Die Küste, 69 PROMORPH (2005), 1-420 1-23

# PROMORPH – Predictions of Medium-Scale Morphodynamics: Project Overview and Executive Summary

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## Summary

This paper presents an overview of the aims, strategies, main findings and deliverables of the research work carried out within the framework of the project PROMORPH – Predictions of Medium-Scale Morphodynamics. The project was funded by the German Ministry of Education and Research over the period 2000 to 2002. Detailed descriptions of the individual investigations and results obtained are presented in the remaining papers of this volume. The overall aim of the project was to develop, calibrate, validate and apply process-based models for the simulation of medium-scale morphodynamics in coastal areas on the basis of existing modelling systems. The study area is the central Dithmarschen Bight located between the Elbe and Eider estuaries on the North Sea coast. The project relied extensively on close cooperation between several research institutes in Germany, with a pooling of expertise, efforts and resources. These specifically include the Institute of Fluid Mechanics and Meteorology of the University of Hannover and the Research and Technology Centre "Westcoast" of the University of Kiel. The papers give a detailed account of the acquisition and analysis of the field data necessary to evaluate patterns of hydrodynamics, sediment dynamics and morphodynamics. The application of existing modelling systems for developing a coupled model for the simulation of flow, waves, sediment transport and bed evolution is also described. Special attention was given to the integration of field measurements and numerical model simulations with a view to improving our understanding of the physics of the system and the predictive capabilities of the models. The set-up and application of a medium-scale morphodynamic model based on a refined procedure for selecting representative conditions are presented. The main deliverables of the project regarding morphological developments in the short and medium-term are briefly described. An overview of typical results of simulations of the morphological impacts of land reclamation and natural developments over a period of several decades is presented. Comparisons between measured and modelled bathymetric developments confirm the suitability of the model for assisting coastal managers in decision-making processes. Recommendations are also made for further studies in areas where data gaps need to be filled and our knowledge of physical processes needs to be improved.



## Zusammenfassung

*Dieser Beitrag gibt einen Überblick zu Zielen, Strategien, und zu den wichtigsten Ergebnissen des rahmengebenden Forschungsprojekts „Vorhersage mittelskaliger Morphodynamik PROMORPH". Das Projekt ist in den Jahren 2000 bis 2002 vom Bundesminister für Bildung und Forschung finanziert worden. Beschreibungen der durchgeführten Arbeiten werden auf den folgenden Seiten dieses Bandes noch genauer vorgestellt. Das übergeordnete Ziel des Projekts lag darin, auf der Basis vorhandener Module prozessorientierte Modellsysteme zur Simulation der mittelskaligen Morphodynamik in Küstengebieten zu entwickeln, kalibrieren, validieren und anzuwenden. Arbeitsgebiet war die zentrale Dithmarscher Bucht zwischen Elbe- und Eider-Ästuar/Nordsee. Das Projekt fand in enger Zusammenarbeit und in besonderer Zusammenführung von Expertise, Kompetenz und Ressourcen aus mehreren deutschen Institutionen statt, namentlich den Instituten für Strömungsmechanik und Meteorologie der Universität Hannover und dem Forschungs- und Technologiezentrum Westküste der Universität Kiel in Büsum. Messdatenerhebung und Datenanalyse, aus denen sich Verbreitungsmuster der Hydrodynamik, Sedi-*

*mentdynamik und Morphodynamik ableiten lassen, werden beschrieben. Anwendungen vorhandener Modellsysteme im Zuge der Entwicklung eines gekoppelten Modells zur Simulation von Strömung, Seegang, Sediment Transport und Seebodenentwicklung werden vorgestellt und erläutert. Ein besonderes Augenmerk wird auf die Integration von Naturmessungen und numerischen Modellsimulationen gelegt, die zu einem verbesserten Verständnis der physikalischen Abläufe und der Vorhersagefähigkeit des Modells führen. Aufbau und Anwendung des mittelskaligen Morphodynamik-Modells, das eine fortentwickelte Prozedur zur Auswahl repräsentativer Bedingungen verwendet, werden vorgestellt. Zusammenfassend beschrieben werden Zentralergebnisse des Projekts mit Darlegung von Messabläufen einschließlich Entwicklung und Test neuer Messgeräte, Messdaten, sowie von prozessorientierten Modellen zur Simulation von Strömung, Seegang, Sediment Transport und Morphologienentwicklung in kurzen und mittleren Zeitskalen. Eine Übersicht über die Ergebnisse typischer Simulationen von Landgewinnungsmaßnahmen und natürlichen Morphologieentwicklungen für die Zeiträume von mehreren Dekaden wird gegeben. Vergleiche der gemessenen und simulierten Bathymetrie-Entwicklungen bestätigen das Potential des Modells, Küstenfachleute bei Entscheidungsabläufen zu unterstützen. Darüber hinaus werden Empfehlungen für weitere Untersuchungen in den Gebieten gegeben, in denen noch Daten- und Wissenslücken existieren.*

## Keywords

Promorph, Dithmarschen Bight, Short-Term and Medium-Scale Morphodynamics, Model Predictions, Research Needs, North Sea

## Contents

Die Küste, 69 PROMORPH (2005), 1-420 1-23



## 1. Introduction

This paper gives an overview of the development of process-based models of flow, waves, sediment transport and bed evolution within the framework of the research project "PROMORPH – Predictions of Medium Scale Coastal Morphodynamics" funded by the German government. The research project was instigated by the need to develop coastal models for predicting morphological changes with time scales of years and decades. Such modelling efforts require accurate and computer-intensive simulations of flow, waves, sediment transport and morphological changes. Because the simulations of medium-scale morphodynamics are performed on the basis of input and process filtering techniques, high predictive capability of the process-based models is essential for the full range of conditions typical of the study area. Emphasis is placed on an evaluation of the performance of the models on the scales of relevance using field measurements with dense spatial and temporal coverage.

The project was initially funded by the German Ministry of Education and Research over a period of three years from 2000 to 2002 and has been continued up to the present. The research work carried out within the framework of the PROMORPH project was undertaken by a consortium comprised of the Institute of Fluid Mechanics and Meteorology of the University of Hannover and the Research and Technology Centre "Westcoast" of the University of Kiel (FTZ Büsum). The project relied extensively on close cooperation between several research institutes in Germany, with a pooling of expertise, efforts and resources. The project participants included experts in the fields of engineering, geology, meteorology and ecology as well as experimentalists and modellers. In conjunction with the main project a two-year investigation was also carried out by the FTZ Büsum and General Acoustics GmbH aimed at developing special devices for measuring near-bed suspended material concentrations.

The investigation area, covering about 600 km$^2$, is the central Dithmarschen Bight located on the German North Sea coast between the Elbe and Eider estuaries (Fig. 1). The study area may be easily accessed from the FTZ Büsum, thus making measuring campaigns less arduous. This particular area was also chosen owing to the availability of long-term monitoring data provided by government agencies as well as data collected during our own previous investigations. The morphology is dominated by tidal flats, sandbanks and a tidal channel system comprised of three tidal channels: the Norderpiep in the north west, the Suederpiep in the south west, and the Piep tidal channel, which originates at the confluence of the Norderpiep and Suederpiep. Under normal conditions the maximum mean water depth in the tidal channels is about 18 m, and approximately 50 % of the domain falls dry at low tide. The tidal flats and sandbanks are exposed at low water. The area is characterized by a meso-tidal regime with a mean tidal range of 3.2 m. Maximum wave heights in the study area are about 3-4 m along the edge of the tidal flats.

This paper summarises the aims, strategies, main findings and deliverables of the project. More detailed descriptions of the various investigations are presented in the following papers of this volume. They also describe the planning, execution and analysis of the field experiments required to determine the patterns of hydrodynamics, sediment dynamics and morphodynamics in the study area as well as the data necessary for adequately developing and testing the performance of the process-based models. The present paper also includes an overview of field measurements with a dense spatial and temporal coverage. The experiences gained in the continuing development and testing of existing measuring devices, especially for sediment concentration, are also outlined. The paper also describes the development of the process-based models and their application for predicting short-term and medium-scale morphological developments in the study area. The main deliverables of the project are listed,

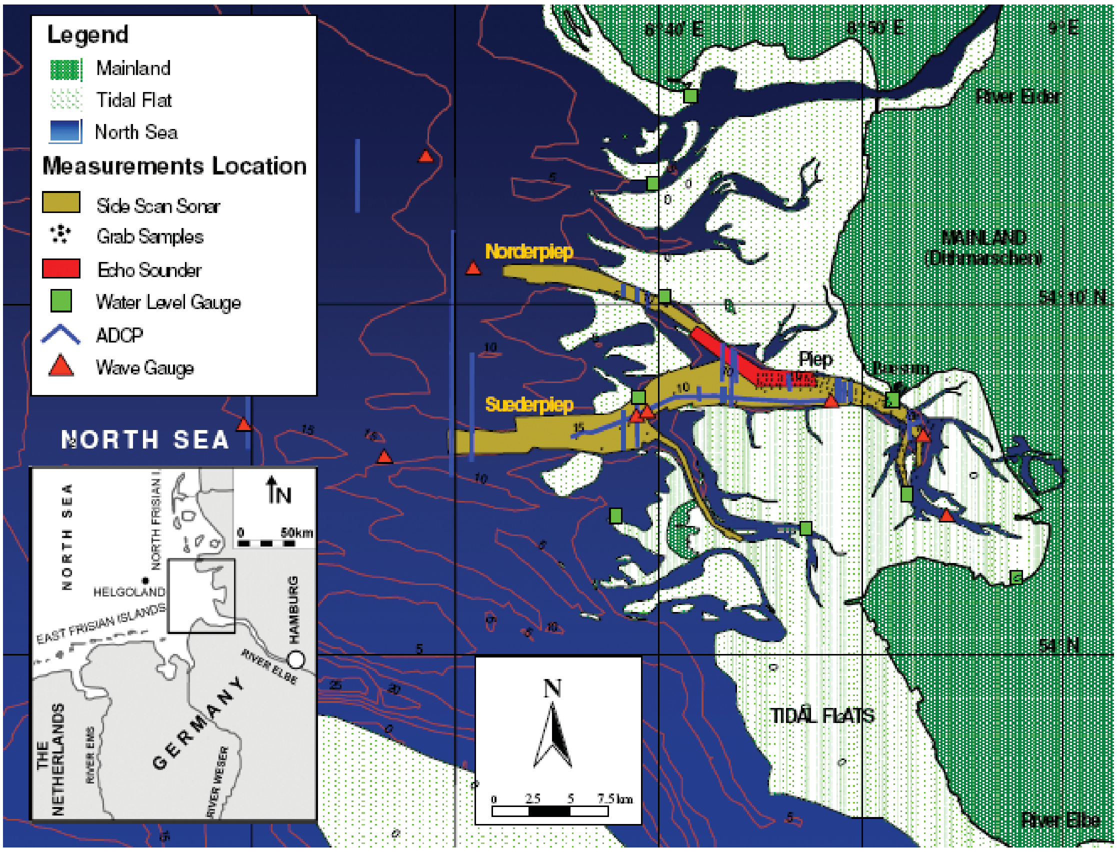



Fig. 1: Investigation area and measurement locations

and the research needs based on the investigations carried out within the framework of the project are identified. Recommendations are also made for further studies required to fill data gaps and improve our understanding of the physical processes involved.

It is hoped that the studies presented in this paper will serve as a platform for future research in the field of coastal engineering. This platform should also be helpful to practising engineers concerned with the evaluation of complex coastal behaviour as well as to coastal managers in the decision-making process relating to the planning and management of coastal areas, in particular the Dithmarschen Bight including the Elbe and Eider estuaries.

## 2. Objectives and Strategies

The main objective of the project described in the present paper was to develop and apply process-based numerical models for the simulation of morphological changes covering time scales of several years in a study area located on the German North Sea coast. In order to realise the project goals the following task areas were identified: 1) collection of suitable data to develop a model for simulating short-term and medium-scale morphodynamics, 2) planning of measurement strategies and testing of new devices specially designed to obtain the required data, 3) improvement of our understanding of the hydrodynamics, sediment dynamics and morphodynamics of the coastal system on the relevant time scales, 4) development and performance testing of process-based models of flow, waves, sediment transport and bed evolution for short periods covering the full range of conditions typical of the inves-

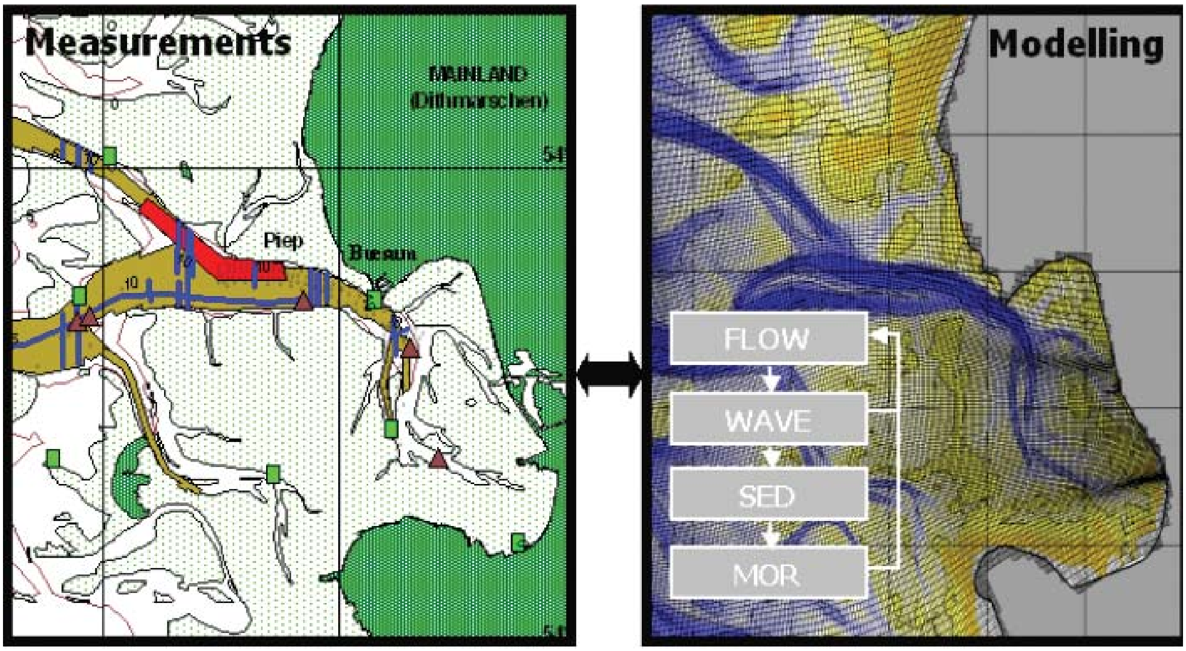



Fig. 2: Integration of process-based measurements and models

tigation area, 5) development and performance testing of a medium-scale morphodynamic model against field data covering several years, and 6) application of the validated model for predicting medium-scale morphodynamic behaviour.

In order to realise the project objectives special attention was focused on the integration of field measurements and numerical model simulations (Fig. 2). Process-based research consisting of field experiments, the compilation of existing data, the identification of information gaps, the planning and execution of measuring campaigns, field data analysis as well as the development of databases forms the basis of the investigations. The acquired data was used in the development and subsequent application of the process-based models. Two existing modelling systems were applied in the investigation area. The performance of these models for reproducing observed conditions was assessed. By adopting input and process filtering techniques the model for simulating morphological changes was further developed to yield a medium-scale morphodynamic model. In the development process special attention was given to the proper selection of representative conditions for the main driving forces, taking into account the morphological developments observed in the medium term. The model was subsequently applied for simulating the effect of individual storm events as well as for predicting morphological changes over periods of about ten years.

## 3. Field Experiments

In the planning and execution of the field surveys, special care was taken to ensure a dense spatial and temporal coverage of the study area for subsequent model development. The main purpose of the field data was to identify the most dominant physical processes governing medium-scale morphodynamics in the study area as well as to provide the data necessary for developing and evaluating the performance of process-based models for simulating hydrodynamics, sediment dynamics and morphodynamics. Testing of state-of-the-art measuring techniques and devices was also carried out.

Although numerical models find increasing application in coastal area management, such models are seldom tested thoroughly. The reason for this is that most of the measurements made in the past were only intended to clarify underlying physical processes and not for model development purposes. The evaluation of models, especially for coastal areas, imposes special requirements on field data, such as detailed measurements along the open sea boundaries and dense spatial and temporal coverage within the modelled area. As the predictive capability of models can be improved significantly with the aid of field measurements, emphasis was placed on the collection of complete sets of data for setting up and verifying the performance of the various process-based models.

Wind climate data, tidal levels, wave data and bathymetric data resulting from the monitoring programmes carried out by the relevant governmental agencies were supplemented by specially-designed field surveys providing dense spatial and temporal coverage of seabed and sediment characteristics, current velocities, suspended sediment concentrations, bed profiles etc. An overview of the spatial coverage of the field measurements is shown in Fig. 1. The field data were collected using a wide variety of devices and methods such as e.g. tide gauges, current meters, ship-mounted and stationary acoustic profilers, boomers, single beam, multiple beam and multiple frequency echo sounders, side-scan sonar, a selection of sediment and water samplers, and advanced remote sensing techniques.

Measurement campaigns were undertaken at regular time intervals (every few months) as well as for specific events. In order to obtain the data necessary to adequately validate the numerical models, a number of fully-equipped research vessels were deployed simultaneously so as to cover a larger area. Comprehensive data sets with dense spatial and temporal coverage were compiled for the purpose of model calibration and validation. An overview of the main investigations and the results obtained from an analysis of the measured data regarding patterns of hydrodynamics, sediment dynamics and morphodynamics is presented in the following.

### 3.1 Hydrodynamics

The patterns of hydrodynamics in the coastal system were investigated by TORO et al. (in this volume) based on measurements of water levels, current velocities and waves. The locations of these measurements are shown in Fig. 1. Water levels monitored by the Regional Office for Rural Areas in Husum (ALR Husum) were made available at several locations for tidal analysis and calibration of the flow models. The main tidal constituents that best represent the observed water levels at the tide gauge locations were derived from these data. Selective field measurements of current velocity at several cross-sections and locations were carried out in order to gain a better understanding of the spatial and temporal variations of flow in the main tidal channels. Due to low seabed roughness in the study area the vertical velocity distribution is fairly uniform. Owing to high tidal dominance, vertical profiles of temperature and salinity were found to be fairly uniform. This finding is consistent with the observed absence of vertical velocity stratification. Under normal conditions, flood dominance was identified in the cross-sections close to the seaward boundary of the investigation area. The maximum depth-averaged current velocity approximately doubles from neap to spring tide.

The analysis of field measurements has also helped to improve our understanding of wave characteristics in the study area. Information on waves was gathered from several sources. Wave data obtained from simultaneous measurements at five locations during a one-month period by the Coastal Research Station of the Lower Saxony Board of Ecology (CRS) on Norderney (NIEMEYER, 1997) were used for calibrating and validating the wave models. Measurements provided by the ALR Husum and the German Federal Maritime and Hydrographic Agency in Hamburg (BSH Hamburg) covering two longer periods of about 12 and 6 months yielded essential information regarding the range and probability of occurrence of wave characteristics. Maximum wave heights some 10 km westward of the outer tidal flats were found to be about 3.5 m. Wave heights of less than 2.0 m were measured along the edge of these tidal flats during the observation period. Based on the analysis of wave periods it was concluded that swell extends to the central part of the outer tidal flats, whereas locally-generated waves constitute the main source of energy further eastwards.

### 3.2 Sediment and Bed-Form Characteristics

The spatial distribution of seabed sediment characteristics in the upper layer over the tidal flats and in the tidal channels was investigated by RICKLEFS and ASP (in this volume) using side-scan sonar imagery as well as grab and water samples. The measurements covered the main tidal flats, sandbanks and tidal channels. It was found that the tidal flats are mainly comprised of fine sand and silt marked by a typical gradation from coarser sand in more exposed areas to finer deposits in sheltered regions. The maximum layer thickness of the young sediment deposits is about 20 m. The early Holocene consolidated clay exhibits a pronounced resistance to erosion, hence affecting bed roughness, sediment transport rates and morphological development. In the tidal channels the seabed is essentially comprised of sandy sediments and mud as well as consolidated deposits. In contrast to observations over the tidal flats, no clear trends could be identified regarding the spatial distribution of sediment sizes in the tidal channels. The very fine to medium-grain silt transported in suspension was found to be several times finer than bottom material (see POERBANDONO and MAYERLE, in this volume (a)). As the effect of bed roughness on sediment transport can be quite significant, investigations were carried out to determine the spatial and temporal variations of bed-form dimensions and associated roughness sizes (MAYERLE et al., in this volume (a)). Measurements of bed-form dimensions were performed at several locations using echo sounders and side-scan sonar devices. The spatial variation of bed-form dimensions was found to be quite significant and highly dependent on the layer thickness of potentially mobile sediments, the characteristics of surficial seabed sediments, and local flow conditions. Mega-ripples and dunes with lengths of up to about 20 m were mainly observed.

### 3.3 Sediment Dynamics

POERBANDONO and MAYERLE (in this volume (b)) studied the spatial distributions of suspended material concentration and transport on the basis of field measurements. Simultaneous measurements of current velocity were performed over several cross-sections using Acoustic Doppler Current Profilers (ADCPs) and optical beam transmissometers suspended from moving vessels. This investigation was focused on three cross-sections of the main tidal channels. Due to the small grain sizes of material transported in suspension and the high levels of turbulence induced by tides and waves, the vertical distribution of concentration was found to be fairly uniform. Depth-averaged suspended material concentrations of up to about 0.55 kg/m$^3$ were observed in the tidal channels. It was found that about 80 % of all material entering and leaving the system is via the Suederpiep tidal channel located in the south west. Estimates obtained with the aid of the numerical model indicate that most of this material is transported in suspension (WINTER et al., in this volume). Moreover, the sediment distribution over the vertical is clearly affected by the early Holocene layer, with limited sediment concentrations in the lower layers. In the deeper parts of the channels where the Holocene layer lies open no sediment is available for entrainment. This fact is clearly reflected in the sediment concentration profiles.

As the measurement of material concentrations in the near-bed region remains problematic, a special investigation programme was undertaken by the FTZ Büsum and General Acoustics GmbH to further the development of special devices for measuring near-bed sediment transport in the tidal channels. Two devices were tested for this purpose, namely a remote acoustic measurement device equipped with a special three-frequency echo sounder combined with a sophisticated digital signal processor system for cross-sectional measurements (EDEN et al., in this volume), and a moored near-bed sampling device designed for measuring and sampling sediment suspensions at a fixed location down to about 10 cm above the seabed (SCHROTTKE and ABBEG, in this volume). These systems were deployed simultaneously at a cross-section in the Piep tidal channel. It was found that both measuring systems are capable of resolving near-bed sediment concentrations reasonably well.

In conjunction with the main investigations, POERBANDONO and MAYERLE (in this volume (b)) tested the effectiveness of several methods for converting acoustic backscatter strength in the water column into suspended material concentrations at several locations in the main tidal channels. This investigation was based on simultaneous measurements performed using an ADCP, an optical beam transmissometer and a Niskin bottle sampler. The results confirm the acceptability of the investigated empirical approaches for converting acoustic backscatter strength into suspended material concentrations. This conversion offers the possibility of simultaneously measuring current velocities and suspended material concentrations, thus permitting direct estimates of sediment transport rates. By conducting measurements with ADCPs from moving vessels, a good spatial coverage can be achieved.

### 3.4 Morphodynamics

RICKLEFS and ASP (in this volume b) and WILKENS and MAYERLE (in this volume) studied the most significant morphological developments on different morphological time scales. Bathymetric data covering the central parts of the Dithmarschen Bight were made available by the BSH in Hamburg. The various digital data sets cover a time span of almost three decades (1974 to 2001) on a mainly annual basis. In order to evaluate medium and short-term morphological developments in the Piep channel system, several bed profiles at selected cross-sections were repeatedly surveyed by the FTZ Büsum from June 2000 to August 2003 (ASP, 2004 and RICKLEFS and ASP, this volume).

A clear landward migration of the most seaward located sandbanks has been observed during the past three to five decades. This was also confirmed by bathymetric survey and remote sensing data derived from optical sensor measurements and radar images (RICKLEFS et al., in this volume). In the deeper parts of the tidal channels the pronounced resistance to erosion of the early Holocene layer restricts morphological development to lateral migrations. Adaptation to land reclamation in the inner Meldorf Bight constitutes an additional ongoing process. Scouring of the channel beds in winter and infilling during the subsequent calm season is an active process on a seasonal scale, resulting in a trend towards narrowing and deepening of the tidal channels. Despite the scarcity of bathymetric measurements on the tidal flats, a tendency towards accretion is clearly evident.

The results of the analysis were applied to the definition of model strategies and representative conditions for the simulation of medium-scale morphodynamics. The data also served for calibrating and validating the numerical models.

## 4. Process-Based Models

Models of flow, waves, sediment transport and bed evolution have been used for the investigation area following the procedures of set-up, sensitivity studies, calibration and validation. Two modelling systems were employed within the scope of this study: the DELFT3D package, developed by Delft Hydraulics in the Netherlands (ROELWINK and VAN BANNING, 1994) and the TELEMAC modelling system, developed by the Laboratoire National d'Hydraulique of the Electricité de France (HERVOUET, 2000; GALAND et al., 1991). In both cases, two-dimensional depth-averaged (2DH) model approximations are implemented.

Fig. 3 shows the areas covered by the models in the present investigation. The DELFT3D model is based on a curvilinear grid covering the entire Dithmarschen Bight, including the Elbe and Eider estuaries, with a grid resolution ranging from 60 to 180 m. The TELEMAC model covers the central region of the bight, with a higher grid resolution ranging from about 30 to 80 m. In both cases the process-based models are coupled to yield a model for simulating morphological evolution. Fig. 3 illustrates the schemes adopted for the simulation of short and medium-term morphodynamics based on continuous model runs and the application of input filtering techniques, respectively.

The strategy adopted in the development of the coupled models for simulating bed evolution was as follows: initially, the flow and wave models were developed (PALACIO et al., in this volume and WILKENS et al., in this volume). At the same time the effectiveness of meteorological forcing for driving the process-based models was investigated (GROß and BENCKEL, in this volume). The calibrated and validated flow and wave models were then used to set up the sediment transport model (WINTER et al., in this volume). Finally, the various process-based models for simulating bed evolution changes were coupled (JUNGE et al., in this volume and WILKENS and MAYERLE, in this volume).

In order to achieve high model predictive capability for the full range of conditions typical of the study area special attention was given to the development and performance evaluation of the models with the aid of field data. Selective measurements of sediment characteristics, bed forms, water levels, current velocities, suspended sediment concentrations and transport rates with a dense spatial and temporal coverage were used for this purpose. In order to go beyond a purely descriptive and qualitative evaluation of model performance several statistical parameters were applied to obtain an objective assessment of model quality (PALACIO et al., in this volume). Moreover, existing quality standards for checking the performance of the models were adopted (WALSTRA et al., 2001 and VAN RIJN et al., 2002). As some of the statistical parameters require information on the accuracy of the measuring devices under field conditions, a method was proposed for this purpose (JIMÉNEZ GONZALEZ et al., in this volume).

The models applied in the investigation area were nested within a larger scale model covering the North Sea. The nesting sequence is based on the Continental Shelf Model

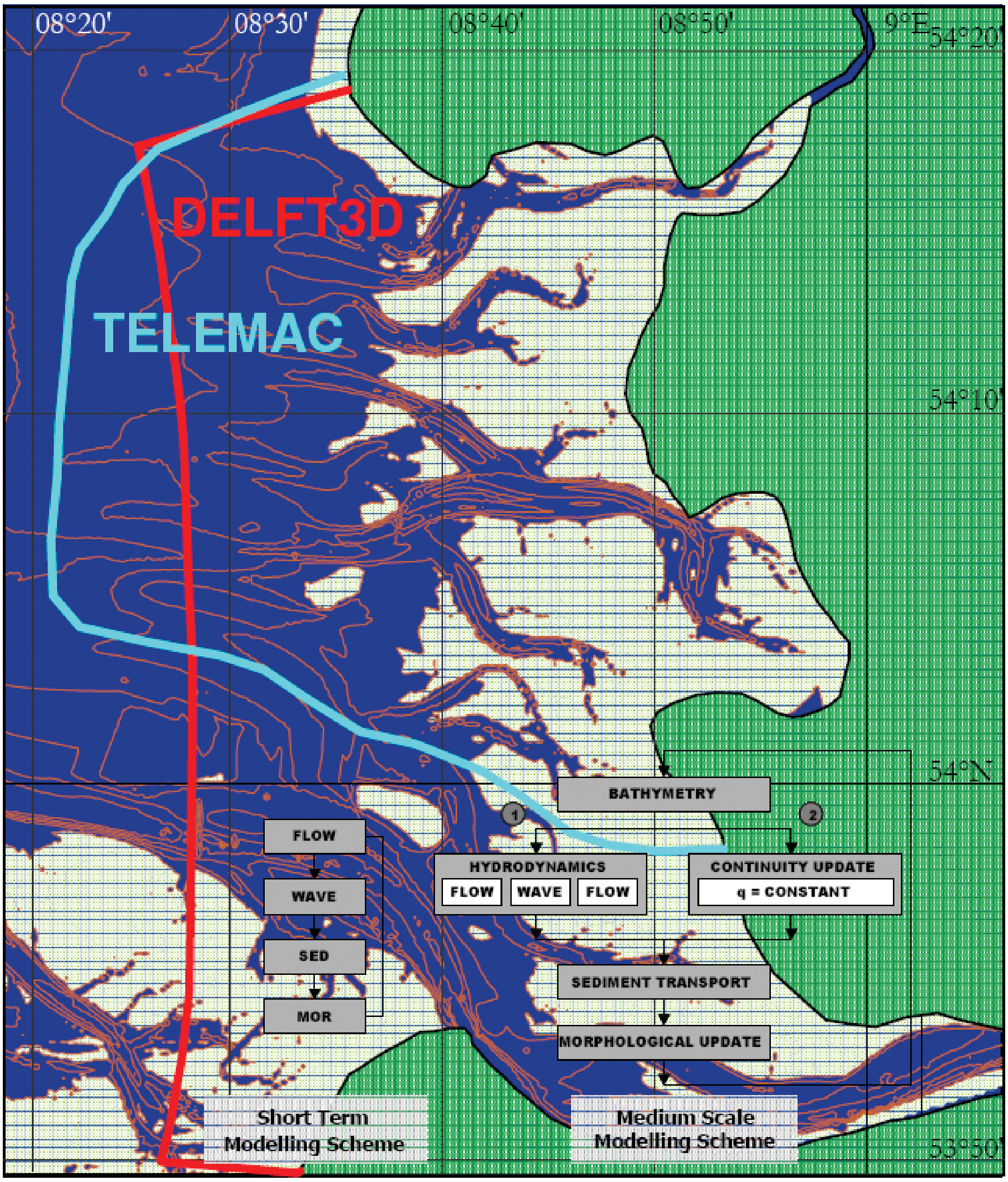



Fig. 3: Model domains and simulation schemes

(CSM) developed by Delft Hydraulics (VERBOOM et al., 1992). The flow model is driven by water levels resulting from the ten main astronomical tidal constituents along the open sea boundaries and by wind fields covering the entire North Sea. This nesting sequence was further extended for the simulation of waves and sediment transport (MAYERLE et al., in this volume (b)). This approach also permits the generation of open sea boundary conditions along other stretches of the German North Sea coast. On the basis of the available meteorological data it is possible to compute medium-scale morphodynamics over a time span of several decades.

Die Küste, 69 PROMORPH (2005), 1-420 1-23



### 4.1 Meteorological Forcing

The effectiveness of the meteorological models driving the process-based models was investigated by BENKEL and GROß (in this volume). In this investigation comparisons were made between the results of the meteorological model of the German National Meteorological Service and the data from the PRISMA interpolation model developed by the Max Planck Institute of Meteorology in Hamburg (LUTHARDT, 1987). The PRISMA model generates synoptic meteorological forcing data for the entire North Sea by applying interpolation techniques to observations along the coastline and at other locations such as oil platforms. This data is available for the period 1989 to 2000. The results showed that although the PRISMA model tends to underestimate long-term mean wind speeds while overestimating the frequency and number of high wind speed events in Heligoland, the generated wind fields provide adequate forcing data for driving the flow and wave models applied in the study area (see also MAYERLE et al., in this volume(b), PALACIO et al., in this volume).

### 4.2 Flow Model

The results of model set-up, sensitivity studies, and model calibration and validation are summarised in PALACIO et al. (in this volume). As the observed profiles of salinity, temperature and suspended material concentration are fairly uniform due to high levels of turbulence of the tidal flow (see TORO et al., in this volume and POERBANDONO and MAYERLE, in this volume), the 2DH approximation was considered to be sufficiently accurate. The flow model is driven by water levels along the open sea boundaries and flow discharges through the open boundaries across the mouths of the Elbe and Eider estuaries. Wind forcing is provided by the PRISMA interpolation model. It was found that hydrodynamic forcing along the open sea boundaries is the most significant factor governing the predictive capability of the model (MAYERLE et al., in this volume(b)). The effect of spatially variable bed roughness on the flow field was found to be less significant (MAYERLE et al., in this volume(a)). Sensitivity studies indicated that the effect of the seasonal variations in bathymetry observed by RICKLEFS and ASP (in this volume) can have a significant effect on current velocities and may be partly responsible for the discrepancies observed between measured and computed values. The validation results showed that the model is capable of reproducing water levels and current velocities in the study area in fair agreement with observations. The mean absolute errors between computed and observed water levels at a number of locations covering periods of several months were found to be less than 10 cm and 20 cm at high and low water levels, respectively. The mean absolute errors between computed and observed depth-averaged current velocities at various cross-sections in the tidal channels were generally found to be less than 0.2 m/s. On the basis of the indicators of generally accepted quality standards (WALSTRA et al., 2001 and VAN RIJN et al., 2002), computed current velocities can be considered to be between good and excellent.

### 4.3 Wave Model

WILKENS et al. (in this volume (a)) summarised the results of calibration, validation and subsequent application of four phase-averaged wave models in the central Dithmarschen Bight. These include the models HISWA (HOLTHUIJSEN et al., 1998) and SWAN (BOOIJ et al., 1999 and RIS et al., 1999) that were set-up within the DELFT3D modelling system, and COWADIS and TOMAWAC (BENOIT et al., 1996), which are modules of the TELEMAC modelling system. The models are driven along the open sea boundaries by measured values or the results of the nesting sequence covering the German Bight (MAYERLE et al., in this volume (b)). Data recorded by five waverider buoys over a period of one month were used for calibration and validation purposes. On the basis of the quality standards usually adopted, the performance of the wave model regarding wave heights was found to vary between reasonable to good. Bearing in mind the complex hydrodynamic patterns and bathymetry of the study area, this result was considered satisfactory. The validated models were applied to analyse the wave height distribution over the study area during moderate conditions and storm scenarios. It was shown that during moderate conditions only locally-generated waves with limited heights occur in the sheltered eastern part of the domain. During storm conditions, however, wave heights may reach 2 m in the eastern part and 5 m near the outer edge of the tidal flats. The effects of waves on the flow field and vice versa were also investigated. The effect of current velocities on the wave field was found to be significant and was therefore taken into account in the computations (see Fig. 3). It could also be shown that waves have a limited effect on tidal currents in shallow areas and that wave-induced currents are negligible in the tidal channels. Boundary conditions for those periods with no wave measurements at the model's open sea boundaries were produced with a nesting sequence. For this purpose, the German Bight Model was implemented for wave computations and forced with PRISMA wind fields (MAYERLE et al., in this volume (b)).

### 4.4 Sediment Transport Model

WINTER et al. (in this volume) deployed the calibrated and validated flow and wave models for the set-up of the sediment transport model of the Central Dithmarschen Bight. The 2DH model computes the total load by the summation of bed and suspended loads. The suspended sediment concentrations are computed by solving the advection-diffusion equation whereas the bed load is determined on the basis of commonly accepted algebraic formulations. It was found that the predictive ability of the model can be improved significantly using measured profiles of suspended material concentration. Sensitivity studies to determine the effects of bed roughness on sediment transport clearly indicated the relevance of the spatial variation of bed roughness in sediment transport computations. Small variations in the bed roughness can have a significant effect on the resulting sediment transport rates. This was also confirmed by the investigations carried out by MAYERLE et al. (in this volume (a)). A quantitative assessment of model quality was carried out on the basis of parameters such as the discrepancy ratio and the adjusted relative mean absolute error. The results showed that the model is capable of predicting sediment concentrations in fair agreement with observations, with a less than two-fold discrepancy between all computed and measured values.

### 4.5 Bed Evolution Model

The model used for predicting short and medium-term morphological evolution was built by coupling the flow, wave and sediment transport modules on the basis of a bed evolution algorithm. The ability of the model to simulate short-term morphological developments was investigated on the basis of a 'real time' hindcast of a well-documented severe storm in the south-eastern part of the German Bight (WILKENS and MAYERLE, in this volume). The simulations were performed over a period of about 12 days with high temporal resolution of the imposed conditions and computed morphological changes. The results obtained were found to be in reasonable agreement with observations.

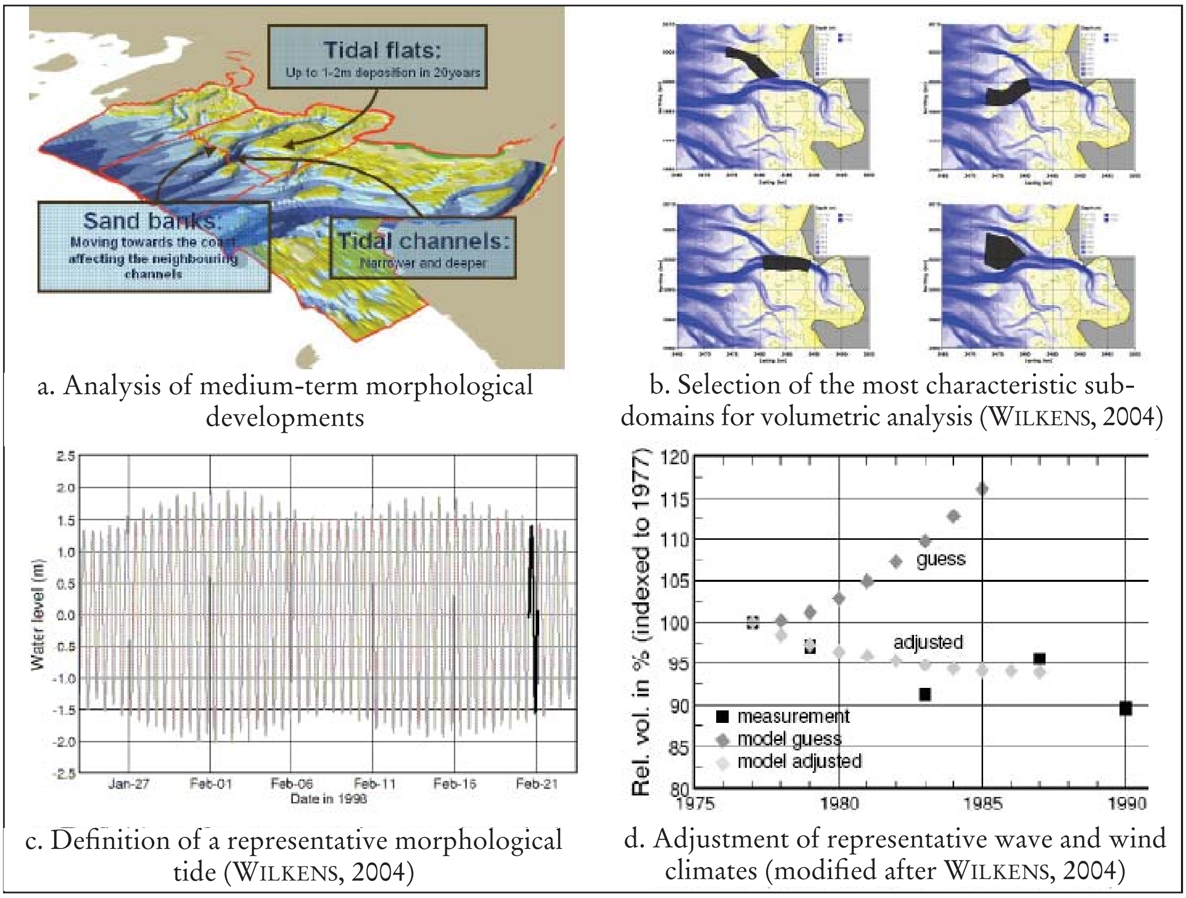
## 5. Medium-Scale Morphodynamic Model

The coupled process-based model for the simulation of flow, waves, sediment transport and bed level evolution was upgraded to a model for simulating medium-scale morphodynamics (JUNGE et al., in this volume and WILKENS, 2004). In order to limit computational requirements input and process reduction techniques were applied for tidal action and swell along the open sea boundaries as well as for the local wind field.

An enhanced procedure was adopted for selecting representative morphodynamic forcing based on an analysis of medium-term morphological evolution (Fig. 4). This procedure includes the definition of a representative tide, identification of the most relevant morphological developments on the medium scale, selection of sub-domains for volumetric analysis and adjustment of representative wave and wind climates. A morphological tide, which is a representative tide yielding a residual transport similar to that of a full spring-neap tidal cycle defined according to the approaches by STEIJN (1992) and LATTEUX (1995), was initially selected (JUNGE et al., in this volume and WILKENS and MAYERLE, in this volume). The representative wave and wind climates were adjusted by comparing modelled and measured bathymetric maps over a period of about 10 years from 1977 to 1987. For this purpose the study area was split into several sub-domains, taking into account the most predominant morphological developments and driving forces. Fine-tuning of the representative wind and wave climates was carried out separately for each sub-domain. By comparing computed morphological changes during storm events to averaged yearly morphological changes (WILKENS, 2004 and WILKENS and MAYERLE, in this volume) it was concluded that the inclusion of a few storms in a one-year morphodynamic simulation has a very limited effect on the resulting morphodynamics on the medium scale. Storm conditions were thus considered to be represented by the imposed swell and wind climate.

The representative conditions were validated on the basis of sedimentation and erosion patterns as well as volumetric analyses in several sub-domains of the central Dithmarschen Bight over a ten-year period from 1990 to 2000. Despite the different trends in morphological developments in different sub-domains of the investigation area, good agreement was obtained in overall terms regarding both morphological trends and quantitative changes in bed levels. On the basis of the latter it was concluded that the model is adequately capable of predicting medium-term morphological developments.

The results of applying the modelling system to forecast natural morphological developments over the period 1999 to 2009 and the significance of natural and anthropogenic influences due to land reclamation carried out in 1972 and 1978 are presented by JUNGE et al., (in this volume), WILKENS, 2004 and WILKENS and MAYERLE, (in this volume). The fact that the model developed for the investigation area was set up within a nested sequence as part of the entire north-west European Continental Shelf Model means that it may be applied to other coastal areas of the North Sea.




a. Analysis of medium-term morphological developments

b. Selection of the most characteristic sub-domains for volumetric analysis (WILKENS, 2004)

c. Definition of a representative morphological tide (WILKENS, 2004)

d. Adjustment of representative wave and wind climates (modified after WILKENS, 2004)

Fig. 4: Procedure proposed for the selection of representative forcing conditions

## 6. Main Deliverables

Having improved various aspects of coastal research, such as a denser spatial and temporal coverage of field data, the development of special measuring procedures and devices and the advancement of process-based models the latter may now be applied in future research or to perform numerical computations with more confidence. Further information is presented in the following sections.

### 6.1 Field Data

Field data on wind climate, tidal levels, waves and bathymetry were available from the ongoing monitoring programmes of governmental agencies. Information based on field measurements carried out within the framework of the PROMORPH research project with a dense spatial and temporal coverage of the seabed and sediment characteristics, bed forms and bed roughness, current velocities, suspended sediment concentrations and bed profiles were also available. These extensive field measurements provide an ideal database for improving our understanding of the physical system.

Besides clarifying various aspects of the modelling strategy, these data also served for testing the performance of the numerical models and assisted in the selection of a 2DH model approximation.

A database containing the data used in the investigation has now been established (JUNGE, in this volume). The stored information relates to the various aspects of the study presented and analysed in several papers of this volume and includes data sets describing the hydrodynamics, sediment characteristics, sediment dynamics and morphodynamics in the study area (POERBANDONO and MAYERLE, in this volume (a), RICKLEFS and ASP, in this volume, RICKELFS et al., in this volume and TORO et al., in this volume).

### 6.2 Measuring Procedures and Devices

Various techniques of field measurements have been investigated in order to provide optimum input data for the numerical models. Suggestions were made regarding the acquisition of the required data, such as current velocities in the tidal channels (TORO et al., in this volume) bed forms, and sediment concentrations (MAYERLE et al., in this volume (a)) and the suggested techniques were applied in the field studies. A new approach for estimating the accuracy of measuring devices under field conditions has also been proposed (JIMÉNEZ GONZALEZ et al., in this volume). In addition to a demonstration of the effectiveness of remote sensing strategies for collecting information on medium-term bathymetric developments (RICKLEFS et al., in this volume), advancements have also been made in the development of measuring devices for suspended material concentration (EDEN et al., in this volume, SCHROTTKE and ABEGG, in this volume, POERBANDONO and MAYERLE, in this volume).

### 6.3 Short-Term Morphodynamic Model

As already mentioned in Section 4.5, the model for simulating short-term morphological evolution was created by coupling the process-based models for flow, waves and sediment transport via the bed evolution model (Fig. 5). Fig. 6 shows the grid system employed in the simulations. The set-up procedure, results of sensitivity studies relative to the main numerical and physical parameters, and the calibration and validation of these models against field data were fully documented by e.g. PALACIO et al. (in this volume), MAYERLE et al. (in this volume (b)), WILKENS et al. (in this volume), WINTER et al. (in this volume) and WILKENS and MAYERLE (in this volume). The simulations of water levels, current velocities, waves, sediment transport and nutrient dynamics using these models have been shown to be in good agreement with observations. Short-term morphodynamic simulations are carried out continuously. The model may serve to assist coastal managers in questions relating to waste water management or in studies of morphological changes resulting from natural causes such as storm events or due to anthropogenic interventions such as land reclamation. Recommendations for improving the performance of the numerical models for coastal areas through the integration of field measurements and models have been derived and successfully applied within the framework of the project.

### 6.4 Medium-Scale Morphodynamic Model

A model with a temporal scale of up to about a decade combined with a spatial scale in the order of several kilometres was constructed using input and process reduction techniques. This model was to perform medium-scale morphodynamic simulations with a focus on the description of morphological features such as sand banks, tidal flats and tidal channels in the central Dithmarschen Bight. The calibration and validation of this model was carried out on the basis of over 20 years of bathymetric measurements. Comparisons between computed and observed morphological changes in the central Dithmarschen Bight (JUNGE et al., in this volume, WILKENS (2004) and WILKENS and MAYERLE, in this volume) show good agreement in both qualitative and quantitative terms. An improved selection process for representative conditions has been proposed and successfully applied, and is now available for use elsewhere. The morphological evolution from 1977 till 1987 was used to evaluate and improve model performance. The quality of the model in predicting the medium scale morphodynamics was verified from 1990 till 1999.

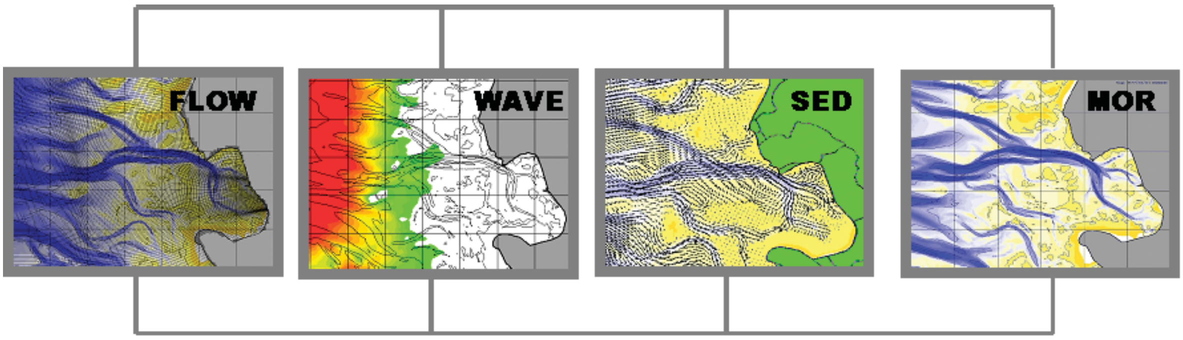



Fig. 5: Model family for the simulation of hydrodynamics, sediment dynamics and morphodynamics

### 6.5 Model Predictions

With regard to medium-scale morphodynamics our model will be helpful to coastal engineers for predicting morphological changes resulting from natural causes or anthropogenic interventions. Various applications of the developed models for supporting coastal managers in decision-making processes are summarised in JUNGE et al. (in this volume), WILKENS (2004) and WILKENS and MAYERLE (2004). We recommend that such models be used for scientific research, engineering analysis and design, and decision-making in the planning and management of coastal waters including issues on climatological changes and sea level rise. The existing model may be used among other things to investigate the effect due to land reclamations similar to those at the Meldorf Bight; due to the construction of coastal structures such as the Eider Storm Surge Barrier and due to the dredging activities in the Elbe Estuary that may impact on the adjacent coastal areas. The set-up of the model within a nesting sequence supports its application in other coastal areas of the North Sea. Fig. 7 shows typical results of the application of the model for predicting medium-term morphological developments. Fig. 7a shows the morphological developments along the eastern boundary of the Meldorf Bight following the construction of two dikes in 1972 and 1978, respectively. As a result of land reclamation the area of the Meldorf Bight was reduced by approximately 40 %, thereby decreasing the drainage area of the Piep tidal channel. Changes in the relative wet volume of the Meldof Bight over a thirty-year simulation period are presented. Both measurements and model results indicate a clear tendency towards a reduction in the relative wet volume at a diminishing rate with respect to time. Predictions of medium-scale morphodynamics have also been made in the central parts of the Dithmarschen Bight. Typical results for the Tertiussand tidal flat are shown in Fig. 7b. The predicted change in the trend of morphological developments from 1999 onwards is due to the formation of a new channel connecting the Suederpiep tidal channel with the open sea.

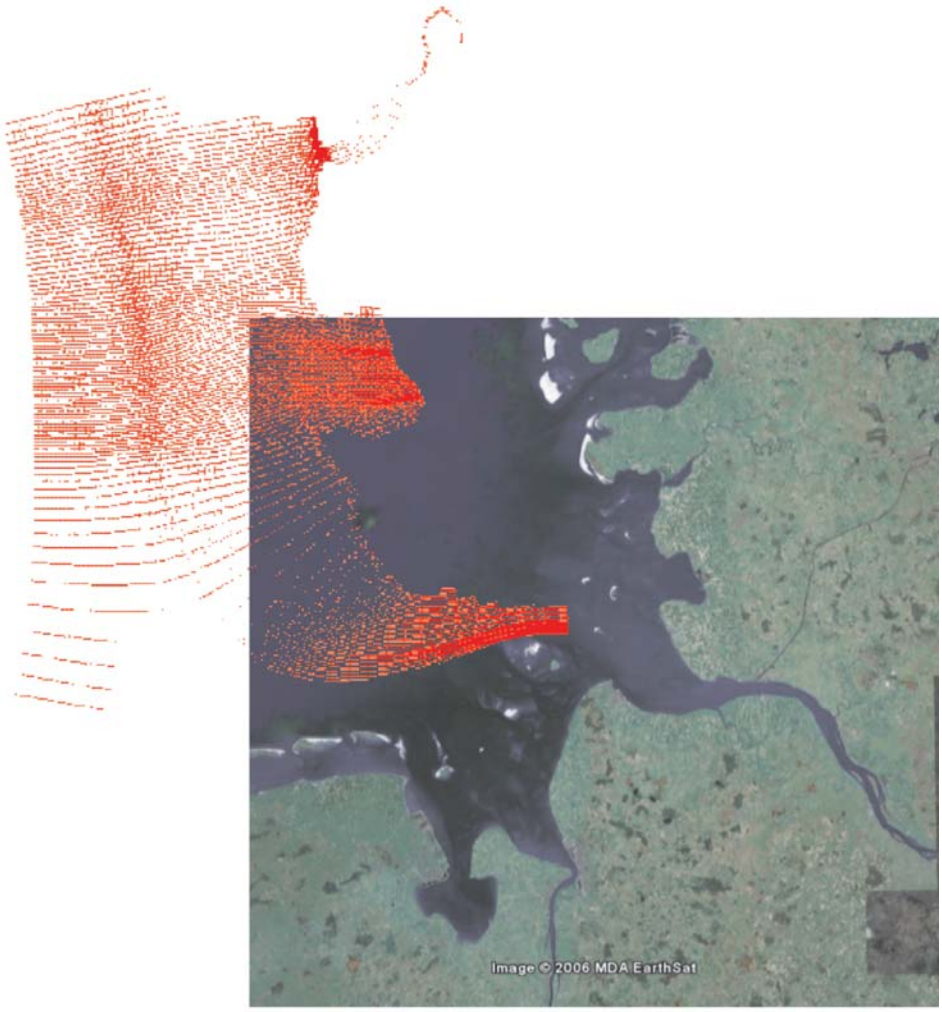
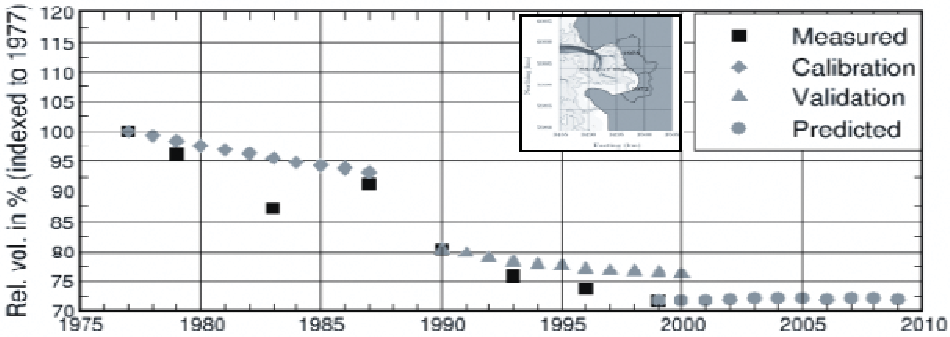


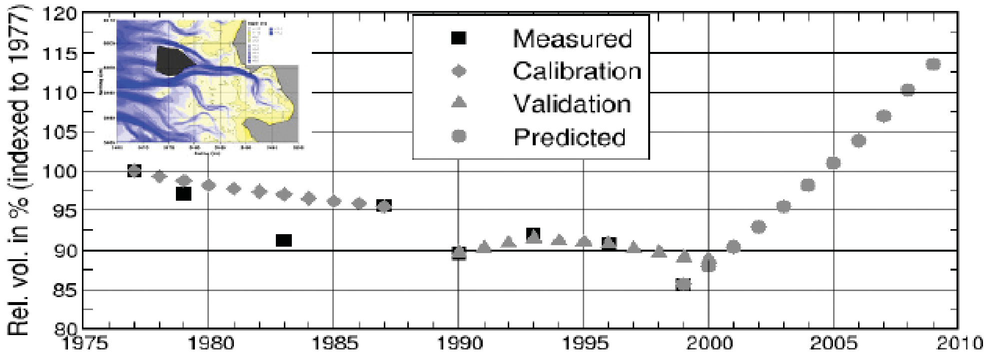

Fig. 6: Model domain and grid

## 7. Developments to Date and Future Research Needs

Significant advancements have been made in recent years regarding near-shore measuring techniques and the numerical modelling of coastal areas. With the exception of sediment concentration and transport the measurement of most of the remaining physical quantities has become standard practice. Instead of point measurements, there is an increasing shift towards measurements over wider areas with a dense spatial and temporal coverage using non-intrusive measuring devices. Moreover, the accuracy of measuring instruments under field conditions is steadily improving. In conjunction with the new developments in measuring devices and techniques there was also a rapid development of numerical models for coastal areas. Models for flow and waves have advanced significantly and have been applied successfully to many coastal areas worldwide. Owing to the difficulty of collecting field data on suspended sediment concentrations and the inherent complexity of sediment transport processes, morphodynamic modelling is still in its infancy. As most of the equations used in morphodynamic models are based on the results of laboratory experiments, uncertainties still remain regarding their applicability under field conditions.




(a) Relative wet volume of the Meldorf Bight resulting from land reclamation (WILKENS and MAYERLE, 2004)




(b) Relative wet volume of the Tertiussand tidal flat (JUNGE et al., this volume)

Fig. 7: Predictions of medium-scale morphodynamics (s.a.)

Modelling of the governing processes of morphological developments for predicting coastal evolution has also advanced significantly. Anthropogenic interventions often have a significant impact on flow and sediment transport patterns and, therefore, their effect on coastal morphodynamics can be reasonably well predicted. Morphological developments due to natural causes, however, are more difficult to trace and to simulate. The modelling of short-term morphodynamics is usually performed continuously with coupling of the component process-based models. As already mentioned, the predictive capability of these models is dependent to a large extent on the performance of the models. Due to a scarcity of data and inaccuracies in measuring bed level changes in the short term, such models are seldom calibrated or validated. Medium-scale morphodynamic models incorporate input and process filtering techniques. The predictive capability of these models thus depends on the proper selection of representative conditions. The availability of bathymetric measurements covering the area of interest on a yearly basis is also essential for improving the predictive capability and reliability of such models.

The findings from the PROMORPH research project also enabled recommendations to be made regarding further studies and research necessary to fill data gaps and improve our knowledge of the physical system. Specific areas are identified in which basic and applied research is still required. The recommendations focus in particular on requirements concerning the development and application of coastal area models using existing modelling systems.

### 7.1 Measurement Requirements

As already mentioned, a lack of understanding of sediment dynamics due to the difficulties in performing accurate measurements under field conditions still remains one of the main limitations in coastal research. In order to fill data gaps and improve our knowledge of the underlying physical processes measuring devices need to be further developed. This is important, in particular, for measuring sediment transport near the seabed. In this context, the necessary adjustment of existing transport formulae to more adequately describe field conditions suffers from a lack of suitable field data. The majority of empirical equations for describing sediment transport rely on experiments carried out in the laboratory. It is therefore recommended to perform simultaneous measurements of bed forms, bed roughness, seabed characteristics, and sediment concentration and transport at several locations for a wide range of conditions. This would permit the testing and improvement of existing equations and/or the development of new sediment transport formulae, and, consequently, advance developments in morphodynamic modelling.

### 7.2 Modelling Requirements

An overview of modelling research needs for the simulation of short and medium-scale morphodynamics is presented in the following. Emphasis should be placed on the definition of quality standards and the selection of statistical parameters to be considered for verifying the performance of the various process-based models at different spatial and temporal scales. In order to advance developments in sediment transport modelling, the spatial and temporal variations of bed forms and bed roughness as well as their effects on sediment transport should be investigated in more detail.

Studies are also required to improve our knowledge of near-bed boundary conditions for solving the advection-diffusion equation for suspended sediment transport, taking into account the variation of seabed characteristics. It is also recommended to carry out further research on the coupling of flow, wave and sediment transport models. Although such coupling has been implemented successfully in several existing models, this approach has seldom been tested using field data. The use of field data for this purpose will provide better descriptions of bed shear stresses and permit more accurate estimates of sediment transport, particularly in the near-bed region.

As far as the modelling of medium-scale morphodynamics is concerned, we have also identified several areas on which future research should be focused. In order to improve the predictive capability of the numerical models these should include more detailed descriptions of the physical system. An example of this is the presence of the early Holocene layer in the investigation area. Unless this layer is properly identified with the help of field measurements and accounted for, both in the sediment transport and bed evolution models, it will not be possible to correctly reproduce sediment transport patterns and lateral migration of the tidal channels. Moreover, the representative conditions for tides, which are usually restricted to lunar cycles, should be extended to take additional account of seasonal effects. The chronology of waves and storm events in relation to medium-term morphodynamics is another aspect that should be investigated. In order to extend the temporal scale of the predictions, attention should also be given to descriptions of sediment concentrations in deeper areas. Equilibrium transport formulations, which are usually adopted to estimate the amount of sediment entering and leaving the coastal area, assume an instantaneous response of the sediment load to local equilibrium hydrodynamic conditions. Under certain conditions, however, the vertical sediment distribution and time lag effects along the open sea boundaries can have a significant influence on the results. In view of the latter, sediment transport models incorporating non-equilibrium equations covering the adjacent sea area should be applied to obtain a better representation of sediment concentrations along the open sea boundaries.

### 7.3 Model Applications

The modelling systems and strategies developed within the framework of the PROMORPH project should be extended for application in other coastal areas. In particular, further application of the modelling system is recommended for predicting short-term and medium-scale morphological developments due to natural causes and anthropogenic interventions. The monitoring of selected areas and the continuous development of numerical models in close cooperation with governmental agencies would greatly advance developments in this field.

It is also important to develop criteria for defining optimum locations and frequencies of measurements in order to provide the minimum data required for adequately verifying model performance and checking the need to implement three-dimensional model approximations. As complete sets of data covering periods of several decades are seldom available, the results of model simulations may be used to fill data gaps. With this aim in mind, the 40-year time series of HIPOCAS data sets (WEIßE et al., 2003) for wind, water levels and waves are currently being validated within the framework of the project "Modelling of Medium-Term Wave Climate in Selected Coastal Areas of the German North Sea – MOSES" (KFKI 80) funded by the German Ministry of Education and Research from 2004 to 2007.

The set-up of models for nowcasting will also promote developments in measuring and modelling strategies. The possibility of measuring and modelling conditions in quasi-real time will provide a much better understanding of the processes involved and assist in defining measuring campaigns specially tailored to provide the required data for further model development. Investigations relating to the above are presently underway within the framework of the research project "Nordsee Monitoring System" funded by the Ministry of Science, Economics and Transport of the State of Schleswig-Holstein from 2005 to 2008. In addition to extensive field measurements using a wide range of modern devices, the model family developed within the framework of the PROMORPH project has been improved and already implemented in a nowcasting system at the FTZ Büsum.

## 8. Concluding Remarks

Process-based models for simulating medium-scale morphodynamics have been developed within the framework of the research project entitled "PROMORPH – Predictions of

Medium – Scale Coastal Morphodynamics". Based on the purpose of the study investigations were concluded satisfactorily and have added significantly to measuring and modelling strategies and techniques.

Special attention was placed on the integration of field measurements in numerical model simulations, leading to an improvement in our understanding of the physics of the system and the predictive capability of the developed models. Several new strategies for field measurements as well as for the development of process-based numerical models in the hydrodynamic and morphodynamic field have been proposed and implemented. In addition to comprehensive data sets specially tailored to match the needs of model development, advancements have been made in the development of measuring strategies and devices for sediment transport investigations.

On the basis of the two modelling systems, i.e. the DELFT3D and TELEMAC packages, simulation models were developed for the Dithmarschen Bight. These process-based models for the simulation of water levels, current velocities, waves and wave-induced currents, sediment transport and bed evolution in the short and medium term were calibrated and verified against extensive field data. Applications of the model system to reproduce a wide range of conditions have confirmed its suitability for use in scientific research, engineering analysis and design, and decision making in the planning and management of coastal waters.

Recommendations for further research have been identified. It has been shown that advancements in the measuring and modelling field can be enhanced by more stringently integrating field measurements. In order to fill information gaps future research should concentrate on field measurements of sediment dynamics in the near-bed boundary layer. An evaluation of the performance of the process-based models in a more quantitative way and the development of suitable quality standards is recommended. Emphasis should also be placed on the continuing development of input filtering techniques to provide a better description of the forcing conditions for tides, waves and sediment transport for medium-scale morphodynamic simulations. In order to advance developments in field applications it is also recommended to extend the approaches and strategies adopted in the present investigation to other coastal areas of the North and Baltic seas.

## 9. Acknowledgements

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