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# Modelling of Medium-Scale Morphodynamics in a Tidal Flat Area in the South-Eastern German Bight

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# Modelling of Medium-Scale Morphodynamics in a Tidal Flat Area in the South-Eastern German Bight

By INGO JUNGE, JORT WILKENS, HELGE HOYME and ROBERTO MAYERLE

## Summary

On the basis of extensively calibrated and validated models for the simulation of tides, waves and sediment transport morphodynamic models have been developed, employing two existing modelling systems. For both systems, approaches are defined for input and process filtering, for the purpose of medium scale morphodynamic simulations, i.e. a temporal scale up to a decade combined with a spatial scale in the order of several kilometres. At this scale, the present investigation focuses on morphological features such as sand banks, tidal flats and channels. The models were calibrated and validated on the basis of sedimentation and erosion patterns as well as on a volumetric analysis for several sub-domains in the central Dithmarschen Bight. The volumetric analysis yielded objective and quantitative comparisons between computed and observed morphological changes. It was concluded that the models produce good results and are able to correctly reproduce the significant morphodynamic trends. After calibration and validation these models were applied to predict morphological changes in the study area between 1999 until 2009. A number of significant changes were computed, related mainly to a predicted splitting of the tidal flat Tertiussand between the two major tidal channels Norderpiep and Suederpiep.

## Zusammenfassung

*Die mesoskalige Simulation von morphodynamischen Entwicklungen im Küstenvorfeld wird durch den Aufbau und die Anwendung zweier Modellsysteme vorgestellt. Mesoskalig kennzeichnet hier Zeiträume von einem Jahrzehnt und eine räumliche Ausdehnung von mehreren Kilometern. Die morphologisch relevanten Prozesse wie Tideströmung, Seegang und Sedimenttransport werden durch unabhängige Einzelmodelle erfasst und separat kalibriert und validiert. Die Kopplung dieser Prozesse führt zu rechenintensiven Gesamtmodellen, so dass Methoden zur Prozessfilterung und zur Reduzierung von Eingabedaten erforderlich sind. Das Untersuchungsgebiet umfasst das Pieprinnensystem der Dithmarscher Bucht an der schleswig-holsteinischen Nordseeküste. Für die Kalibrierung und Validierung der Gesamtmodelle werden Erosions- und Depositionsmuster analysiert und Volumenbilanzen für einzelne Wattflächen und Rinnenabschnitte ausgewertet. Ein Vergleich mit Messungen zeigt, dass die Modelle die morphologischen Änderungen und Trends qualitativ wie auch quantitativ gut reproduzieren. Abschließend werden die Modelle für eine morphologische Prognoserechnung für den Zeitraum 1999 bis 2009 eingesetzt. Das Ergebnis zeigt einige deutliche Bathymetrieänderungen, wie zum Beispiel die Zerteilung der Wattfläche Tertiussand zwischen Norder- und Süderpiep.*

## Keywords

Morphodynamic Modelling, Morphology, Dithmarschen Bight, Promorph, Calibration, Validation, Medium Scale, DELFT3D, TELEMAC

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## Contents



## 1. Introduction

The major objective of this investigation is to set-up, optimise and apply several process-based numerical models to investigate and predict medium scale morphodynamic behaviour in the central Dithmarschen Bight, situated in the south eastern part of the North Sea. Medium scale morphodynamics are defined here as changes occurring on the spatial scale of tidal channels, tidal flats and sand banks. The corresponding time scale is in the order of several years. The existing morphodynamic models include the calibrated and validated individual process models for the same area, as described in PALACIO et al. (in this volume), WILKENS et al. (in this volume), and WINTER et al. (in this volume) for tidal flow, coupled flow and waves, and coupled flow, waves and sediment transport, respectively. The good results obtained from an evaluation of the individual models form a sound basis for the overall morphodynamic models and increase their reliability for analysing the significance of designated processes and conditions governing the morphodynamic behaviour of the study area.

The model is driven by means of a limited number of imposed conditions determined with the aid of input reduction methods for tidal, swell and wind conditions. Tidal conditions were obtained from a model-nesting sequence whereas swell and wind conditions were defined on the basis of long-term data sets derived from measurements at nearby locations.

The morphodynamic models were optimised and evaluated on the basis of bathymetric data covering the period 1977 to 1999. Calibration and validation of the models were carried out for the periods 1977 to 1987 and 1990 to 1999, respectively. Evaluation of the models is based on a volumetric analysis of selected tidal channel sections and a tidal flat.

The measured data used in the investigation are described in Section 2. The applied morphodynamic modelling systems and the set-up models are presented in Section 3. The input reduction methods are discussed in Section 4, followed by a description of the calibration and validation procedures in Section 5. The results of a 10-year model prediction study are presented in Section 6, followed by the conclusions in Section 7.

## 2. Measurement Data

Bathymetric data for the central Dithmarschen Bight (Fig. 1) were available from two sources. The Federal Maritime and Hydrographic Agency (BSH) in Hamburg provided data from yearly bathymetric surveys. These surveys cover the tidal channels and lower tidal flats in the study area. A combination of approximately three years of data yielded full coverage of the deeper areas. A bathymetric data set with full area coverage based on data collected around 1990 was provided by the Office of Rural Development (ALR) in Husum. This data set also covers the higher tidal flats and was therefore very useful for supplementing the data provided by the BSH. Since no other sets of bathymetric data are available for the shallow areas, these were also used to generate model bathymetries for years other than 1990.

Additional data required in the investigation were long-term swell and wind data. Since long-term swell data were not available for the study area, wave statistics from observations near Sylt were used to provide a data base (BMFT, 1994). The fact that this location is somewhat more exposed to the open sea means that the measured wave climate is likely to be more severe than in the study area. These wave statistics, however, provide an insight into

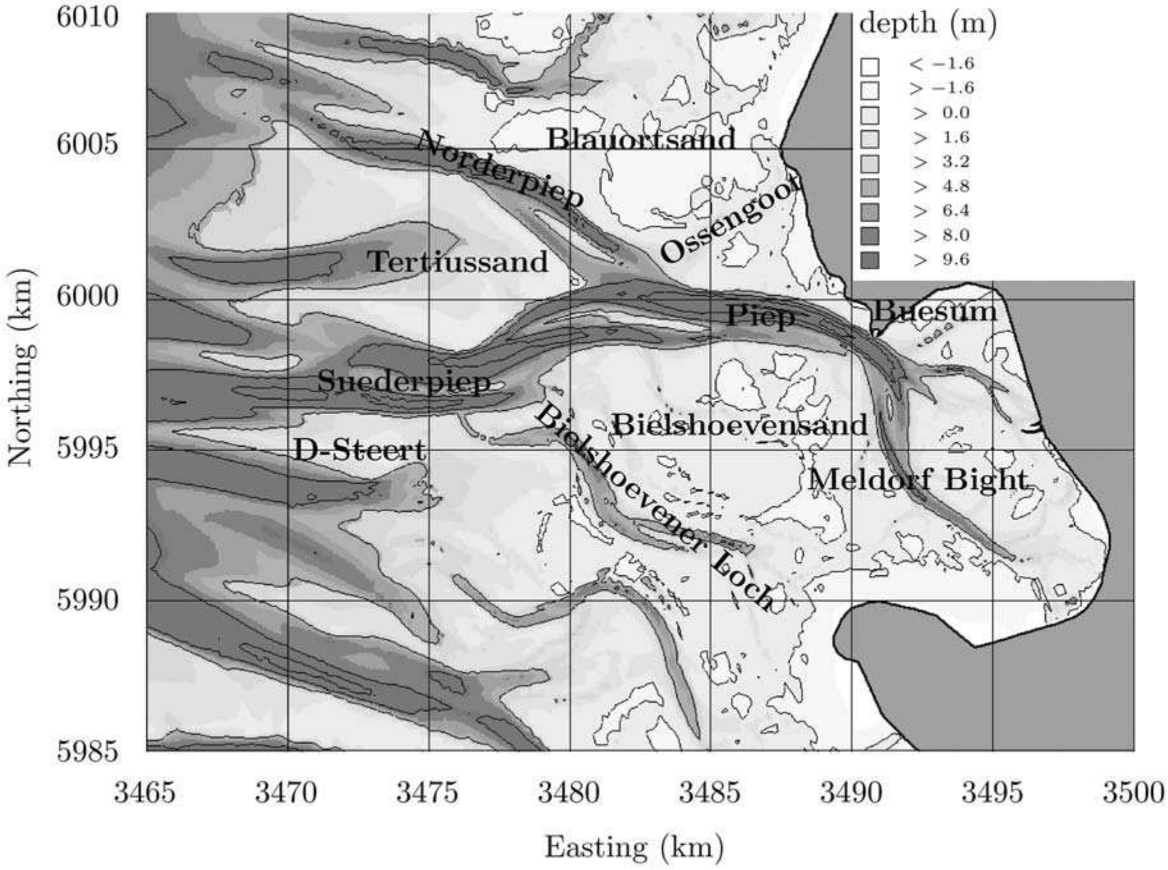


Fig. 1: The study area of the central Dithmarschen Bight (WILKENS, 2004)

the approximate wave conditions in the Dithmarschen Bight. The wind data applied in the investigation were provided by the PRISMA interpolation model, a synoptic meteorological model with a 42 km resolution (LUTHARDT, 1987). The results from this model were used in preference to data from measurement stations since they give a spatially consistent overview of dominant wind conditions. The wind data were verified on the basis of observations made at the measurement station of the Research and Technology Centre Westcoast in Buesum (FTZ). This verification showed good agreement between wind speed as well as wind direction (WILKENS, 2004).

## 3. Description of the Applied Morphodynamic Models

Two modelling systems were applied within the scope of this study; the DELFT3D package, developed by Delft Hydraulics in the Netherlands (ROELVINK 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).

The DELFT3D model is based on a curvilinear grid that covers the entire Dithmarschen Bight including the Elbe and Eider estuaries. The TELEMAC model covers the centre of the Dithmarschen Bight with a higher resolution. The computational grids and bathymetries of these models are shown in Figs. 2 and 3. The DELFT3D model incorporates the SWAN wave model (BOOIJ et al., 1999; RIS et al., 1999) whereas the TELEMAC model implements the TOMAWAC wave model. The depth-integrated approach is adopted in both hydrodynamic models.

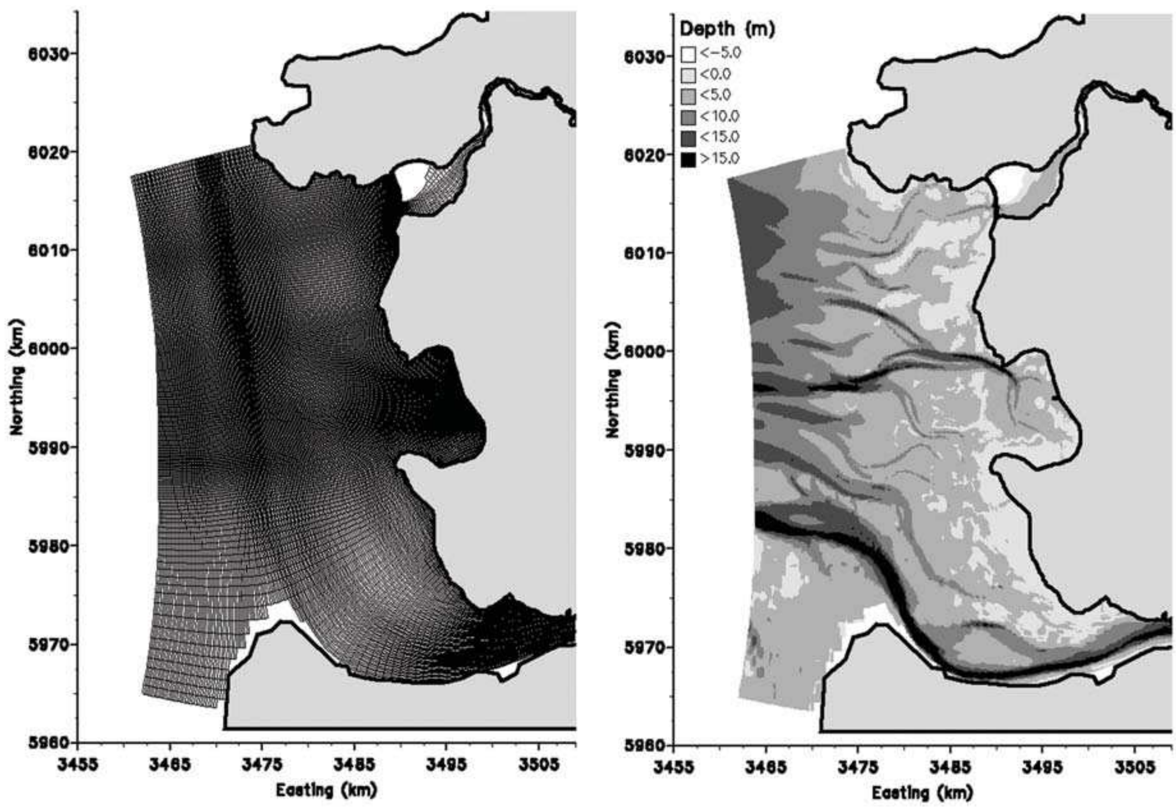


Fig. 2: Model grid and bathymetry of the DELFT3D morphodynamic model (WILKENS, 2004)

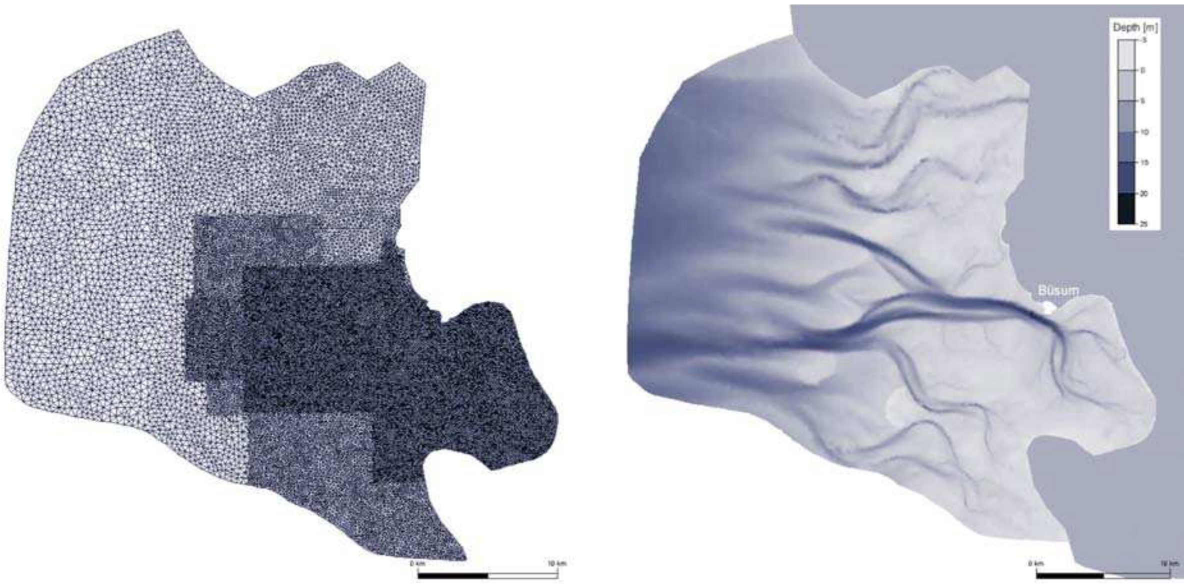


Fig. 3: Model grid and bathymetry of the TELEMAC morphodynamic model

An overview of the general model characteristics is given in Table 1.

Table 1: General settings of the applied morphodynamic models

| **Model** | **DELFT3D** | **TELEMAC** |
|---|---|---|
| Grid type | Finite difference, curvilinear | Finite elements |
| element size | 80 – 600 m | 30 – 80 m |
| Flow model | DELFT3D-FLOW | TELEMAC2D |
| model type | 2Dh | 2Dh |
| Wave model | SWAN | TOMAWAC |
| model type | Stationary | Instationary |
| Sediment transport model | DELFT3D-TRSSUS | SISYPHE |
| transport formula | BIJKER, 1971 | BIJKER, 1971/ENGELUND-HANSEN, 1967 |
| Morphodynamic model | DELFT3D-MOR | TELEMAC |

The DELFT3D and TELEMAC models are constructed from calibrated and validated individual process models. Details about these models may be found in PALACIO et al. (in this volume), WILKENS et al. (in this volume) and WINTER et al. (in this volume) for tidal flow, coupled flow and waves, and coupled flow, waves and sediment transport, respectively. The fact that the calibration and validation of these underlying models yielded good results implies that the individual processes are correctly modelled in both qualitative and quantitative terms. This guarantees the reliability of the models for predicting morphological evolution in the study area.

In stationary wave models, the assumption is made that the imposed conditions with respect to local wind as well as to the imposed swell along the open boundaries are relatively constant for the period of time needed for waves to travel through the model domain. Since the imposed conditions are strongly reduced through statistical methods, a stationary approach is generally acceptable for medium scale morphodynamic modelling.

The sediment transport formula by BIJKER (1971) is defined as:

$$S_{tot} = S_{bed} + S_{susp}$$

$$S_{bed} = bD_{50}\frac{u}{C}\sqrt{g}\,(1-p)\exp\left(\frac{-0.27(s-1)D_{50}\rho g}{\mu\tau_{b,wc}}\right)$$

$$S_{susp} = 1.83 S_{bed}\left(I_1 \ln\left(\frac{33.0h}{r_c}\right) + I_2\right)$$

With:

| | |
|---|---|
| $S_{tot}$ | Total load transport |
| $S_{bed}$ | Bed load transport |
| $S_{susp}$ | Suspended load transport |
| b | Empirical constant |
| $D_{50}$ | Median grain size |
| u | Current velocity |
| C | Chézy coefficient |
| g | Gravity constant |
| p | Porosity |
| s | Relative sediment density |
| μ | Ripple factor |
| $\tau_{b,cw}$ | Shear stress at the bed due to currents and waves |
| $I_1$,$I_2$ | Einstein integrals (EINSTEIN, 1950) |
| h | Water depth |
| $r_c$ | Bottom roughness |

The transport formula by ENGELUND and HANSEN (1967) reads:

$$q_b = 0.05\left(\frac{1}{1-p}\right)\sqrt{(s-1)\frac{d_{50}^3}{g}C^2 T_2^{5/2}}$$

With:

| | |
|---|---|
| $q_b$ | Sediment transport |
| p | Porosity |
| s | Relative sediment density |
| $d_{50}$ | Median grain size |
| G | Gravity constant |
| C | Chézy coefficient |
| $T_2$ | Transport capacity, related to current related shear stress |

## 4. Computation Reduction Methods

The hydrodynamic components (flow and wave models) of morphodynamic models are by far the most expensive in terms of computational costs. Two methods are generally applied to reduce computation time without a significant loss in accuracy. The first method concerns the modelling scheme of the morphodynamic simulations. The second method concerns the number of hydrodynamic conditions that are modelled within a morphodynamic simulation.

Due to the differing characteristics of the DELFT3D and TELEMAC modelling systems, these approaches are applied in different manners for each system. These approaches are discussed separately in the following.

## 4.1 DELFT3D Modelling Scheme

The DELFT3D model consists of separate modules for currents, waves, bed load and suspended load sediment transport, and bottom evolution. These are coupled as shown in Fig. 4. The hydrodynamic computation over a double tidal cycle is followed by a calculation of sediment transport. Morphological updating is carried out on the basis of the average sediment transport over the second tidal cycle. This approach eliminates possible initialisation effects. The update is performed over a dynamic time step determined by the magnitude of the computed sediment transport and the grid size, taking into account the Courant number limitation for explicit numerical schemes. The old bathymetry is then replaced by the newly-computed bathymetry at the beginning of the loop, and the computations are repeated until the end of the defined simulation period has been reached.

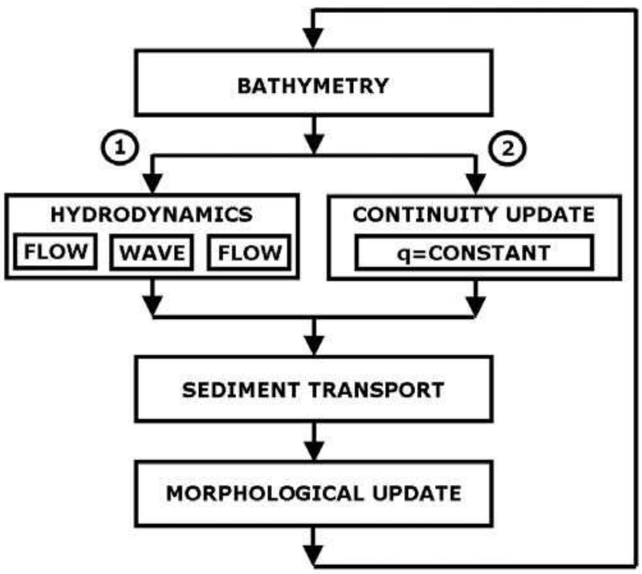


Fig. 4: Morphodynamic model scheme of the DELFT3D Dithmarschen Bight model

Generally speaking, small morphological changes do not significantly influence horizontal flow patterns. Considering this fact, a continuity update may be carried out instead of a full hydrodynamic computation (indicated by ①). In this continuity update, indicated by ②, the discharge at a location is assumed to be constant and the velocity is corrected for the changed water depth. After a number of such updates a new hydrodynamic computation is necessary, as the underlying assumption of constant horizontal flow patterns no longer holds. For the underlying model a maximum of five continuity updates was found to be the optimum on the basis of a sensitivity analysis. This approach greatly reduces the required computation time without a significant loss of accuracy in the morphodynamic results.

### 4.2 DELFT3D Input Reduction

In order to limit the computational requirements of the medium scale morphodynamic simulations, input reduction was applied for the tidal, swell and local wind boundary conditions. A single representative tidal cycle was defined under consideration of the approaches by STEIJN (1992) and LATTEUX (1995). The computed sediment transport values at a number of locations in the study area were averaged over a full spring-neap tidal cycle. These average transport values were compared to the average transport values over each single tidal cycle. Subsequently, the tidal cycle with average transport values closest to those of the entire spring-neap tidal cycle for the majority of the locations was defined as being representative.

A number of representative conditions were defined for swell and local wind behaviour. These conditions were deduced from long-term measurements. On the basis of a statistical reduction the observed conditions were grouped into a limited number of representative conditions with corresponding probabilities, which together make up the representative swell and wind climates. These representative climates form the starting point for a sensitivity analysis in which the morphological response of the model over a 10-year period is investigated. The climates were optimised to yield an overall response in agreement with the observed morphological changes.

Each year of the morphodynamic simulation is subdivided into a number of sub-simulations with varying representative conditions for swell and local wind behaviour. This is shown schematically in Fig. 5. The length of these sub-simulations corresponds to the probabilities of the imposed conditions. These swell and local wind conditions are combined with a representative tidal cycle. A definition of the representative conditions is described in the following sub-section. In applying this technique the same conditions are repeated for consecutive years. Although a sensitivity analysis showed a limited effect on the computed results of the order of the imposed conditions, the conditions were mixed with regard to their severity, i.e. wind speed, wave height and wave period.

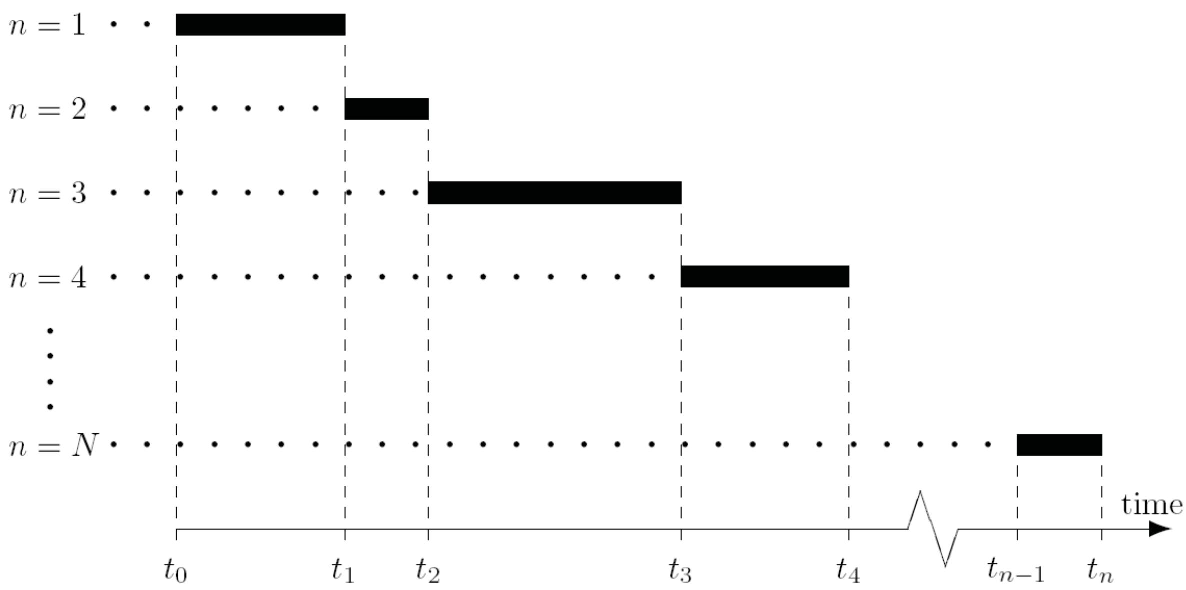


Fig. 5: Scheme for dividing the simulation into $N$ sub-simulations with varying conditions and simulation periods. For each sub-simulation $n$ the scheme of Fig. 4 is implemented (WILKENS, 2004)

### 4.2.1 Representative Tidal Conditions

A total of 31 locations (17 in the tidal channels and 14 on the tidal flats) were defined as representative for deducing the morphologically representative tide (see also WILKENS, 2004). These locations are shown in Fig. 6. A simulation with the coupled flow-sediment transport model was performed over a full tidal cycle. Both models were thoroughly calibrated and validated as described in PALACIO et al. (in this volume) and WINTER et al. (in this volume). The computed sediment transport values in both horizontal directions were averaged over the simulation period for each of these locations. These average transport values were to be reproduced as accurately as possible by the single representative tide. In order to determine this optimum tide the computed sediment transport values were temporally averaged for each tidal cycle within the simulation period. Factors $\lambda_{x,i}$ and $\lambda_{y,i}$ define the quality of representation and were determined for tide i in the x and y directions, respectively, as being the ratio of the tide average to the spring-neap average. A value of $\lambda = 1$ thus indicates a perfect match.

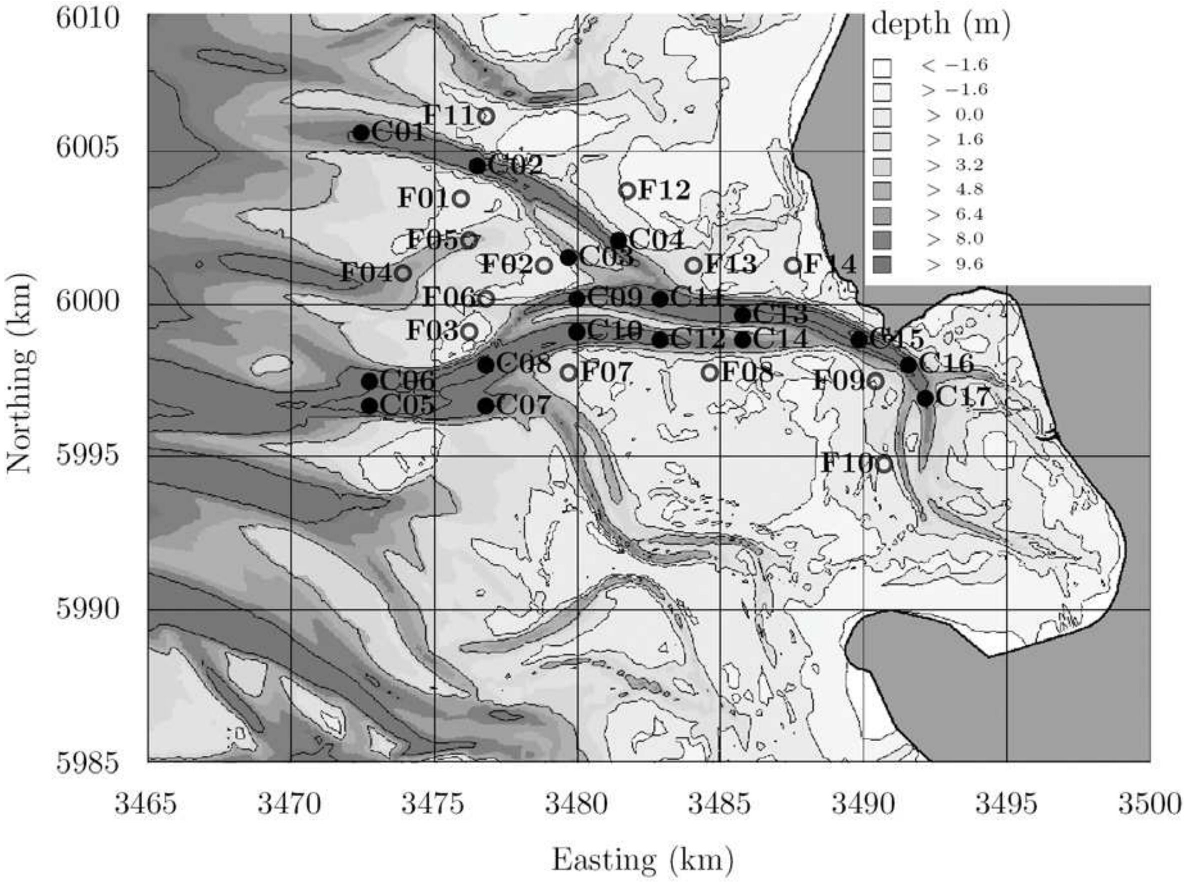


Fig. 6: Location of the defined points in the channels (dots) and on the tidal flats (circles) for the selection of the representative tidal cycle (WILKENS, 2004)

An evaluation of this procedure showed that a tidal cycle with an average tidal range of about 3.5 m yields the optimum representation for the area under consideration. The minimum and maximum values of λ were found to be 0.7 and 1.3, respectively, with values ranging between 0.95 and 1.05 for about 80 percent of the selected locations. It is thus concluded that representation of the considered spring-neap tidal cycle by an average tide is justified.

Compared to the results of the previously-mentioned studies by STEIJN and LATTEUX, the tidal range of this representative tide is found to be lower. The authors suggest representative tidal cycles with a tidal range of 10 percent higher, respectively 7 to 20 percent higher than the average tidal range. These differences may well be related to differing characteristics of the coastal areas investigated, such as the dominant acting forces and sediment characteristics.

Comparisons of the computed morphological effects over a one-month period were made in order to assess the applicability of the defined representative tide (WILKENS, 2004). In the first case, only tidal forcing was considered in the computations. In the second case tidal forcing was combined with representative wind and swell climates; definitions of the latter are given in the following sub-sections. For both cases a simulation was performed for both the full spring-neap tidal cycle and the representative tide. The resulting deposition and erosion patterns are shown in Figs. 7 and 8. It should be noted that the results were obtained from the validated morphodynamic model.

These results indicate that the computed morphological changes for the full spring-neap tidal cycle and the representative tide are very similar. It is thus concluded that the selected representative tide is acceptable for correctly simulating medium scale morphodynamics.

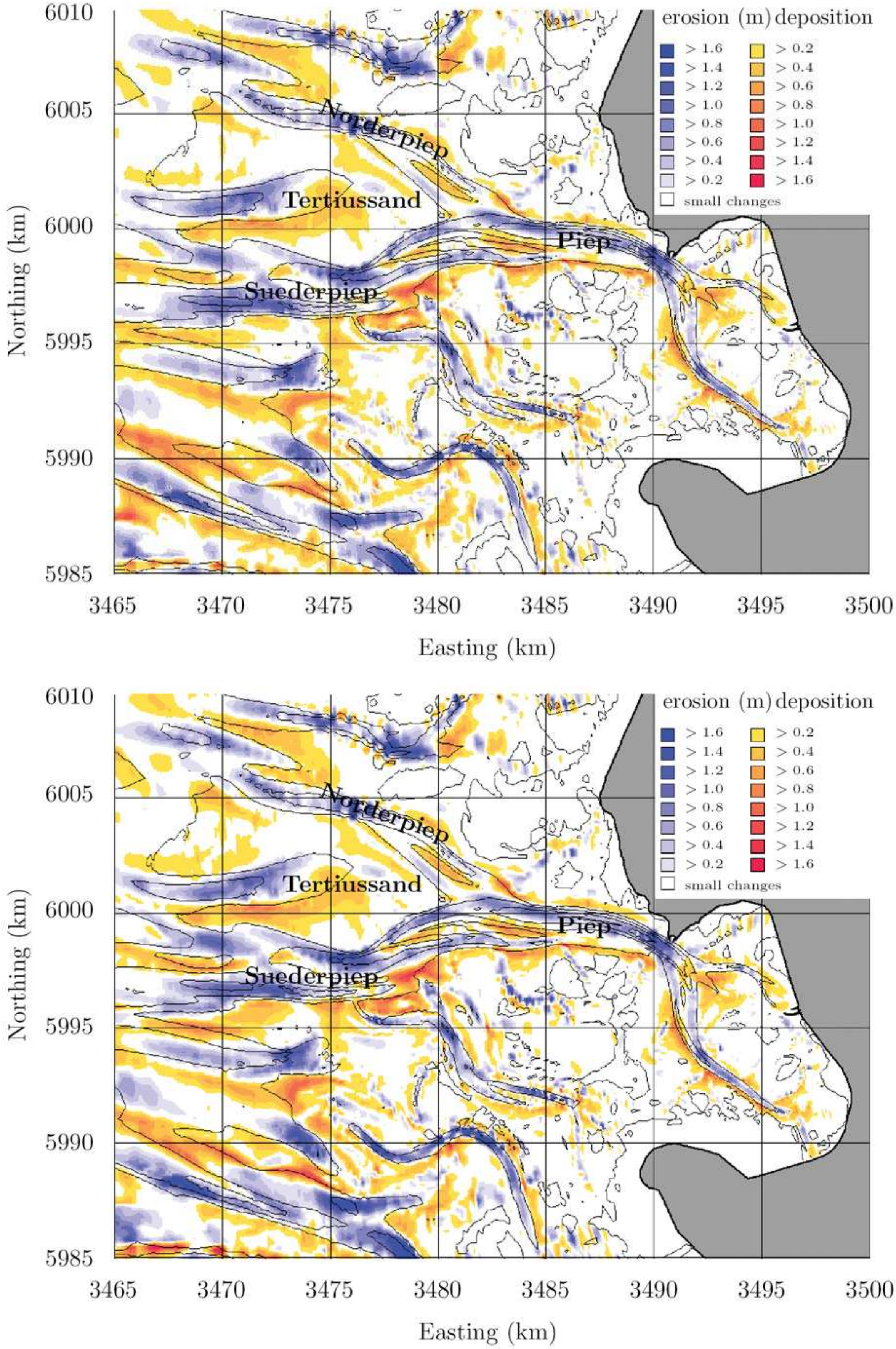


Fig. 7: Computed deposition and erosion over a one-year period using a representative tide (upper) and full spring-neap tidal cycle (lower). Simulations without wind and swell (WILKENS, 2004)

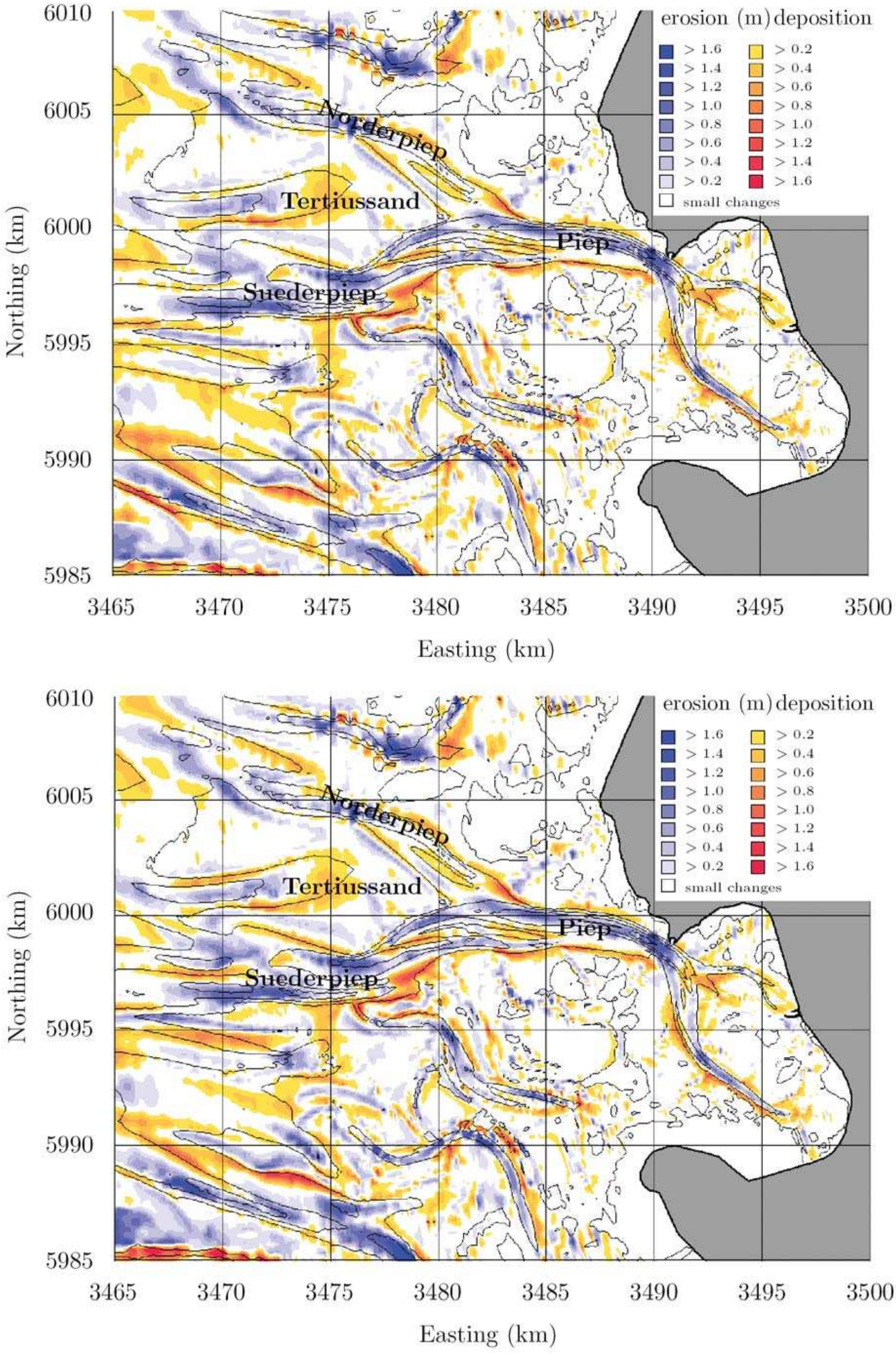


Fig. 8: Computed deposition and erosion over one year using a representative tide (upper) and a full spring-neap cycle (lower). Simulations include representative wind and swell climates (WILKENS, 2004)

### 4.2.2 Representative Swell Conditions

A limited number of representative swell conditions were determined. The swell data used in the analysis are based on long-term wave climate statistics derived from a study carried out in the coastal zone of the Island of Sylt (BMFT, 1994). Statistical values include the probability of occurrence of wave heights for wave height intervals of 0.25 m and directional sectors of 30 degrees, combined with related wave periods. Although these observations were made some distance from the Dithmarschen Bight and in an area somewhat more exposed to incoming swell from the North Sea, they provide a good measure of swell and its characteristics along the western boundary of the model and are shown in the form of a wave rose in Fig. 9.

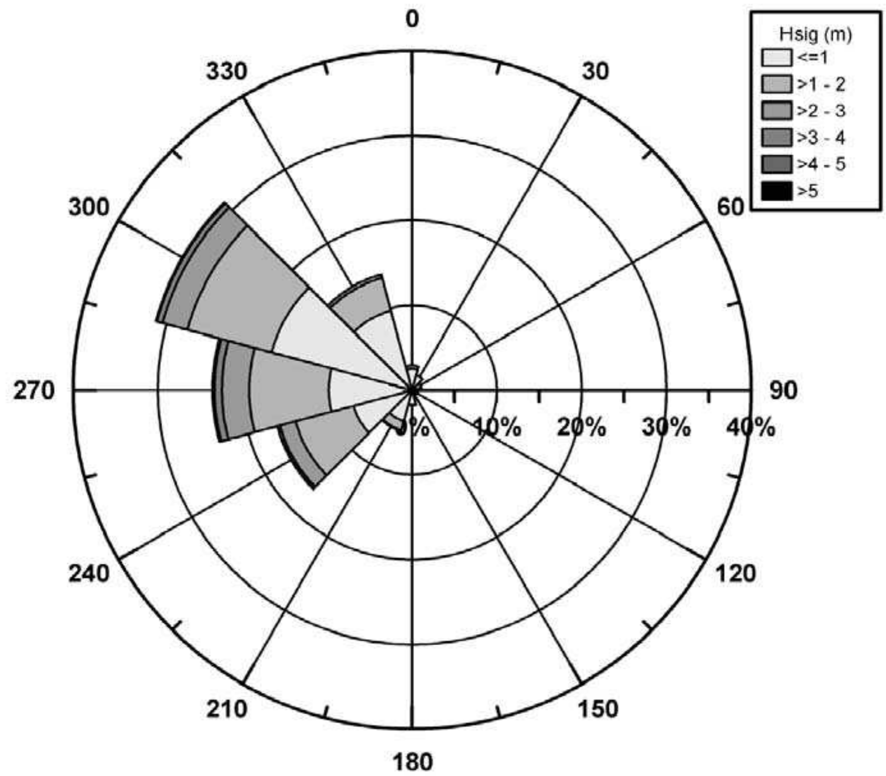


Fig. 9: Wave rose for the Island of Sylt, based on wave climate statistics as presented in BMFT (1994). The directions are in nautical convention; the percentages on the radial axis denote the probability of occurrence per wave height interval (WILKENS, 2004)

The present study follows the approach by STEIJN (1992), in which the effect of waves on the morphology is subdivided into the effects of wave-induced currents and stirring effects. Wave-induced currents are proportional to $H_s^{2.5}$, whereas the stirring effect is proportional to $H_s$. By applying these relationships the large number of swell conditions (combinations of wave height and direction) are subdivided into three categories, as shown in Table 2. The large reduction of the number of swell conditions is acceptable since the swell is limited to the small directional sector between 240 and 330 °N (see Fig. 9). It is acknowledged that swell from the southwest is probably less significant for the area under investigation than for the Island of Sylt. A sensitivity analysis showed that subdivision of the swell climate into as many as ten categories did not influence the computed morphodynamics to such an extent that justifies the additional computational effort otherwise required.

Table 2: Representative swell conditions

| Condition | $H_s$ (m) | $T_p$ (s) | Θ (°N) | Probability (%) |
|---|---|---|---|---|
| Low | 0.2 | 2.0 | 300 | 16 |
| Moderate | 1.0 | 4.0 | 300 | 73 |
| High | 2.0 | 7.0 | 270 | 11 |

The representative swell conditions defined in this way formed the starting point for the calibration. A qualitative calibration of these boundary conditions was found necessary in order to approximately simulate the correct morphological response of the outer tidal flats. This aspect is described in more detail in Section 5.

### 4.2.3 Representative Local Wind Conditions

Local wind conditions were defined so as to account for local wave generation. As will be shown in Section 6, local wind conditions have an effect on morphodynamic evolution in parts of the study area. A sensitivity analysis showed that wind-induced currents are not so important at the medium scale considered in the present investigation.

The definition of representative local wind conditions is based on a twelve-year data set derived from the synoptic PRISMA model (LUTHARDT, 1987). On the basis of observations along the coastline and at other locations such as oil platforms, this meteorological model computes wind velocities and air pressure fields for the North Sea by the application of interpolation techniques. A comparison of the PRISMA data with direct meteorological observations at the Research and Technology Centre Westcoast in Buesum showed good agreement between both data sets. The resulting wind rose is shown in Fig. 10.

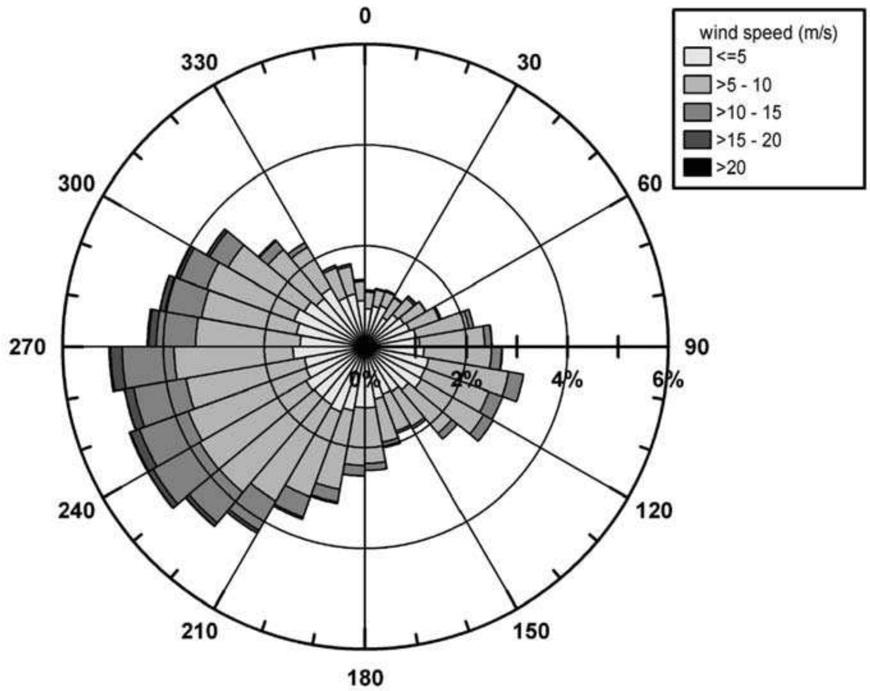


Fig. 10: Wind rose for the study area, based on data extracted from the synoptic PRISMA meteorological model (LUTHARDT, 1987). Nautical convention for the direction; the radial axis shows the probability of occurrence per wind speed interval (WILKENS, 2004)

A statistical reduction of the number of wind conditions (combinations of wind speed and direction) leads to the five representative wind conditions listed in Table 3. The directional sectors (of 30 degrees) with the highest probability per wind speed were defined as being representative for the respective wind speed interval (of 5 m/s). The related probabilities were set equal to the total probability for the considered wind speed interval. The consequence of this approach is that the less probable easterly directions are neglected. The main influence of local wind on morphodynamics is related to locally-generated waves. The method adopted is acceptable since easterly wind directions have a very limited fetch in the study area.

Table 3: Representative wind conditions

| Condition | $U_w$ (m/s) | $\Theta_w$ (°N) | Probability (%) |
|---|---|---|---|
| 1 | 2.5 | 180 | 27.7 |
| 2 | 7.5 | 240 | 49.8 |
| 3 | 12.5 | 255 | 19.3 |
| 4 | 17.5 | 270 | 3.0 |
| 5 | 22.5 | 300 | 0.3 |

#### 4.2.4 Sediment Transport and Morphological Conditions

At the open boundaries, conditions also have to be specified for the sediment transport and morphology. Long-term information about the bed load and suspended load sediment transport at locations near the open boundaries is not available, however. Thus, statistically representative conditions could not be determined. An alternative is available, however, in which simplified conditions are imposed. These simplified conditions are given either as a constant value or as a function of the local hydrodynamic quantities.

In this study, the simplified conditions have been imposed by defining the bed level at the open boundaries to remain at its initial value, together with conditions for the suspended load sediment transport. The latter are divided into an inflow-condition and an outflow-conditions. In the case of inflow, during the flood phase, the equilibrium concentration and subsequently the suspended load sediment transport are determined with the sediment transport formula considering the local flow conditions. For outflow, the up-stream concentration is applied to the open boundary, effectively setting the sediment concentration gradient to zero.

Due to the remote location of the open boundaries, the effect of these conditions is rather limited. This is true also for medium term simulations over periods of up to ten years, as a sensitivity analysis has shown. The somewhat unrealistic morphodynamic behaviour near the open boundaries does not affect the model results in the area of interest.

#### 4.2.5 Summary

The selected representative conditions for tide, swell and wind were combined to yield a representative annual climate. Mild and severe conditions were arbitrarily mixed in order to avoid a prolonged sequence of storm or mild conditions. With regard to driving the morphodynamic model, such a sequence could well result in irreversible morphological changes that would not otherwise occur under thoroughly mixed conditions (see for example SOUTHGATE, 1995).

The results are listed in Table 4. Due to the low probability of occurrence of a 22.5 m/s wind speed condition, this condition is only represented in combination with the medium swell condition. These conditions were imposed in the initial morphodynamic model prior to calibration. Although a number of severe wind and wave conditions are included, specific storm conditions are not represented. In order to simulate storm events realistically it is necessary to include highly deformed water level signals, intruding swell and high locally-generated waves. This requires high temporal resolution of the imposed conditions and computed morphological changes and hence, a rather different model set-up. WILKENS (2004) and WILKENS and MAYERLE (in this volume) describe such simulations for the central Dithmarschen Bight and compare computed morphological changes to average yearly morphological changes. From these studies it was concluded that the inclusion of one or two storms in a one-year morphodynamic simulation has a very limited effect on the resulting morphodynamics at the medium scale of the applied model. Storm conditions were thus considered to be represented by the imposed swell and wind climate.

Table 4: Combined representative climate for swell and wind

| Condition | $H_s$ (m) | Θ (°N) | $U_w$ (m/s) | $\Theta_w$ (°N) | Probability (%) |
|---|---|---|---|---|---|
| 1 | 0.2 | 300 | 2.5 | 180 | 4.43 |
| 2 | 0.2 | 300 | 7.5 | 240 | 7.97 |
| 3 | 0.2 | 300 | 12.5 | 255 | 3.09 |
| 4 | 0.2 | 300 | 17.5 | 270 | 0.48 |
| 5 | 1.0 | 300 | 2.5 | 180 | 20.22 |
| 6 | 1.0 | 300 | 7.5 | 240 | 36.35 |
| 7 | 1.0 | 300 | 12.5 | 255 | 14.09 |
| 8 | 1.0 | 300 | 17.5 | 270 | 2.19 |
| 9 | 1.0 | 300 | 22.5 | 300 | 0.22 |
| 10 | 2.0 | 270 | 2.5 | 180 | 3.05 |
| 11 | 2.0 | 270 | 7.5 | 240 | 5.48 |
| 12 | 2.0 | 270 | 12.5 | 255 | 2.12 |
| 13 | 2.0 | 270 | 17.5 | 270 | 0.33 |

### 4.3 TELEMAC Modelling Scheme

The modelling strategy adopted in the TELEMAC model essentially corresponds to the previously-described procedure implemented in the DELFT3D model (see Fig. 11). In the first step a hydrodynamic simulation is performed over a period of 24 hours. If waves are taken into consideration, water levels, currents and wind data over a time interval of 15 minutes are transferred to the instationary wave model TOMAWAC. The subsequent one-day sea-state simulation also generates wave parameters at 15 minute intervals for the investigation area. Thereafter, the hydrodynamic simulation may be repeated with the inclusion of wave-induced flow forces. The updated flow field then enters the morphology module together with the wave parameters. This module computes sediment transport rates over a period of 24 hours and solves the bottom evolution equation. By subsequently repeating the morphodynamic computation seven times, the bottom evolution is calculated for a period of one week. Similar to the procedure adopted in the DELFT3D model, the currents are modified by means of the continuity equation. Following each week of bottom evolution the flow field is updated by performing a new hydrodynamic computation. The simulated one-day flow field may be generated on the basis of a representative double tidal cycle or a sequence of several days, e.g. a neap-spring cycle.

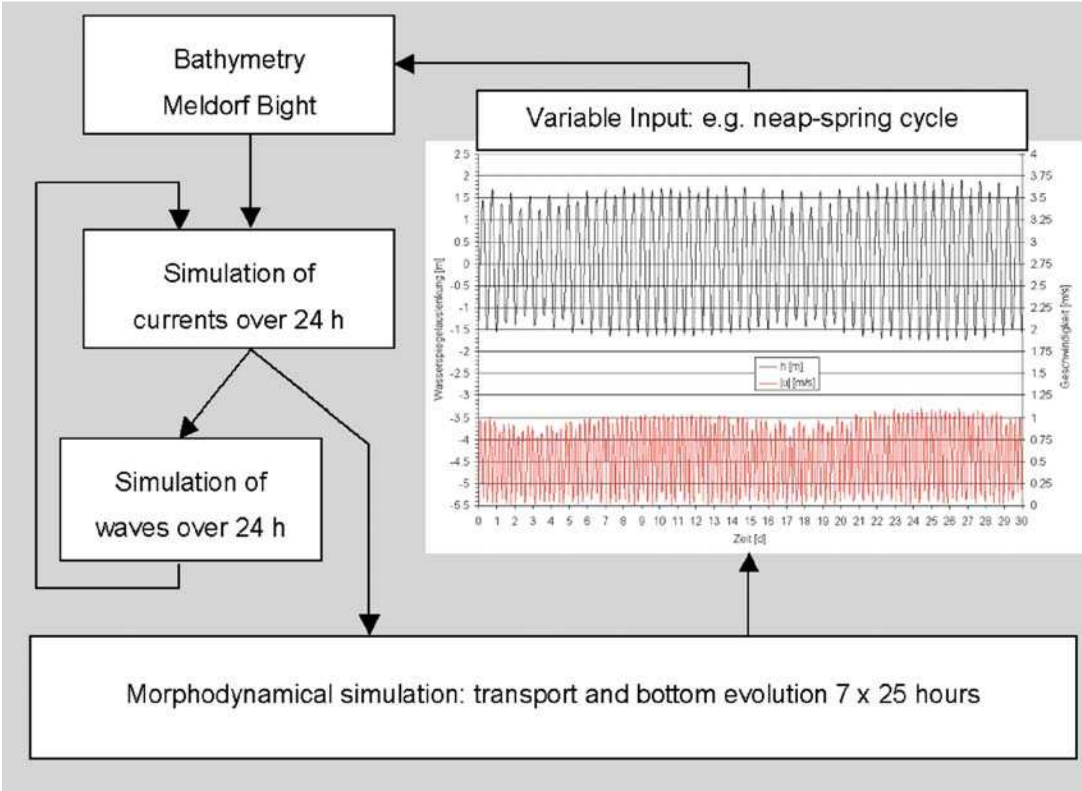


Fig. 11: Morphodynamic simulation scheme

### 4.4 TELEMAC Input Reduction

The application of the TELEMAC program system for long-term morphodynamic simulations requires the extraction and reduction of boundary conditions similar to the method described in the preceding section for the DELFT3D model. A reduction in computational effort is particularly important in the case of the TELEMAC model due to the fact that the hydrodynamic computations are performed for instationary wave characteristics using the finite element method.

#### 4.4.1 Representative Tidal Conditions

A sequence of different tidal inputs was tested to determine feasible boundary conditions for the hydrodynamic simulation. Considering the modelling scheme shown in Fig. 11, the flow dynamics of the month September 1990 and a neap-spring cycle were specified along the open boundary over a 30-day simulation period. The resulting deviations of the morphodynamic development are comparatively small (ZIELKE, 2001). In this context long-term simulations were also performed using a representative tide, which is described in detail in

ZIELKE (2001). This tide could be implemented in the simulation scheme after doubling to a 25 hour period. Comparatively long-term simulations showed that the use of only one representative tide is an acceptable approach. Fig. 12 presents the simulated bathymetric changes under the boundary conditions stipulated for September 1990 with varying wind as well as for a representative tide with constant wind. September 1990 was chosen as the simulation period because it includes a moderate storm event. The simulations were performed using the ENGELUND-HANSEN formula (1967) with an average grain size of 300 µm. A comparison of the results of the two simulations (see Fig. 12) shows that the patterns of morphological changes are almost identical, with a slightly higher intensity of bottom evolution for the case of a representative tide. These results indicate that both boundary inputs are suitable for long-term simulations. This is also confirmed by a further simulation using real boundary conditions for the period 1990 to 1995 without a sevenfold morphological time step (ZIELKE, 2003). In this case the boundary conditions were determined for each day from PRISMA data (LUTHARDT, 1987). The results of the so-called 1 to 1 simulation are found to only differ slightly from the results presented in Fig. 12. It may thus be concluded that the modelling strategies adopted in the present investigation do not significantly impair the quality of results.

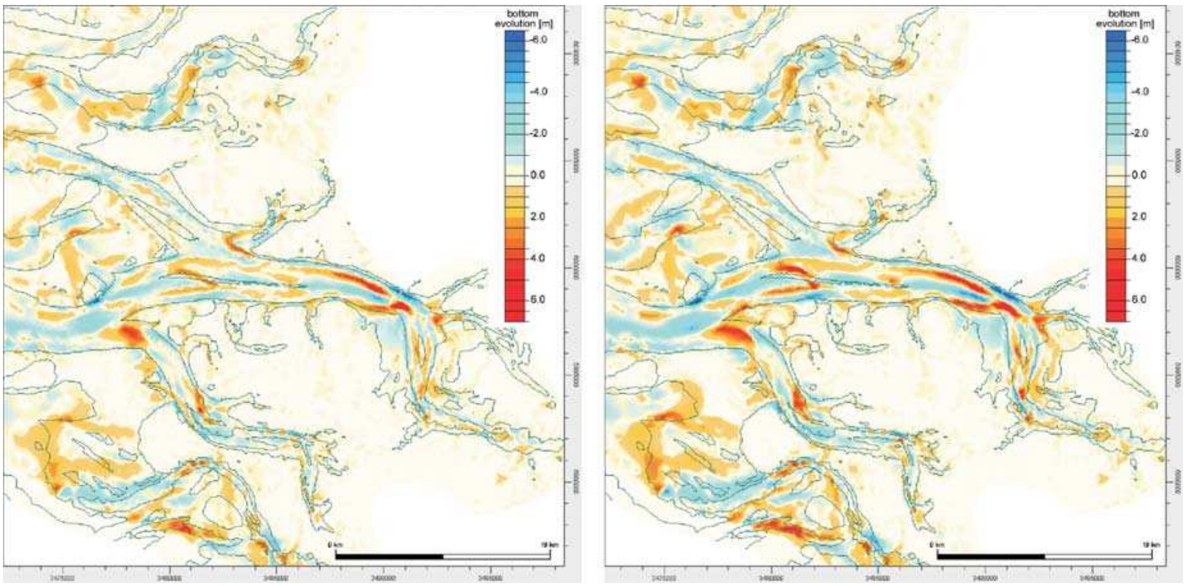


Fig. 12: Five-year simulation under prototype (monthly) conditions with varying wind (left) and for a representative tide with constant wind (right); red: accretion, blue: erosion

### 4.4.2 Representative Local Wind and Sea State Conditions

Compared to the specification of hydrodynamic boundary conditions, far more effort is generally required for specifying a variable sea state on the model boundary due to the additional statistical analysis of the input data, particularly if the amount of available data is insufficient. It is thus helpful if the wave model is able to deduce wave information from wind data without an explicit presetting of wave parameters along the open boundary. The instationary wave model TOMAWAC (WILKENS et al., in this volume), which belongs to the TELEMAC program system (BENOIT et al., 1996), generates wave parameters along the open model boundary under consideration of wind data, an imposed wind fetch and the predefinition of a JONSWAP wave spectrum.

Table 5: Wind statistics for the Dithmarschen Bight study area

| $U_w$ (m/s) | $\Theta_w$ (°N) | Probability (%) | Probability within 14 tides [tide] |
|---|---|---|---|
| 2.5 | 180 | 27.7 | 4 |
| 7.5 | 240 | 49.8 | 7 |
| 12.5 | 255 | 19.3 | 3 (13.3 m/s, 257.5°N) |
| 17.5 | 270 | 3.0 | |
| 22.5 | 300 | 0.3 | |

Table 5 shows the statistically analysed wind situation for the Dithmarschen Bight study area (WILKENS, 2004). If the probability of occurrence is distributed over a period of 14 tides, the wind conditions may be expressed over a cycle of one week with only two one-day wind sequences (see Fig. 13). The first wind field of weak to moderate intensity is combined with a fetch of 20 km and a duration of four days. During the remaining three days the stronger wind field is combined with a fetch of 50 km. In order to ensure harmonic transitions when changes in the wind field occur, the transitions are undertaken during slack water when the wave influence is low in the investigation area. For the same reason the two wind fields start and end with a moderate wind phase.

For the hydrodynamic calculation a constant wind with an intensity of 8.75 m/s from the southwest direction was imposed. This presetting is the result of a detailed statistical

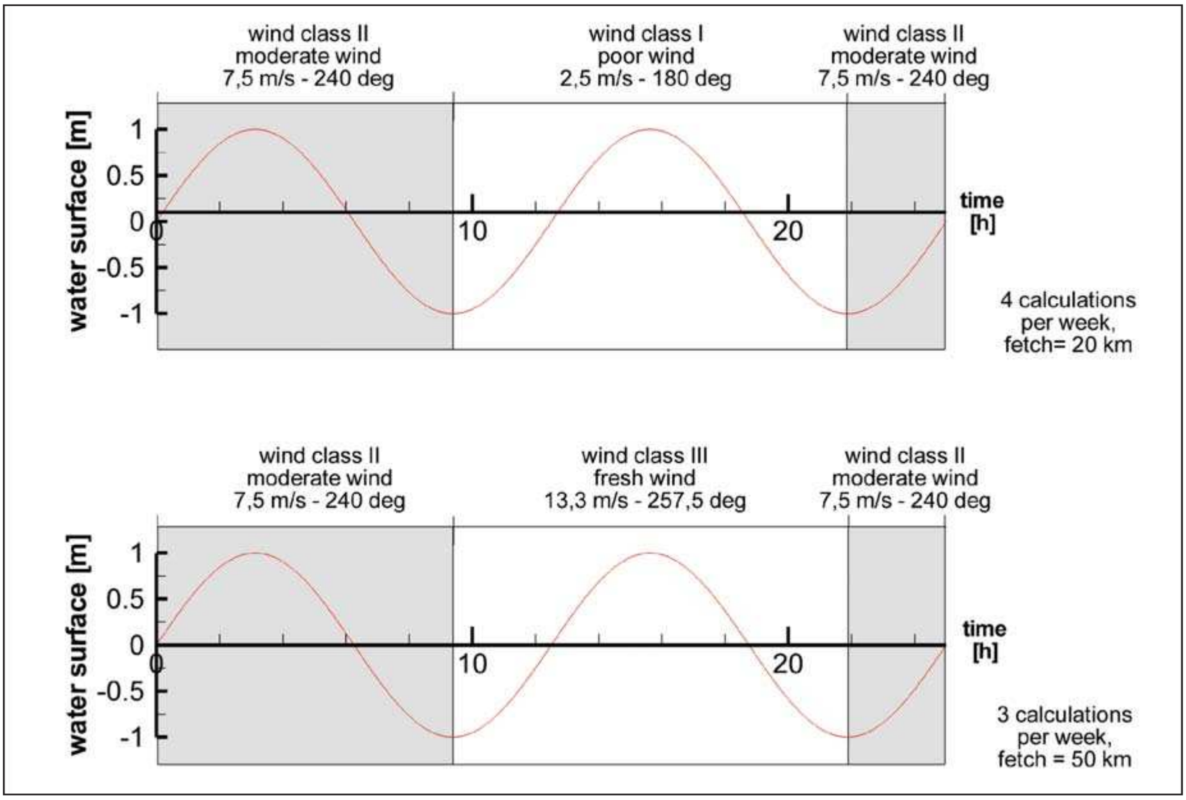


Fig. 13: Representative wind fields for wave modelling

analysis (ZIELKE, 2003) and serves as a representative average value for the investigation area. Comparative calculations with a selected measured wind sequence over 30 days showed no significant improvement in the results.

## 5. Calibration and Validation of the Morphodynamic Models

The morphodynamic model was calibrated and validated for medium scale periods of about ten years. The evaluation was based on bathymetric measurements from surveys carried out by the BSH. Due to the varying extent of coverage of these surveys, full coverage of the main channels Norderpiep, Suederpiep, Piep and the tidal flat Tertiussand (see Fig. 1) was available every three years. Calibration and validation of the DELFT3D model were carried out for the periods 1977 to 1987 and 1990 to 1999, respectively. Only the period 1990 to 1999 was considered for calibrating the two versions of the TELEMAC model.

In conjunction with a qualitative comparison between computed and observed deposition and erosion patterns and depth contours a quantitative evaluation was made using the two versions of the TELEMAC model under consideration of the volumetric changes in several sub-domains (see Fig. 14). Due to the limited availability and questionable quality of bathymetric data in areas above mean sea level (MSL; German Normal Null – NN), only

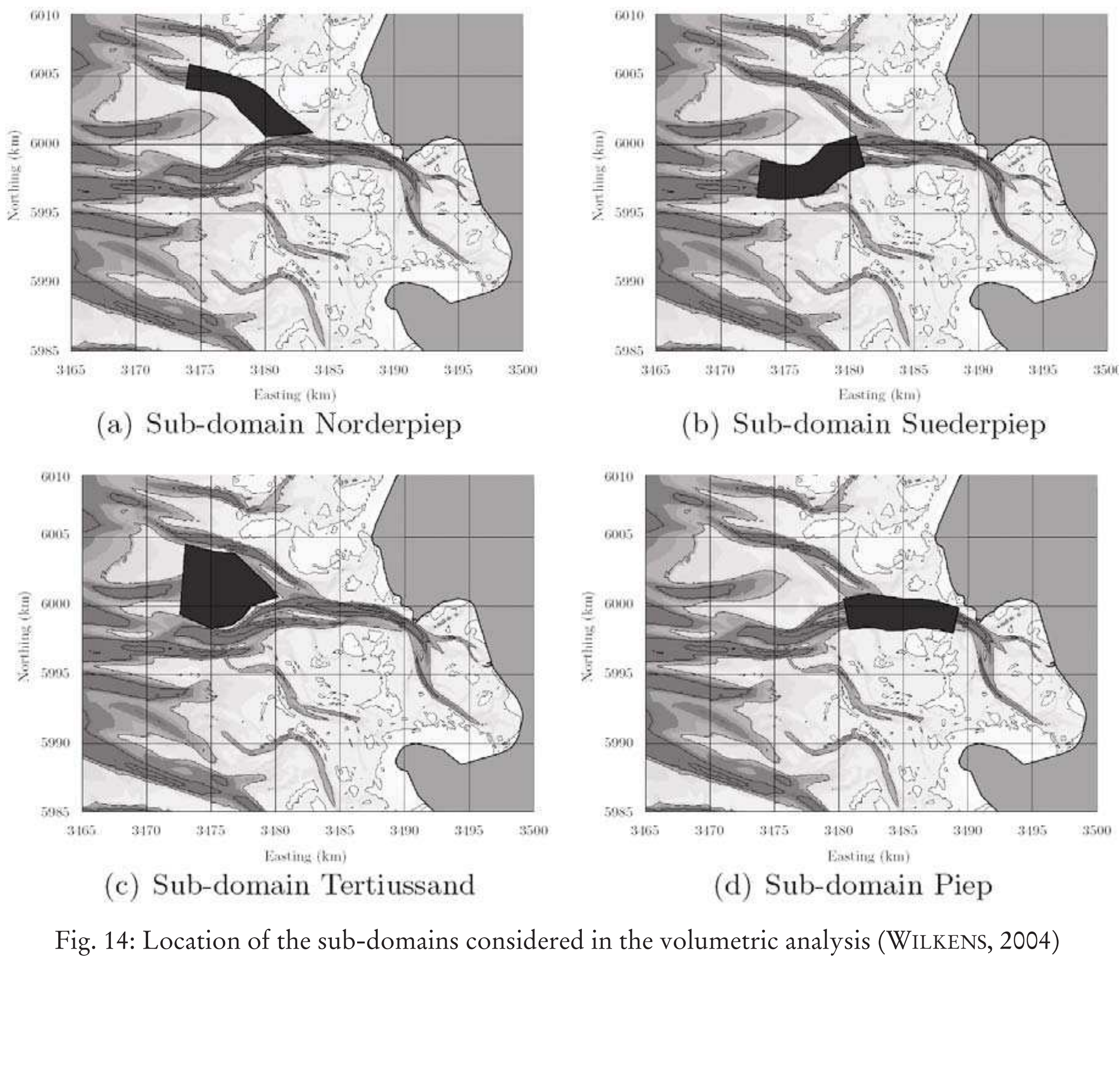


Fig. 14: Location of the sub-domains considered in the volumetric analysis (WILKENS, 2004)

wet volumes below this level were considered. Furthermore, the available data for the eastern Meldorf Bight did not permit an acceptable volumetric analysis. The volumes considered in the analysis are related to the volumes for the year 1977 as follows:

$$V_{rel,i} = \frac{V_i}{V_{1977}} * 100\%$$

with:

| | |
|---|---|
| $\boldsymbol{V_{rel,i}}$ | relative wet volume below MSL of a sub-domain in year $\boldsymbol{i}$ |
| $\boldsymbol{V_{1977}}$ | wet volume below MSL of a sub-domain in 1977 |
| $\boldsymbol{V_i}$ | wet volume below MSL of a sub-domain in year $\boldsymbol{i}$ |

### 5.1 Calibration and Validation of the DELFT3D Model

Calibration of the DELFT3D model was carried out in two stages. An in-depth description may be found in WILKENS (2004). The first stage concerns an *external calibration*, in which the imposed conditions were optimised starting from the defined representative conditions (see Section 4). In this calibration the imposed wind and swell climates were adapted to realise an overall correct response of the computed morphological changes. This mainly affected the westerly tidal flats and channels, whose morphological behaviour is highly dependent on the imposed swell climate. A reduction of 50 % of the imposed wave heights yielded the best results. Improvements could also be achieved by a reduction of the local wind climate. In this case also, a reduction of 50 % proved to optimal.

The reductions of the imposed wind and swell conditions are quite large. It is noted that the computed morphological changes depend on the one hand on the imposed conditions and on the other hand on the sediment transports induced by these conditions. The magnitude of these sediment transports depends on the applied formula; in this study being the formula by BIJKER (1971) as described in Section 3. The use of another formula or different parameter settings in the current one could lead to different magnitudes of reduction of the imposed conditions. The 50 %-reduction is thus the result of a balance between the imposed conditions and the applied formula.

Furthermore, it is noted that the considered wave data stem from measurements off the coast of Sylt. This location protrudes further into the North Sea and it is therefore likely that the amount of wave energy is higher here than along the open boundaries of the Dithmarschen Bight Model. The necessity of reducing the statistically determined wave climate on the basis of these data thus appears logical, to the purpose of approaching the actual conditions along the model boundaries in a better way.

The second stage is an *internal calibration*. In this case the time management set-up and several parameters in the sediment transport model were adapted to improve the results. In the time management set-up the number of wave calculations per tidal cycle and different types of interaction between the modules was evaluated. In this respect the set-up described in Subsection 4.1 was found to be optimal. Since the sediment transport model has already been calibrated and validated (see WINTER et al., in this volume) further changes to the model were not deemed to be necessary. Since the evaluation of the sediment transport model was based on calm weather situations without significant wave action, however, further calibration was found to be necessary. The calibration parameter that yielded the largest improvements is related to the balance and intensity of sediment transport due either to tidal currents or to wave action. This parameter is referred to as the constant b in BIJKER's transport formula (BIJKER, 1971).

In the validated sediment transport model chosen, this parameter is defined uniformly with a constant value of 3. As a result of further calibration a varying value ranging from 1 to 5 proved to be optimal. A value of 1 is applied for deep-water wave conditions whereas for shallow-water wave conditions a value of 5 is adopted; interpolation between these values is carried out for intermediate conditions. The influence of waves on the total sediment transport is thus enhanced relative to the influence of tidal currents.

The results of the volumetric analysis for a simulation using the calibrated model over the period 1977 to 1987 are shown in Figs. 15 to 18 for the four investigated sub-domains. This includes the period 1990 to 1999. As may be seen in the figures, the observed values are not perfectly consistent in time. This may be due to shorter-term fluctuations as well as to inaccuracies in the bathymetric measurements (including interpolation errors). It is also evident that the observed medium-term trends are reproduced fairly well by the model during both the calibration and the validation period. Although some differences are noticeable, the quality of the model results is sufficient to justify the application of the model as a useful tool for predicting morphodynamic evolution as well as for analysing the underlying physical processes.

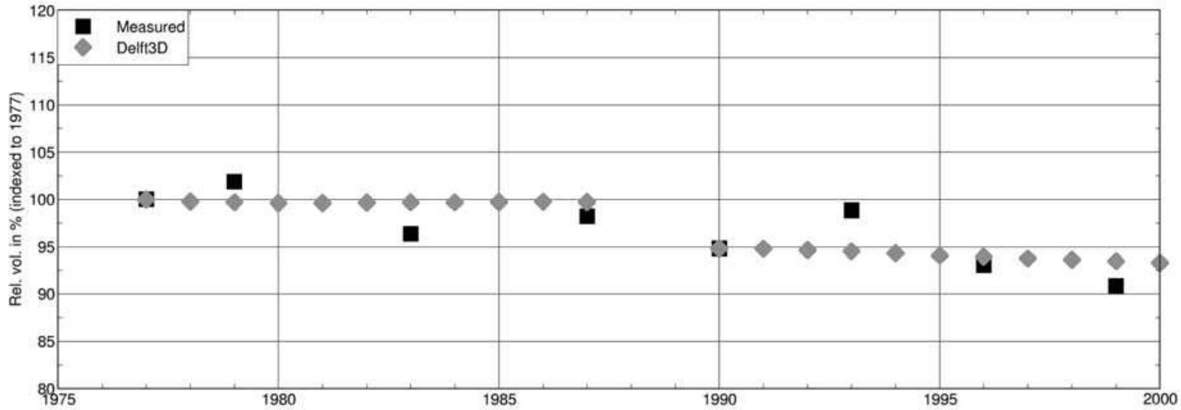


Fig. 15: Relative wet volume changes below MSL for sub-domain Norderpiep

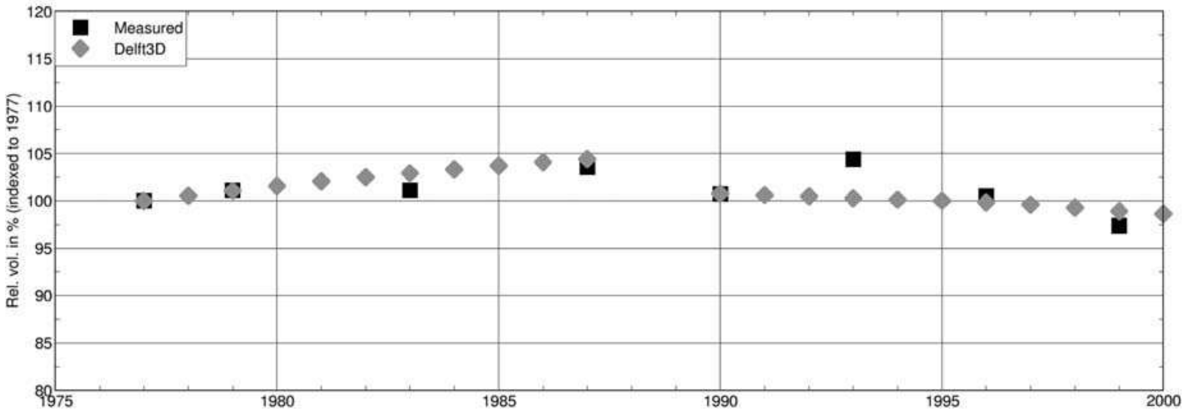


Fig. 16: Relative wet volume changes below MSL for sub-domain Suederpiep

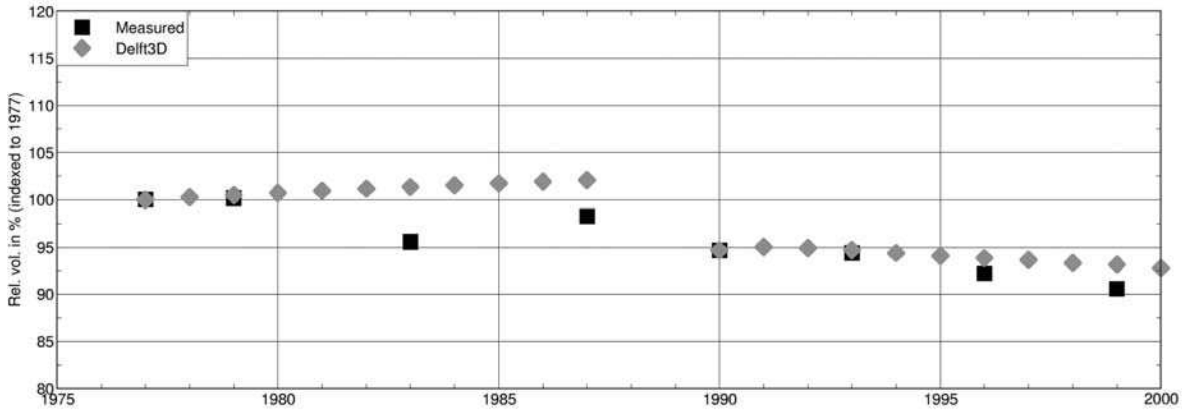


Fig. 17: Relative wet volume changes below MSL for sub-domain Piep

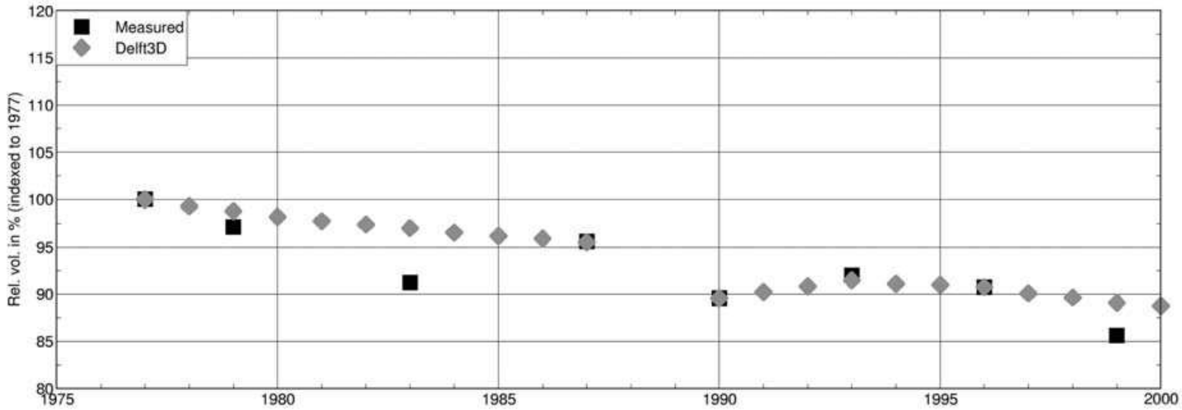


Fig. 18: Relative wet volume changes below MSL for sub-domain Tertiussand

## 5.2 Calibration and Validation of the TELEMAC Model

Although the calibration and validation process for the TELEMAC model is similar to the strategy for the DELFT3D model, the simulated periods are shorter. The simulations mainly relate to the period from 1990 to 2000, for which extensive field measurements are available.

A reliable method of verifying the results of morphodynamic models is to examine the extent to which the changed sediment volume in specific areas agrees with measurements. Especially in tidal flat areas, this procedure provides a good indication of the quality of the simulated results. As shown in Fig. 19 (left), three tidal flat areas in the Dithmarschen Bight were specified for a volumetric analysis according to the method already outlined in the preceding subsection. The yearly bathymetric measurements provided by the BSH were interpolated onto the model grid and the "wet" volume, i.e. the volume of water below MSL, was calculated. A comparison between measured and simulated wet volumes, expressed as a percentage of the reference value in 1977, is shown in Fig. 21. The trends indicate that the wet volume decreases in Polygon P1, whereas in P3, it increases. This result implies overall erosion in P3 and an overall accretion of sediment in P1. The same trends are followed by the simulated results. In Polygon 2 the simulation yields a slight erosion trend which cannot be clearly confirmed by measurements. The yearly measurements should be treated with caution, however, as they do not cover the complete study area in all cases.

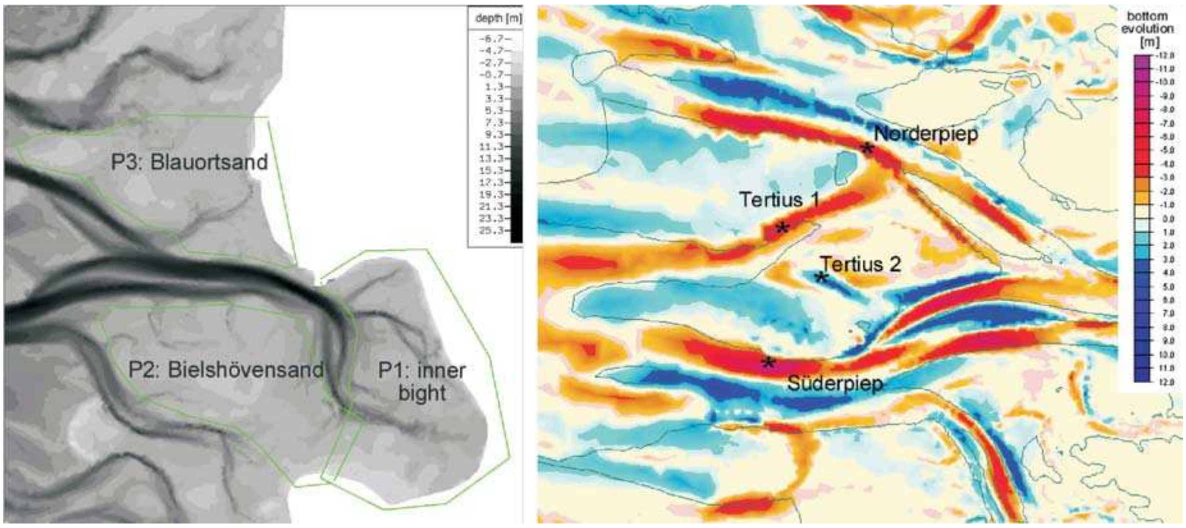


Fig. 19: Location of the polygons for a mass balance on the tidal flats (left); bathymetric changes based on measurements (1990 to 2000) in the vicinity of Tertiussand, indicating positions of observation points (right)

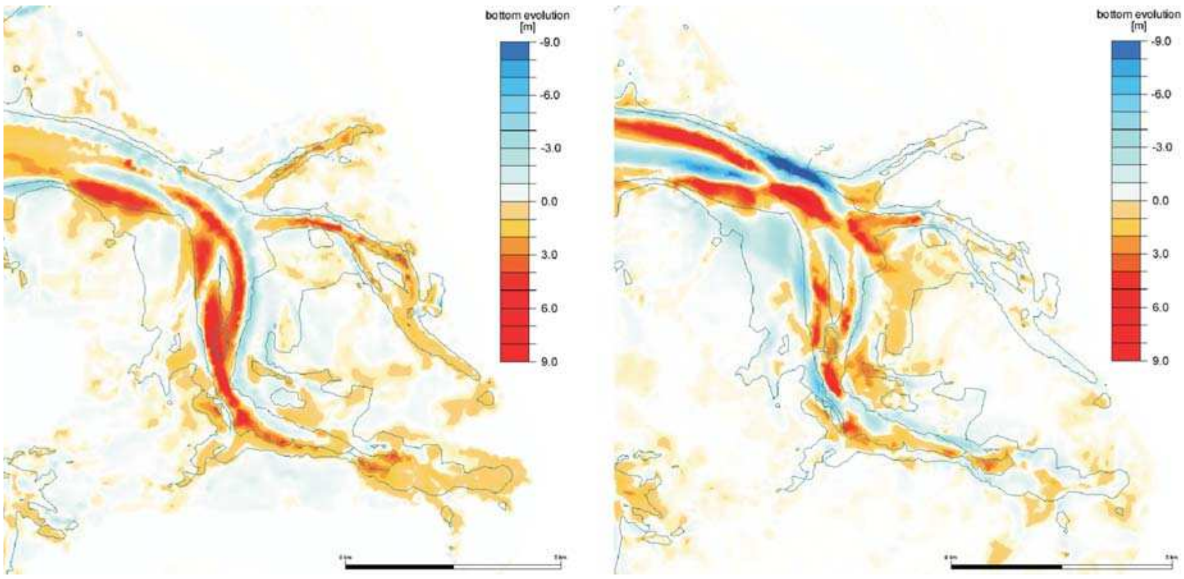


Fig. 20: Measured (left) and simulated bottom evolution (1990-1999) in the Meldorf bight: red = deposition, blue = erosion

The measured and computed bathymetric changes within the Piep and the Meldorf bight area are shown in Fig. 20. Many morphologic developments are well reproduced by the model, even though some changes are somewhat exaggerated. The significant erosion and sedimentations patterns near Buesum, the long narrow erosion band along the northern and eastern banks of the Piep channel and the strong accretion of the sand bank in the Piep southerly of Buesum are reproduced rather well. The computed erosion trend on the Biels-hoevensand cannot be clearly confirmed by measurements. Possibly additional influx of sediment due to wave action over the Bielshoevensand causes this effect as was suggested by HIRSCHHAEUSER (2004).

The results presented in Figs. 20 and 21 were computed using the transport formula of ENGELUND and HANSEN (1967) with a representative tide at the seaward boundary. This means that the influence of waves is not taken into account. Although this is acceptable in the region of the Meldorf Bight and the eastern Piep channel (see WILKENS, 2004), wave influence cannot be neglected in the outer regions, i.e. Tertiussand, Norderpiep and Suederpiep. Against this background a further simulation was performed under consideration of sea state using the transport formula of BIJKER (1971). The wave parameters were generated by the instationary wave model TOMAWAC (WILKENS et al., in this volume) under consideration of representative wind conditions likewise introduced in Subsection 4.4.2. In order to investigate the influence of waves a morphodynamic simulation was performed for a 10-year period using both transport formulae. The measured bottom evolution for the region bordering Tertiussand is plotted on the right in Fig. 19. Fig. 22 shows the morphological evolution at four observation points placed at the centres of regions in which significant bottom changes occur. It may be seen in the Figure that the results obtained using the transport formula of BIJKER (1971) (under consideration of waves) are in close agreement with the observed trends. The computation using the formula of ENGELUND and HANSEN (1967), which yields good results in the middle and eastern part of the study area, is unable to correctly reproduce the trends over the exposed tidal flats in the west. This impression is confirmed by the results of a volumetric analysis, as shown in Fig. 23. The polygons used are the same as those already introduced in Fig. 14. The morphological trends calculated according to ENGELUND and HANSEN (1967) agree well with measurements in the Piep and Tertiussand polygon. The results of the BIJKER (1971) simulation fit the trends more appropriately, even though the calculated changes seem to be somewhat excessive. The predicted erosion trend for the Tertiussand is caused by strong sediment movement to the border regions which are not completely covered by the analysed sub-domain.

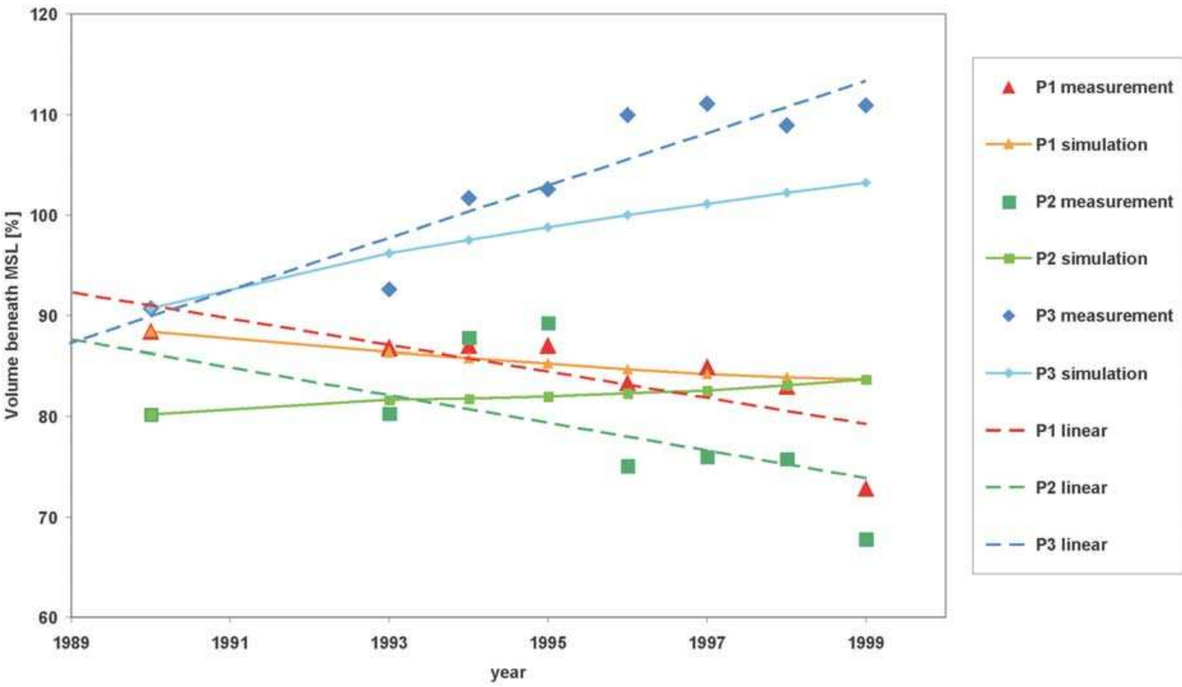


Fig. 21: Comparison of measured and computed (numerical simulation) water volumes below MSL

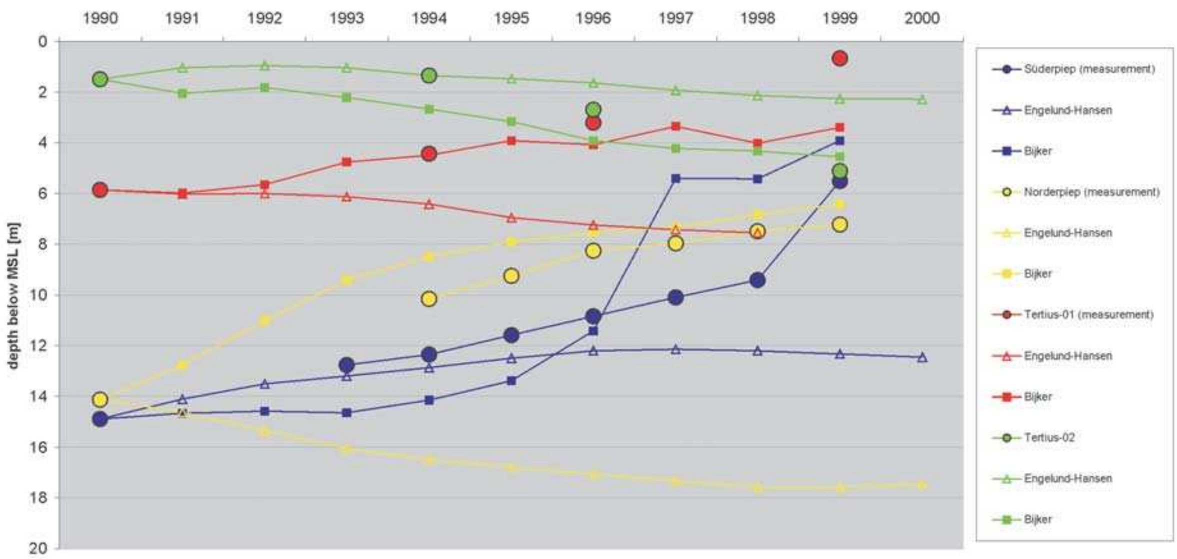


Fig. 22: Bottom evolution at different observation points in the region of Tertiussand (1990–2000)

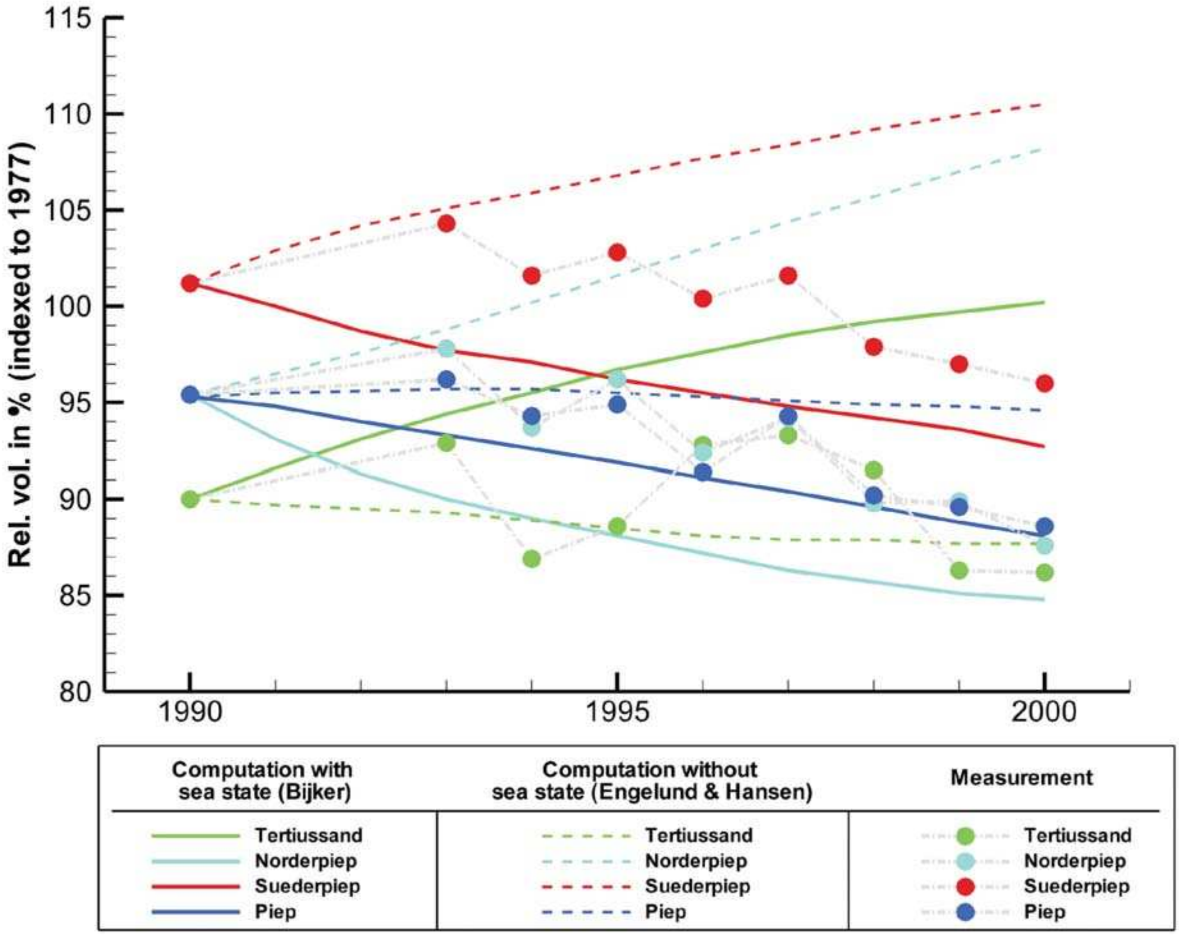


Fig. 23: Relative wet volume changes below MSL for different sub-domains

# 6. Model Predictions over a Ten-Year Period

The calibrated and validated models were applied to predict morphological evolution in the study area during the period 1999 to 2009. The results of the DELFT3D model prediction for the tidal channel system of the central Dithmarschen Bight, covering the afore-mentioned sub-domains, are presented in the following. Furthermore, the results of the TELEMAC model are presented for the easterly Meldorf Bight.

## 6.1 Model Prediction for the Central Dithmarschen Bight with the DELFT3D Model

Applying the optimised settings for the imposed boundary conditions and model parameters, as defined in the calibration phase of the model, a simulation was performed to estimate the morphological evolution of the tidal channel system. The initial bathymetry for this simulation is shown in Fig. 24 while the final bathymetry predicted for 2009 is shown in Fig. 25. The morphological changes are shown in Fig. 26.

As may be seen in the figures, a number of significant changes are predicted, especially in the region of Tertiussand. The small channel branching from the Suederpiep is seen to gradually break through the tidal flat, thereby forming a connection to the open sea. The cut-off part of Tertiussand to the south is seen to migrate further southward towards the Suederpiep. Due to the fact that the southern channel bank is retained by the presence of the D-Steert shoal, this migration results in a narrowing of the Suederpiep. A progression towards the northeast is discernable on the north-eastern side of Tertiussand, as also confirmed by measurements over the past twenty years (WILKENS, 2004). The south-western sub-channel of the Norderpiep is seen to gradually fill with sediment, creating a connection between the tidal flat and the submerged bar in this channel. On the southeastern side the Suederpiep channel is seen to erode the edge of Tertiussand. This process is enhanced by the presence of the newly-created channel through the tidal flat. Further deepening of the Piep is also predicted towards the east. The submerged bar in this channel shows signs of erosion, which is contrary to the observed and computed accretion between 1977 and 1999. This change of behaviour may also be related to the initiation of the channel over Tertiussand due to a re-orientation of the main current patterns.

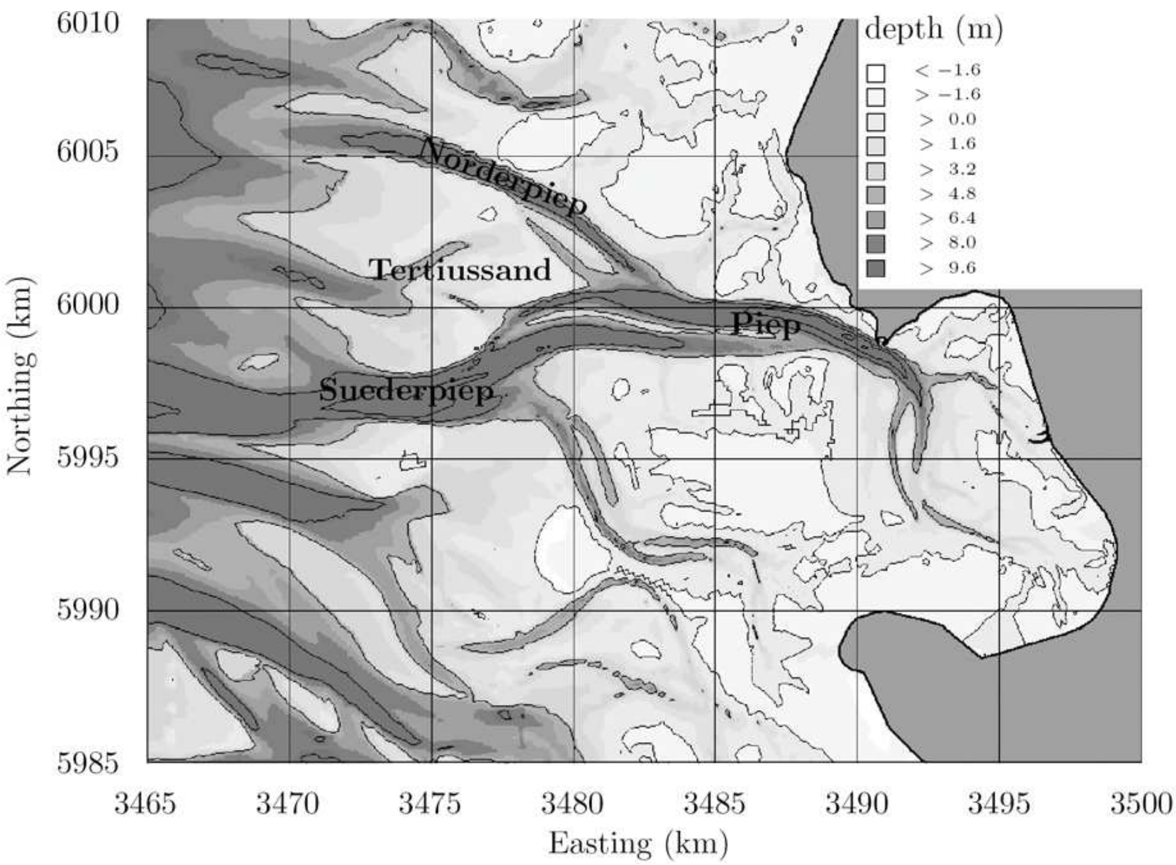


Fig. 24: Initial bathymetry (1999) for the DELFT3D model simulation (WILKENS, 2004)

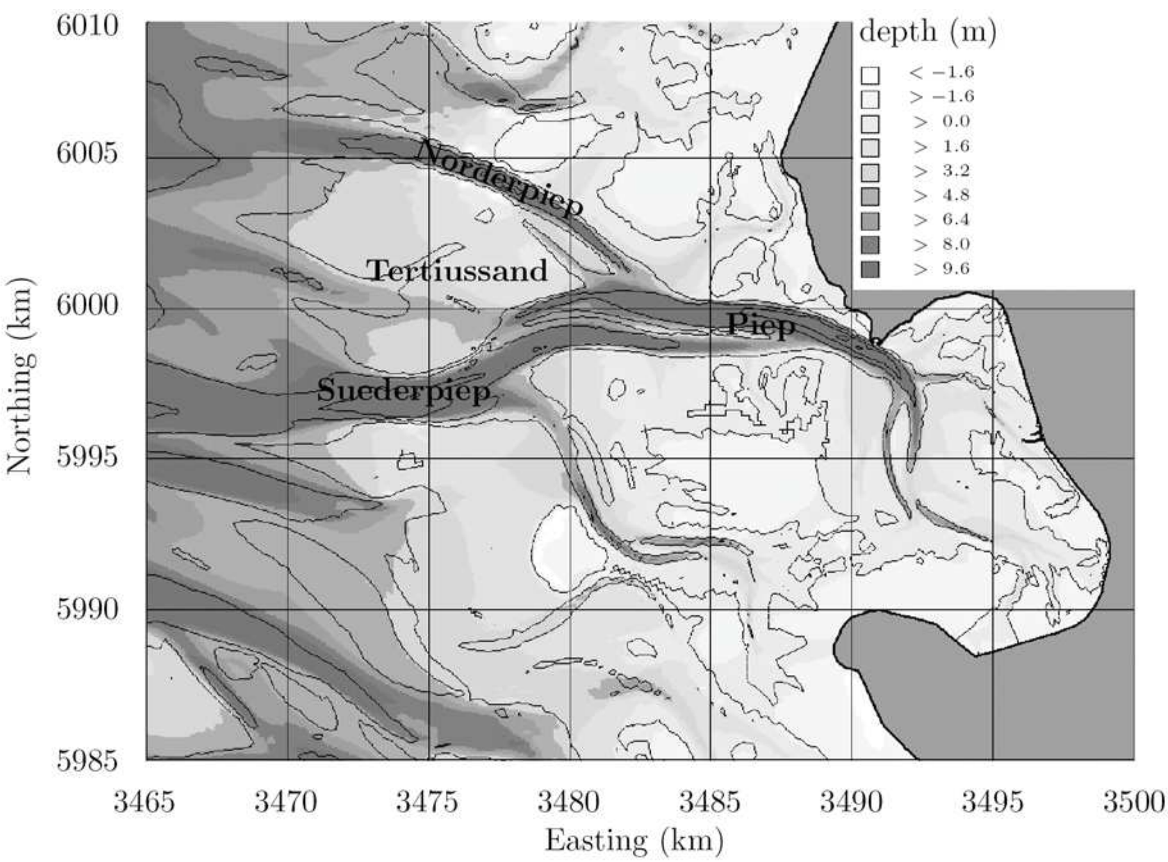


Fig. 25: Bathymetry predicted by the DELFT3D model for 2009. Iso-lines from 1999 (WILKENS, 2004)

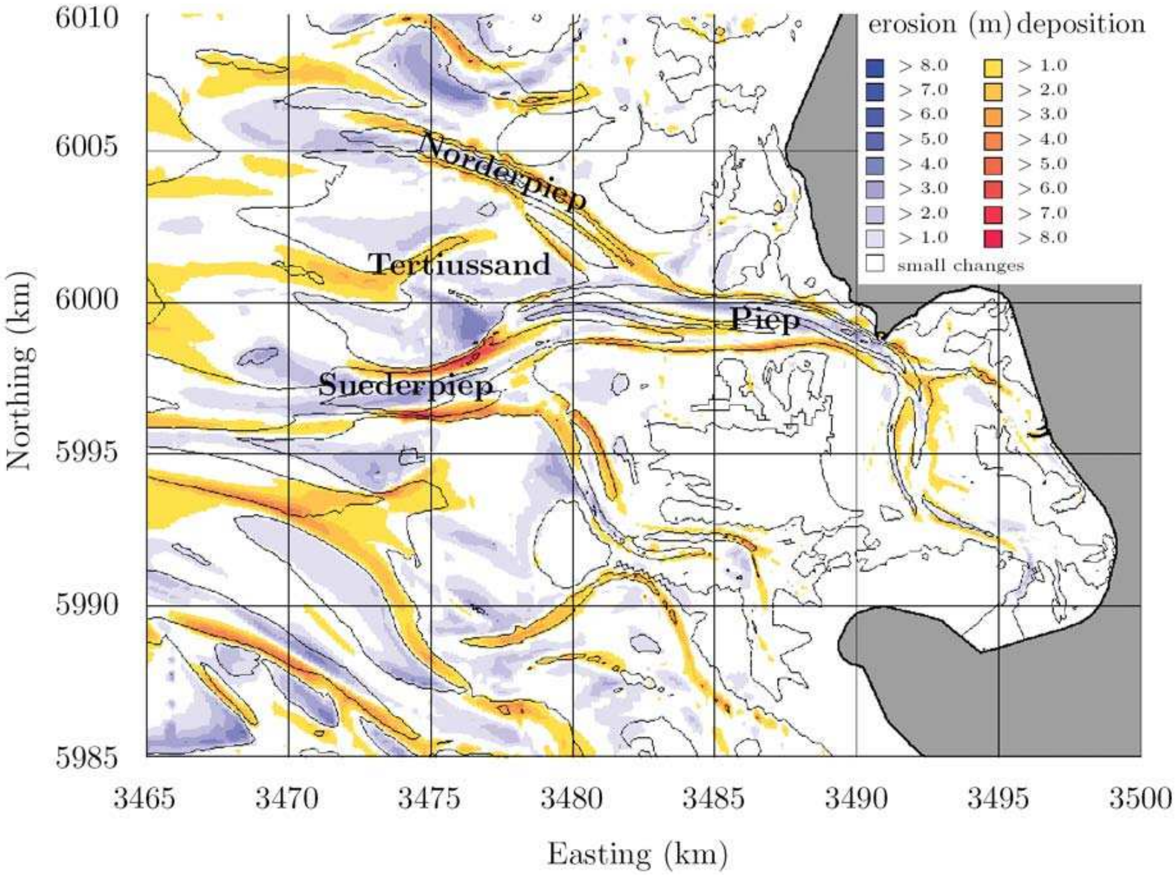


Fig. 26: Morphological changes predicted by the DELFT3D model from 1999–2009 (WILKENS, 2004)

## 6.2 Model Prediction for the Meldorf Bight with the TELEMAC Model

A simulation over a period of ten years was performed for the Meldorf Bight in order to test whether the model is capable of simulating morphodynamic evolution over a longer period in this study area. The various bathymetries relating to this simulation are shown in Fig. 27. The images in the top part of the Figure represent the measured bathymetries of 1990 and 1999. The bathymetry of 1999 is also used as the initial bathymetry for the 10-year simulation. The boundary conditions for the simulation are based on observations for the month September 1990, as shown in Fig. 11. Sediment transport was calculated using the transport formula of ENGELUND and HANSEN (1967) with a grain size of 300 µm.

It was found that many tendencies in the observed morphological behaviour are also predicted by the simulation, e.g. shifting of the Ossengoot channel (location 1) to the southeast and deepening and shifting of the interstitial channel at location 2. The deepening of the Suederpiep (location 3) and the narrowing of the Marner Plate (location 4) as well as the shifting of the Piep in the vicinity of Buesum (location 5) to the northeast proceed rapidly. It will be interesting to verify whether the deepening and creation of a new interstitial channel at location 5 will in fact occur during the coming years. This trend seems to be indicated in the 1990 to 1999 measurements. Another area of massive sediment movement is around the sandbank in the Piep channel south of Buesum. The sandbank is seen to grow rapidly

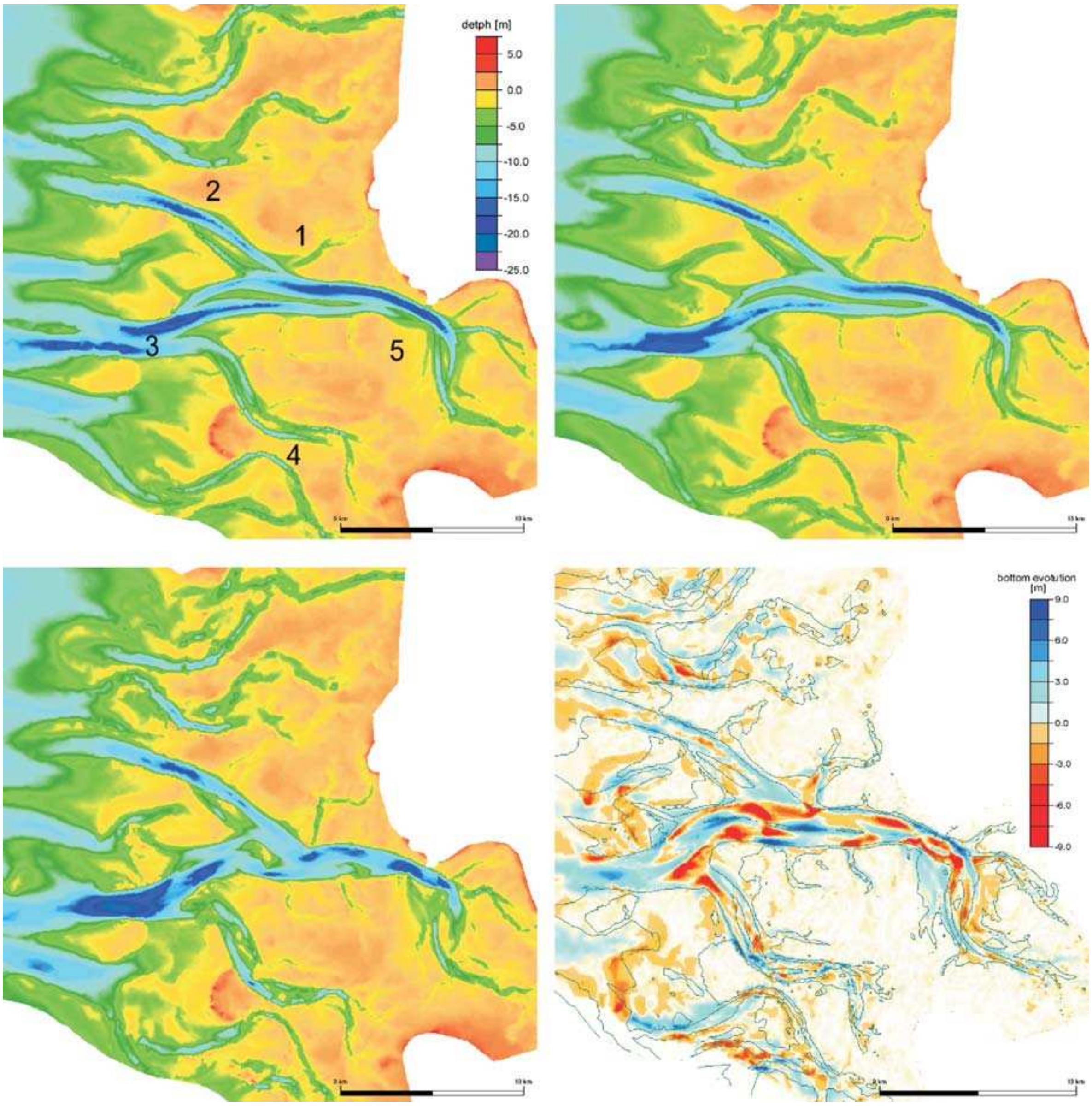


Fig. 27: Results of a 10-year morphological simulation: bathymetry surveyed in 1990 (top left), initial bathymetry of 1999 for the model simulation (top right), predicted bathymetry after 10 years (bottom left) and bed evolution: red = deposition, blue = erosion (bottom right)

in the southern direction, dividing the Piep channel into two tidal creeks. This trend is also observed in the simulation results. Due to the creation of a new interstitial channel at location 5 the southern Meldorf Bight now mainly drains via the western channel, which is different to the observed situation in 1999. The simulated bottom changes between 1999 and 2009 are presented in the lower right part of Fig. 27. Especially for the region of the Meldorf Bight, the bathymetric development is found to agree well with the morphological behaviour observed between 1990 and 1999 (see HIRSCHHAEUSER, 2004). In summing up, it may be stated that the model yields plausible results in most areas for a 10-year simulation period.

## 7. Conclusions

The combination of thoroughly calibrated and validated individual models for the simulation of tides, waves and sediment transport forms a sound basis for the construction of morphodynamic models for simulating bathymetric changes. Since a new model is formed when these individual models are combined, recalibration and revalidation of the combined model system are necessary. By implementing input and process filtering techniques it was possible to extend the applicability of the models to morphodynamic modelling on the medium scale. The resulting calibrated and validated models proved to be suitable for making morphodynamic predictions. The use of an objective, quantitative approach for model evaluation based on a volumetric analysis places higher confidence in the models than would be expected from the single application of a subjective evaluation of sedimentation and erosion patterns. Based on the promising evaluation results obtained during the model calibration and validation phases the models were subsequently applied to predict morphological changes in the study region over the period 1999 to 2009. Although some significant changes are predicted, these are not deemed to be unrealistic, considering the solid basis underlying the validated process models. Using both modelling systems it was possible to perform realistic simulations of morphodynamic evolution.

## 8. Acknowledgements

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