment mass across the profiles. The UnTRIM-simulation generated a residual mean mass deposition of about 28 $Mtyr^{-1}$ = 28,000,000 t/yr. In relation to the area of the German Bight of about 32,000 km^2 and a mean sediment dry bed density of 1600 kg /m^3, a theoretical mean deposition height of about 0.5 mm can be calculated. In reality this small “coat” is not homogeneous in space and is variable due to the local bathymetry und dynamic.

The highest net deposition quantity of the investigated yearly simulations is 42 $Mtyr^{-1}$. This amount is only reproduced in other years to a 1/2 or 1/3 amount. The comparison of the different model results shows e. g. for the year 1998 a relatively good agreement (40.5 – 46.5 $Mtyr^{-1}$). In 2006 the difference is distinct (30 Mt/a – 44 $Mtyr^{-1}$).

The comparison with the duration of high wind speed shows a predominantly large correlation with the net deposition quantity. This suggests that meteorological forcing has a strong effect in relation to the magnitude and direction of the residual velocities / transport in the German Bight.

The depth variable distribution of the net transport mass is of special interest. Detailed analyses show that a predominant portion is transported in a depth range of between 10 - 20 m. The transport rates behind the East Frisian Islands, on the wadden area towards the coast, are noticeably smaller.

7 Conclusion

There are many reasons why the assessment of morphological conditions in the German Bight is associated with great uncertainties. The measuring techniques and field data in themselves fail to provide a reasonably sufficient level of accuracy. Of course, all models are based on numerous simplifications, and simulation models as such are also restricted due to the numerical approximation of physics and the limitations (construction, evolution …) of computer systems.

It will only be possible to obtain greater confidence concerning the reproduction, analysis and prediction of sediment transport and morphodynamics in the German Bight within a multidisciplinary approach. This integrated concept provides a broad consistent dataset for future analyses and numeric modelling of morphodynamic processes in the German Bight.

Uncertainty can be reduced by adopting a multi-model approach to data and process based simulation models. The application of different spatial and temporal model improvements, as well as miscellaneous physical approximations in different modelling systems, will also improve the accuracy of the overall findings.

The process-based modelling approach enables large area circulation and sediment transport processes in the entire German Bight to be simulated and analyzed. This is essential in order to stipulate seaward boundary conditions when setting up estuary modelling. Model simulation results show a high level of local variability of magnitude and direction in overall cyclonic coastal sediment transport in the German Bight. Furthermore, the model results suggest an equivalent effect of the tidal-driven sediment transport in contrast to the overall transport based on tides, winds and waves.

It is not possible at present to provide reliable validation of the transported sediment mass on the basis of the available measurement data. A quantitative analogy with geological analysis confirms the overall role of the German Bight as a net deposition area of sediment. The models used predict a net deposition rate of between 13 and over 46 $Mtyr^{-1}$. To date this balance does not show the interaction between the coastal and estuarine transport process very well.

The sediment deposition rate is closely linked with current variable meteorological forcing. Future research should consider the influence of dredging and dumping activities in the outer estuaries which are crucial for the net deposition rate.

The morphodynamic studies of **AufMod** also show large variation between the various simulation results. Evaluation of the AufMod project is limited, however, by the uncertainty in the measurement data in space and time. Further development of morphodynamic modelling, especially for the effects of interactions between the coast and estuaries, presents an ongoing challenge for future research projects.

An elaborated final report, which includes all the results from the various institutions, is also available (Heyer and Schrottke, 2013).

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