# Longshore Sediment Transport Modeling in 1 and 2 Dimensions

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## Abstract

*The knowledge of local littoral processes is of utmost importance for any coastal zone management with regard to coastal protection and maintenance of navigation channels. Observations of wave conditions and nearshore current patterns have long been used to determine the sediment transport in the littoral zone.*

*Several methods of quantifying the longshore transport rate at a particular location are applied such as a well known CERC formula and numerical models for longshore modeling along 1D coastal profiles and 2D area morphodynamic modeling. Since the results of all methods critically depend on the wave input data, careful compilation of site specific wave characteristics is essential in morphodynamic studies.*

*We discuss longshore transport phenomena for a time span of 5 years in Gellen bay which is located at the German coast of the southern Baltic Sea. Special attention is paid to the preparation of boundary conditions for the different study methods and to the complementary information gained from the individual analysis tools.*

## 1 Introduction

The German coastal regions of the southern Baltic Sea can be characterized as micro-tidal regimes where shorelines are formed by wind-generated waves and currents. Littoral drift accumulates material into large sand flats which are above sea level and dry most of the time but which can be flooded up to 1.5m during extreme events. Sand transported southward along the barrier islands of Hiddensee and eastward along the Zingst coast forms the sand flat "Bock" located in the inner part of the Gellen bay (Figure 1). It extends over approximately 10x3km$^2$ in the vicinity of the northern access channel to the port of Stralsund. In particular at Gellen inlet, the natural channel system is morhodynamically very active and continuous dredging is required in order to maintain this waterway at a target depth of 4.5 meter below MSL.

Early concepts of the physical flow and transport phenomena in this coastal region have been reported in the literature [9] based on long term observations. Numerical studies of coastal processes started with a research project KLIBO [4] aiming at the

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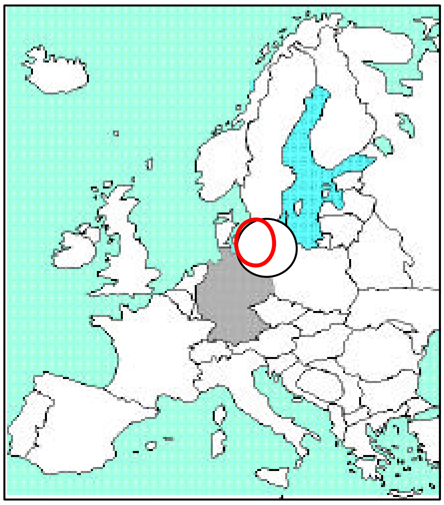


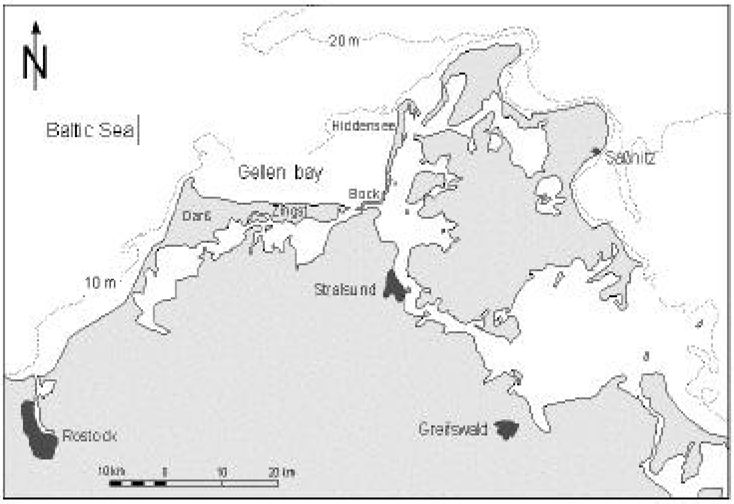



Figure 1: MorWin project domain. Coastal area at Baltic Sea in Germany

impact of climatic change and continues with the MorWin [7] project presented here with focus on morphodynamic evolution. Morphodynamic modeling techniques are deployed in order to study the causality of physical processes which are incited by meteorological conditions; the resulting flow and wave fields subsequently induce sediment transport.

## 2 Modeling Concepts

The analysis of data collected in the littoral zone has resulted in a variety of empirical formulae relating the driving forces of winds, waves, currents, tides and sediment properties to the motion of sediment. For a great number of design tasks, the coastal engineering community relies on methods recommended e.g. in the Shore Protection Manual [11]. However, these procedures only provide answers limited to specific sites.

With the help of numerical process models, nonlinear interactions of the acting forces can be modeled for entire coastal regions. 1D longshore transport models constitute state-of-the-art tools for estimating littoral transport for alongshore uniform situations. In general, these models are very sensitive to specified wave directions and to a somewhat lesser extent to sediment parameters and bottom friction. Input data at the location of coastal profiles is best obtained from regional hydrodynamic circulation and wave models. Due to premises and limitations focal points of interest such as coastal inlets cannot be handled by this model type.

More complex domains require 2D area morphodynamic modeling with continuous update of the model bathymetry due to sediment accretion or erosion. Various modeling concepts have been published in the literature [1] with applications to schematic test cases [2] and a tidal river [12]. Usually, a sequence of process models is applied in order to determine the evolution of bathymetry. A wind driven wave model produces radiation stresses as additional forcing for a flow model which provides the velocities for a sediment transport model where source and sink terms are parameterized according to the dynamical state of the system. Results depend critically on the consistency of boundary conditions for all processes involved. In particular, the wave boundary conditions and the parameterizations chosen for wave-current interaction, wave breaking and sediment mobility determine the details of the computed littoral transport.

## 2.1 0D Modeling

Based on energy flux considerations outlined in [11], the sediment transport rate Q is given in units [$m^3$/yr] as a function of wave parameters at the breaker line.

$$Q = 1290 \frac{1}{2} \cdot c_{gB} \cdot \rho \cdot g \frac{H_B^2}{8} \cdot \sin(2\alpha_B) \quad (1)$$

with parameters $C_{gB}$ = group velocity, $H_B$ = wave height reduced by shoaling and refraction, $\alpha_B$ = angle between wave crest and shoreline, and a dimensional constant.

Given the water depth, mean water level, wave length, wave period, wave height and direction for any period of time, the sediment transport rates can be computed and summed up to give the cumulative transport.

## 2.2 1D Modeling

The local wave height H is calculated from the deep water wave height $H_0$

$$H = K_s \cdot K_r \cdot H_0 \quad (2)$$

with coefficients for shoaling $K_s$ and refraction $K_r$ which are given for straight, parallel beach contours according to

$$K_s = \sqrt{\frac{C_{g_0}}{C_g}} \quad \text{and} \quad K_r = \sqrt{\frac{\cos\alpha_0}{\cos\alpha}} \quad (3)$$

where $C_g$ is the group velocity and $\alpha$ is determined from Snell's law

$$\sin\alpha = \frac{c}{c_0} \sin\alpha_0 \quad (4)$$

Using the concept of radiation stresses $S_{xy}$ [5], the wave induced current is determined and the sediment transport is calculated [8] with the energetics approach.

The COSMOS-2D longshore model of HR Wallingford [10] was used to compute cross shore distributions of sediment transport rates along coastal profiles. The model accounts for wave transformations of refraction, shoaling and energy dissipation due to bottom friction and wave breaking.

The necessary boundary conditions are specified at the off shore end of the coastal profiles. They are essentially identical to those required by 0D modeling.

## 2.3 2D Modeling

The 2D area morphodynamic modeling is carried out with a simulation tool which solves the partial differential equations for waves, flow and sediment transport all in one system [6]. Waves are represented by the following 4 equations

$$\frac{\partial K_i}{\partial t} = -\frac{\partial \sigma_a}{\partial x_i} + C_g \frac{K_j}{k}\left(\frac{\partial K_j}{\partial x_i} - \frac{\partial K_i}{\partial x_j}\right) \tag{5}$$

$$k^2 = K^2 - \delta^+ \tag{6}$$

$$\sigma_a = \sqrt{gk \frac{\tanh(kd) + s}{1 + s \cdot \tanh(kd)}} + \vec{K}\vec{U} \tag{7}$$

$$\frac{\partial a}{\partial t} = -\frac{1}{2a}\frac{\partial}{\partial x_i}\left(U_i + C_{E_i}\right)a^2 - \frac{S_{ij}}{\rho g a}\frac{\partial U_i}{\partial x_i} + \frac{U_i\left(T_i - T_i^B\right)}{\rho g a} + \frac{\epsilon_B}{\rho g a} \tag{8}$$

which account for K = wave number vector, k = wave number, $\sigma$ = radian frequency, a = wave amplitude and $C_g$ = group velocity, $C_E$ = wave energy transport velocity, $\varepsilon_B$ = breaking coefficient, $S_{ij}$ = radiation stress, T = turbulent effects, $T^B$ = bottom friction.

The flow field with U = vertically integrated velocities, $\eta$ = free surface and d = water depth at rest, g = acceleration of gravity, $\rho$ = water density

$$\frac{\partial \eta}{\partial t} = -\frac{\partial U_j d}{\partial x_j} \tag{9}$$

$$\frac{\partial U_i}{\partial t} = -U_j \frac{\partial U_i}{\partial x_i} - g\frac{\partial \eta}{\partial x_i} - \frac{1}{\rho d}\frac{\partial S_{ij}}{\partial x_i} + \frac{1}{\rho d}\left(T_i - T_i^B\right) \tag{10}$$

The sediment transport with C = suspended sediment concentration, S = source and sink term, q = total load, $q_b$ = bed load, h = water depth at rest

$$\frac{\partial C}{\partial t} = -U_i \frac{\partial C}{\partial x_i} + \frac{\partial}{\partial x_i}\left(\tau_i \frac{\partial C}{\partial x_i}\right) + S \tag{11}$$

$$q_i = \int_{-h}^{\eta} U_i C\, dz + q_{b_i} \tag{12}$$

$$\frac{\partial h}{\partial t} = -\frac{\partial q_i}{\partial x_i} \tag{13}$$

## 3 Model application

The model concepts are used to study morphodynamic changes along the shores of Gellen bay. Data on wave conditions in the study domain have been collected at the 4 locations indicated in Figure 2. However, only the wave rider buoy at Darss sill (position I) which is operated by the GKSS research institute in Geesthacht/Germany provides a data set from 1993 through 1997 at time intervals of 3 hours which can be used for the intended long term study of longshore transport.

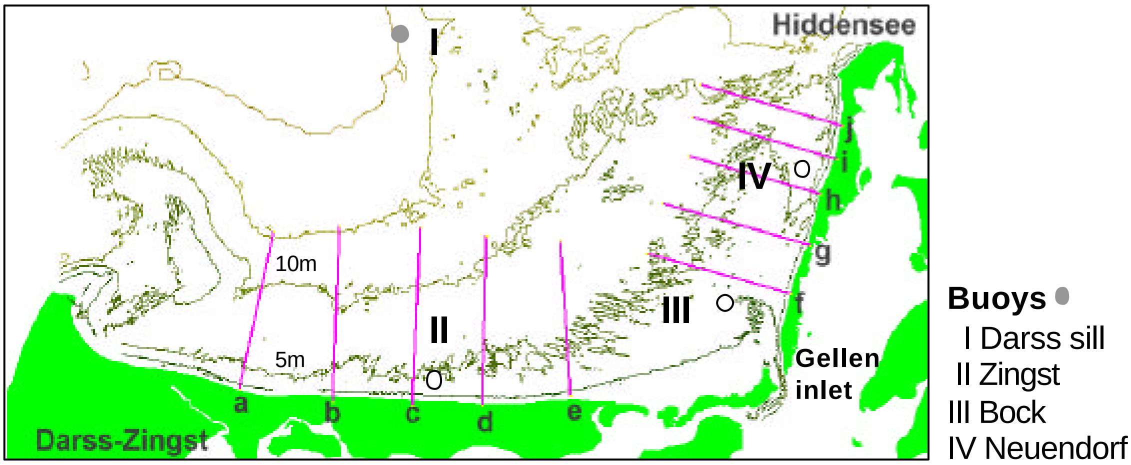


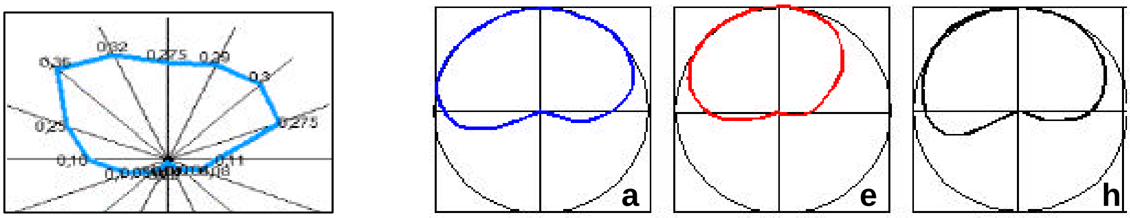

Figure 2: Profiles for long shore modeling at Darss-Zingst peninsula and Hiddensee island

The bathymetry data base compiled in the MorWin project [7] was used for the instantiation of different model types. The FEM computational grid for the 2D area modeling with minimal resolution in the surf zone in the order of 10m and the coastal profiles shown in Figure 2 used for 1D longshore modeling are extracted from this source.

### 3.1 Boundary Conditions

The coastal region of Gellen bay has long open boundaries to the Baltic Sea where hydrodynamic and wave boundary conditions must be specified. These are obtained from a global circulation model of the Baltic Sea [3]. Water levels and current parameters at the open boundaries and the wind field over the entire domain are provided at 6 hours intervals by the operational model of the Federal Maritime Agency (BSH) in Hamburg.

The grid resolution of the available large scale wave model, however, is too coarse for creating boundary conditions for small scale models in the coastal region. Wave parameters at the off shore end of the profiles used in the longshore model are computed by transfer functions as shown in Figure 3. The ratio of the measured wave heights at the off shore location of Darss sill and the near shore location of Zingst in the left panel of Figure 3 clearly shows wave attenuation which strongly depends on




a) Ratio of measured wave heights at Darss sill and Zingst

b)Transfer functions at offshore ends of selected beach profiles (a, e, h) along Darss-Zingst peninsula and Hiddensee island

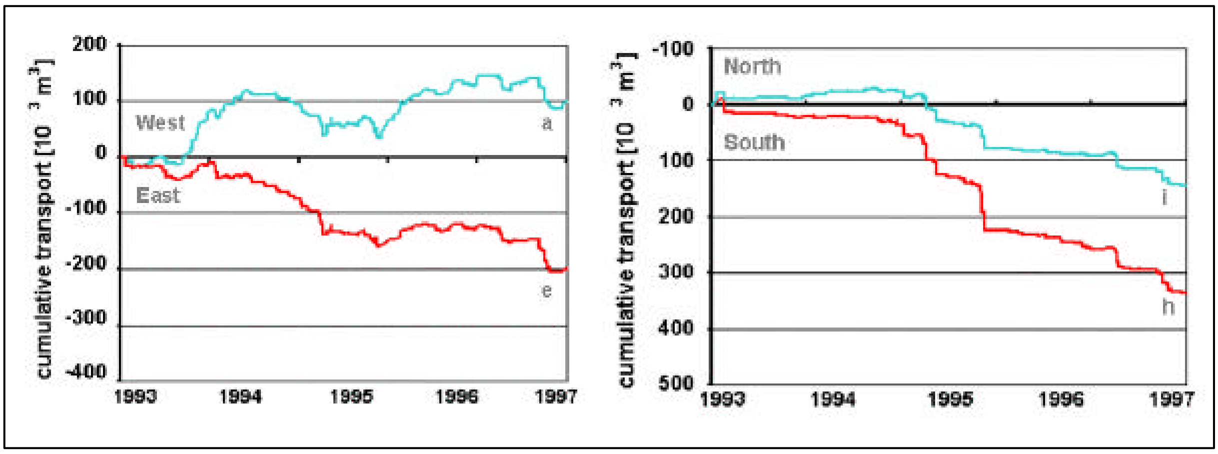
Figure 3: Transfer functions for wave boundary conditions

directions. Wave data from Darss sill are transformed to the required locations by using transfer functions shown in the right panel of Figure 3. These are determined from a wave atlas modeling exercise with stationary wave boundary conditions $H_s$ = 2.5m, $T_p$ = 4.5s and eight directions using the 2D area wave model [6] cited earlier. The modeled ratios shown are smoothed results based on the input data at Darss sill and model results at the denoted locations.

Waves from the SW sector cannot reach the inner part of Gellen bay directly. Diffraction at the spit of the far west end of Darss-Zingst peninsula and refraction along the coastline let them propagate from westerly directions. The coast of Darss-Zingst and the southern part of Hiddensee island are sheltered from SW waves. Similarly, waves from the NE sector cannot enter the bay but arrive from northerly directions with wave heights very much reduced along the coastlines. N, W and NW waves enter the domain directly and undisturbed, the latter being refracted towards the Darss-Zingst coastline. According to these distributions, significant wave heights of 2m are to be expected at the Gellen inlet and on the adjacent sand bank Bock.

## 3.2 Model results

By application of the 0D model, the cumulative transport at several locations is computed for the 5 year period of 1993 through 1997. Along Darss-Zingst peninsula,




a) Darss-Zingst peninsula

b) Hiddensee island

Figure 4: Cumulative sediment transport 1993 – 1997 (0D modeling)

the sediment balance at profile a is directed towards the west. Near the Gellen inlet at profile e there is continuous eastward transport amounting to $200x10^3 m^3$ for 1993 to 1997. The cumulative transport at profiles of Hiddensee island is mainly directed southward and amounts to $>300x10^3 m^3$ at location h for this period. Extreme storm events can be detected from the plots as large changes within few time steps.

This integral information is further illustrated by using results of the 1D longshore model. The cross shore distributions of longshore sediment transport rates for the years 1993 through 1997 shown in Figure 5 are distinctively different for each simulation year. The hydrodynamic state of this region with negligible tides strongly depends on the meteorological conditions which vary from year to year. At times, there is a small tendency of northward transport at locations of the northern profile i. Further south at profile h, the transport appears to be directed southward under all conditions.

During 1995, there are several extreme events in spring and fall which have a significant impact on the sediment transport rates of this year. At profile h, the impact of storm high waters exceeds all other results by a factor of 3 which must be taken into account when working with average values in long term studies. Cumulative transports computed with the 1D approach are practically indistinguishable from those calculated with the 0D approach.

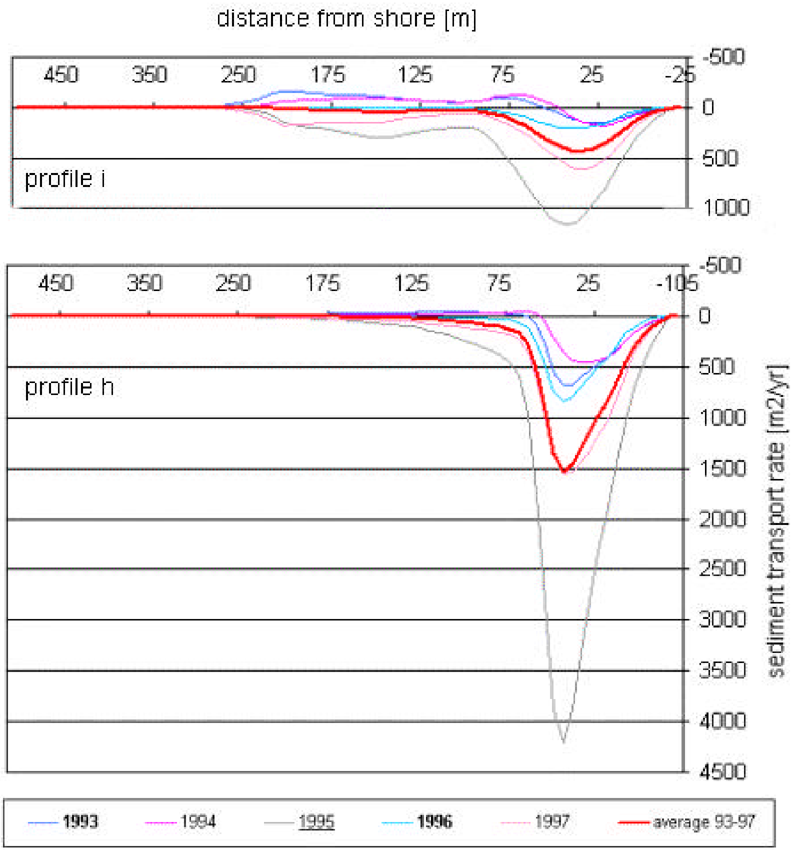
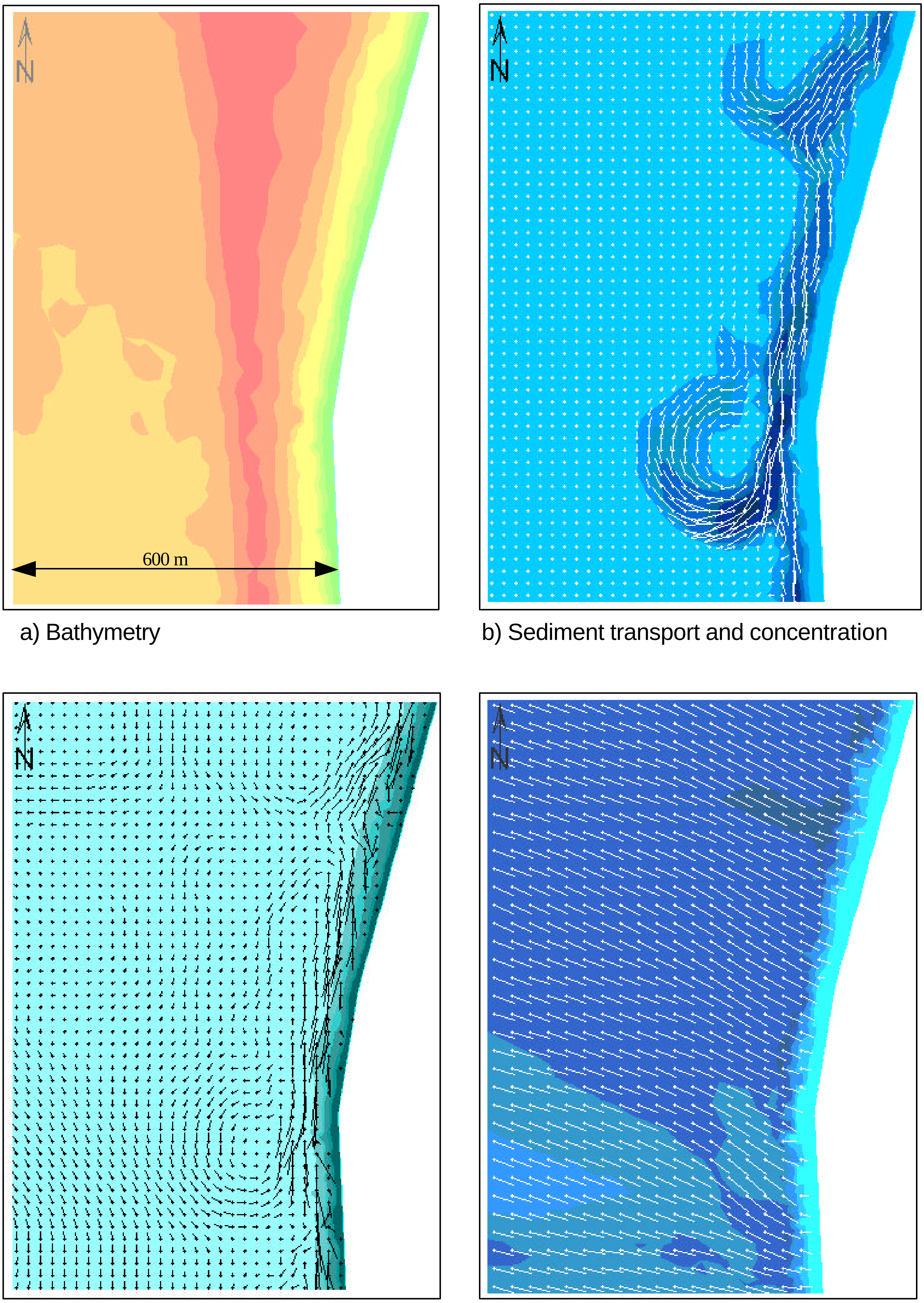



Figure 5: Sediment transport rates 1993 – 1997at selected Hiddensee profiles (1D modeling)




a) Bathymetry

b) Sediment transport and concentration

c) Flow field and water level

d) Wave hight and wave direction

Figure 6: 2D area morphodynamic modeling off Hiddensee island

The information obtained from 1D longshore modeling does not explain the different behavior of the adjacent profiles i and h as shown in Figure 5. The sequence of plots in Figure 6 shows in panel a the nearshore bathymetry of the area in the vicinity of these coastal profiles together with the flow, wave and sediment transport fields as computed by the 2D area mode.

The flow field vectors are plotted on top of the contour lines of water level. Due to the breaking of waves which propagate in a typical situation from NW towards the coast, there is appreciable variation in water levels within the first 80m of the shore. The wave heights reduce and induce a considerable longshore current which is topographically guided and forms eddies with 250m diameter. High flow velocities give rise to sediment transport which follows the flow patterns, as seen in panel b of Figure 6.

Width and location of the observed long shore transport bands are in keeping with the location of maximum sediment transport rates which are computed by the 1D longshore model. The transport rates at profile i in Figure 5 for the years 1993/1994 indicate transport in opposite directions along the first 250m of the coastal profile which is about the extent of the observed eddies.

## 5 Conclusions

Simple models based on empirical formulae are as reliable as more sophisticated models in carrying out cumulative sediment transport computations, in particular for long term studies. In any case, good quality of the wave input data is most important.

Choose the best model with the least complexity for each question to answer. The combination of complementary modeling concepts helps to gain insight efficiently. Successful detailed morphodynamic modeling depends on careful scenario selection.

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