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Modelling of Suspended Sediment Dynamics in Tidal Channels of the German Bight

By CHRISTIAN WINTER, POERBANDONO, HELGE HOYME and ROBERTO MAYERLE

Summary

The performance of two-dimensional depth averaged numerical sediment transport models has been evaluated based on extensive field data within the framework of the BMBF founded research project "Predictions of Medium Scale Morphodynamics (PROMORPH)". A validated two-dimensional depth integrated hydrodynamic coastal area model has been complemented by a transport module. The dynamics of suspended sediment concentration are computed from an advection diffusion equation. The bed load and equilibrium transport is determined based on commonly accepted algebraic formulations (VAN RIJN, 1984; BIJKER, 1971). Sensitivity studies show the dependency of the model results on input parameters, mainly the bottom roughness. Acceptable results therefore necessarily require a thorough model calibration. This has been carried out by comparison to measured suspended sediment concentrations at three cross-sections of the Dithmarschen Bight to find the most suitable set of input parameters. A quantitative assessment of the model performance has been based on parameters as the discrepancy ratio and the relative mean absolute error. Similar accuracy was achieved for both the calibration data and independent validation data-sets. It is concluded that after calibration the model can be expected to produce reasonable results. However significant deviations from field data in terms of absolute (quantitative) values might occur locally.

Zusammenfassung

Im Rahmen des vom BMBF geförderten Forschungsprojekts „Prognose mittelfristiger Morphologieänderung (PROMOPRH)" wurden umfangreiche Naturmessdaten für die Kalibrierung und Validierung von numerischen Sedimenttransportmodellen verwendet. Ein validiertes zweidimensional-tiefenintegriertes hydrodynamisch-numerisches Flächenmodell wurde um ein Sedimenttransportmodul erweitert. Die Dynamik suspendierten Sediments wird durch die numerische Lösung einer Advektions-Diffusionsgleichung beschrieben. Der Geschiebetransport wird durch bekannte algebraische Formulierungen (BIJKER, 1971, VAN RIJN, 1984) ausgedrückt. Sensitivitätsstudien zeigen die Abhängigkeit des Modells von Eingabeparametern, insbesondere der Bodenrauhigkeit. Es wird deutlich, dass auch bei der Verwendung allgemein akzeptierter und weit verbreiteter Transportformeln eine Kalibrierung der Modelle an Naturmessdaten notwendig ist. Diese wurde anhand gemessener Sedimentkonzentrationen an drei Rinnenquerschnitten der Dithmarscher Bucht durchgeführt. Zur quantitativen Beurteilung der Modellgüte wurden statistische Kenngrößen verwendet. Eine Validierung des Sedimenttransportmodells anhand unabhängiger Datensätze zeigt gleiche Qualität. Es wird gezeigt, dass das Modell die Schwebstoffdynamik im Untersuchungsgebiet weitgehend nachbildet. Allerdings muss lokal mit zum Teil erheblichen quantitativen Abweichungen gerechnet werden.

Keywords

Suspended Sediment Transport, Coastal Area Model, Calibration, Validation, Promorph, Meldorfer Bucht, Dithmarscher Bucht, Nordsee, North Sea

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Contents

1. Introduction

Coastal dynamics are mainly affected by hydrodynamic and climatic forcing, local sedimentology and morphology. Sediment continuously is eroded, transported and deposited leading to an ongoing evolution of the bed in all spatial and temporal scales. The investigation and understanding of the governing dynamic processes is crucial for the prediction of future coastal development e.g. the impact assessment of coastal structures. Comprehensive studies of sediment- and morphodynamics combine field measurements and modelling approaches of different structure and complexity. Two main model concepts can be distinguished: Empirical models on the one hand, which are based on empirical relationships between the geometry of the coastal environment and physical parameters. Dynamic models, on the other hand, which base their predictions on mathematical formulations of the relevant physical processes. These process based models involve different concepts such as coastline models, for the large scale description of longshore behaviour; coastal profile models, which simulate the cross-shore morphological evolution and coastal area models, in which both horizontal dimensions are taken into account. Here the focus is set on the latter process-based coastal area models which typically are developed for and applied in engineering time and length scales (days to months, tens to hundreds of kilometres). A number of these, following different physical and numerical approaches and strategies have been developed in the past decades (NICHOLSON et al., 1997). A majority are based on the quasi steady assumption, that the bed may be considered immobile in hydrodynamic timescale. This leads to a decoupling of computational modules, i.e. a separate, successive calculation of currents, waves, sediment transport and bed evolution.

Adapted field data has to be available to set-up, calibrate, validate and drive numerical models. Vice versa the validated model can be applied for the spatial and temporal inter- and extrapolation of measured data (hindcast), and predictive (forecast) studies. Within the framework of the BMBF funded research project 'Prognosis of Meso-scale Morphodynamics (PROMORPH)' (ZIELKE et al., 2000) a large set of field data has been obtained from measurement campaigns designed for the development of numerical models. This paper describes the set-up, calibration and validation of a numerical model for the simulation of sediment dynamics in the tidal channels of the Dithmarschen Bight of the German Wadden Sea.

Generally, model validation with field measurements is based on discrete series of measured and computed data. To overcome a purely descriptive and qualitative evaluation values are often presented as anomalies (differences) or correlations. Recent comparative studies tend to present model quality in terms of the discrepancy ratio, i.e. the percentage of computed versus observed concentrations that range within a certain distance from parity (e.g. DAMGAARD et al., 2001). VAN RIJN et al. (2002) proposed a quantitative measure to evaluate the performance of numerical wave and current models based on a relative mean absolute error, adjusted for the accuracy of the measuring device. As this measure is less sensitive to outliers than e.g. the mean error, it was chosen to serve as a quality criterion in this study.

In the following chapter a brief overview is given about the study area and the field measurements which have been carried out throughout the research project PROMORPH. The third chapter describes the numerical modelling system and the set-up of a model of the Dithmarschen Bight. Also the parameters used for model evaluation are introduced. The calibration of the sediment transport model using field data is presented in the fourth chapter. The validation of the model and a quantitative evaluation is given in the fifth chapter. Results then are discussed and final conclusions are drawn in chapter 6.

2. Study Area

The study area covers the tidal flats and channels of the Dithmarschen Bight in the South-Western North Sea (Fig.1). Focus is set on the main tidal channel system comprising the Norderpiep, Suederpiep and Piep tidal channels which connect the open North Sea with the Meldorf Bight. Tides are semi-diurnal with a mean tidal range of about 3.2 m. The tidal prism of this channel system is in the order of $500 \cdot 10^6$ m³.

The composition of the well sorted bed sediments is of mainly very fine to fine sands with median grain sizes (D_{50}) varying from 80 to 170 µm (D_{90} are about 1.2 to 2 times D_{50}). Bed sediments with larger mud content are found in some of the deeper parts of the main channels, where a consolidated, rigid mud layer crops out. The sediments transported in suspension are finer: Sampled mean grain sizes here range from 6 to 86 µm. In general, fairly uniform vertical distributions of suspended sediment concentration were found.

Within the framework of the project extensive field measurements of current velocities and suspended sediment concentrations in the tidal channels were carried out (TORO et al., in this volume; POERBANDONO and MAYERLE, in the volume). The campaigns mainly cover climatically mild conditions due to technical restrictions of ship based surveys. Three cross-sections, i.e. T1 on the Norderpiep tidal channel on the Northwest of the domain, T2 on the Suederpiep tidal channel on the centre of the domain and T3 on the Piep tidal channel closer to the coast have been monitored. Current velocities were measured from moving vessels using acoustic profilers covering the entire cross-sections. Measurements of suspended sediment concentration over the vertical at defined locations of the cross-sections were made simultaneously with the current velocity measurements. Optical transmissometers that have been calibrated using direct water samples were employed. The depth-integrated suspended sediment concentrations in the tidal channels vary from a background concentration about 0.05 kg/m³ at slack water to 0.4–0.5 kg/m³ after maximum flood and ebb currents. Table 1 summarizes the surveys conducted at the three cross-sections the data sets of which have been used here for the calibration and validation of the hydrodynamic and sediment dynamic models.

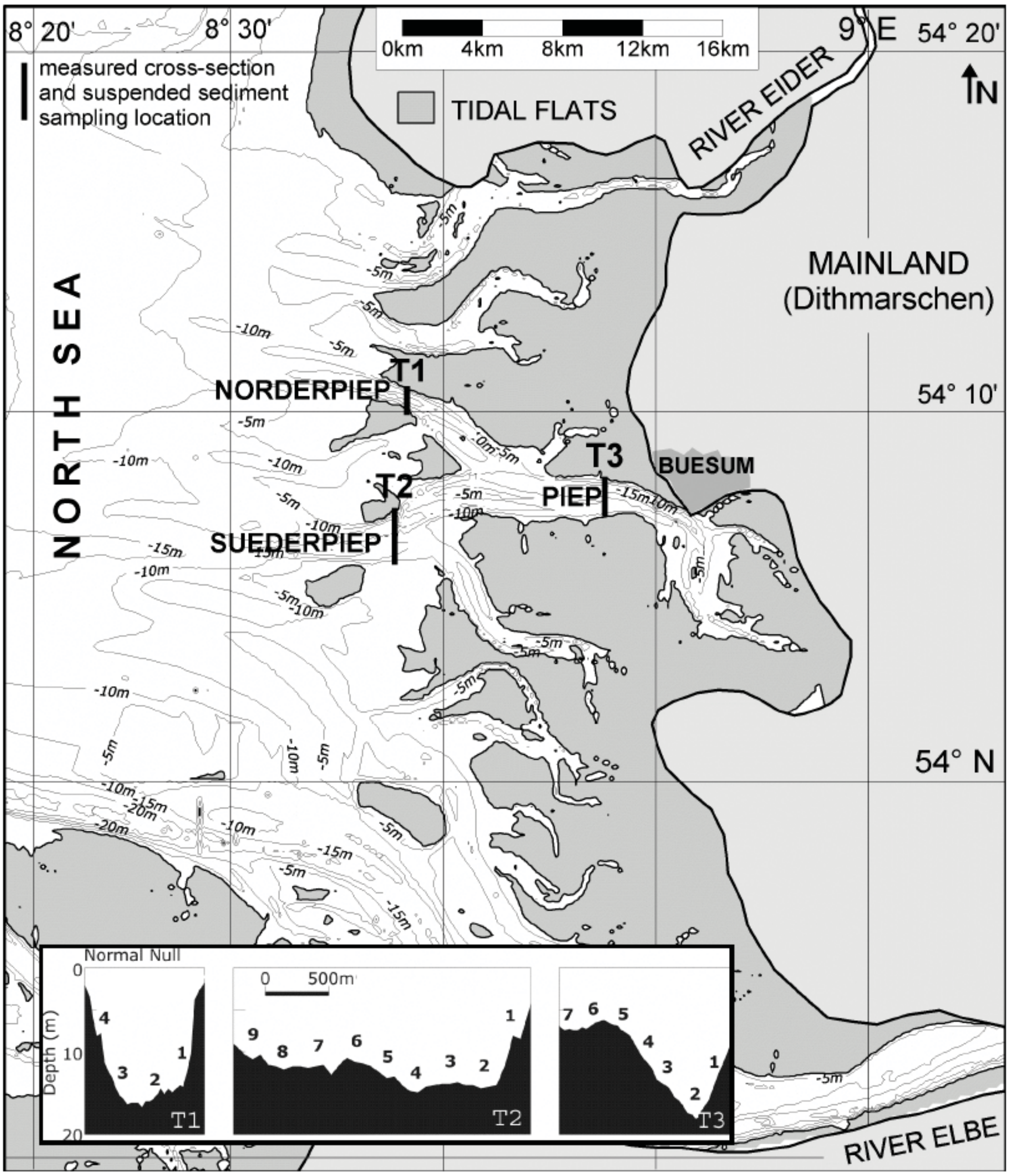

Fig. 1: Study area Dithmarschen Bight in the South Eastern North Sea and monitored cross-sections T1, T2, T3 with numbered measuring positions

Fig. 2 exemplarily shows the variation of measured depth-integrated velocity and suspended sediment concentration at the cross-sections T1, T2 and T3. Measurements were carried out on March 21 to 23, 2000 over full tidal cycles around spring tide. This period was characterised by calm weather conditions with westerly winds below 5 m/s.

Current velocities in the 0.8 km wide, 15 m deep, u-shaped northern channel Norderpiep (T1) may reach up to 1.25 m/s and are centred in the middle of the cross-section during flood. During ebb the depth averaged velocities are slightly higher (<1.25 m/s) and their maximum is found to be shifted towards the North. Depth-averaged sediment concentrations range between 0.08 and 0.14 kg/m³ during flood and up to 0.19 kg/m³ during ebb in the southern part of the cross-section. The peak in concentration lags the maximum ebb velocities by about 90 minutes.

Table 1: Field data on suspended sediment dynamics used for calibration and validation of the models

Data Set	Measuring Campaign	Date	Tidal Range [m]	Cross Section	Measuring Stations	Duration [h]	Remarks
1	March, 2000	22	4.0	T1	4	12:00	
		21	4.1	T2	9	11:55	Calibration
		23	4.2	T3	7	13:04	
2	June, 2000	5	3.7	T1	4	06:36	
		5	3.7	T2	12	08:26	Validation
		6	3.9	T3	7	08:12	
3	September, 2000	5	3.1	T1	4	10:28	
		5	3.1	T2	12	09:54	Validation
		6	2.9	T3	7	10:47	
4	September, 2000	12	3.3	T1	4	11:38	
		12	3.3	T2	10	10:59	Validation
		13	3.5	T3	7	04:34	
5	December, 2000	5	2.3	T1	4	05:33	
		5	2.3	T2	10	10:50	Validation
		6	2.5	T3	6	12:06	

Depth averaged flood currents in the Suederpiep tidal channel reach 1.5 m/s in the southern part of the 2 km wide cross-section T2. Maximum ebb currents go up to 1.2 m/s mainly at the northern part of the cross-section. Depth averaged sediment transport concentrations range from 0.1 to 0.2 kg/m³ in the northern part, and up to 0.5 kg/m³ in the southern part of the cross-section. The time lag between maximum flood currents and maximum concentrations is about 2 hours. Maximum concentrations lag the maximum ebb currents for about one hour.

The 1.2 km wide cross-section T3 is located east of the confluence of the main Piep tidal channel and a smaller, shallower tributary channel. This channel has been found to have a unique local bed morphology and sediment characteristics: In the northern part of the channel the bed sediment mainly consists of consolidated mud. Bedforms rarely exist. In the southern part of the channel the bed sediment consists of mainly fine sand with a mud content of less than 5%. Maximum flood currents occur in two maxima in the northern and southern part of the cross-section with depth averaged velocities up to 1.1 m/s. The ebb current is centred in the northern part of the cross-section with maximum depth averaged velocities of 1.4 m/s. The local sedimentology influences the transport behaviour: Depth averaged sediment transport concentrations range from 0.1 to 0.2 kg/m³ in the northern part and up to 0.3 kg/m³ (flood) and 0.4 kg/m³ (ebb) in the southern part of the cross-section. Depth averaged concentrations lag maximum flood currents by about one hour and ebb currents by about 30 min.

The calculated flow discharge and suspended transport load at the three cross-sections is plotted in Fig. 3. The main mass flux into and out of the Meldorf Bight is exchanged through the Suederpiep tidal channel, with a maximum flow discharge in the order of 30×10^6 m³/s and maximum suspended sediment loads of 10 t/s. The contribution through cross-section T1 is considerably smaller: Maximum flow discharge ranges in the order of 10×10^6 m³/s and maximum suspended sediment loads reach around 2 t/s. Due to the restrictions to only a few surveyed tidal cycles and limited cross-sections no final conclusions on budgets and ebb or flood domination of channels are drawn from the measurements.

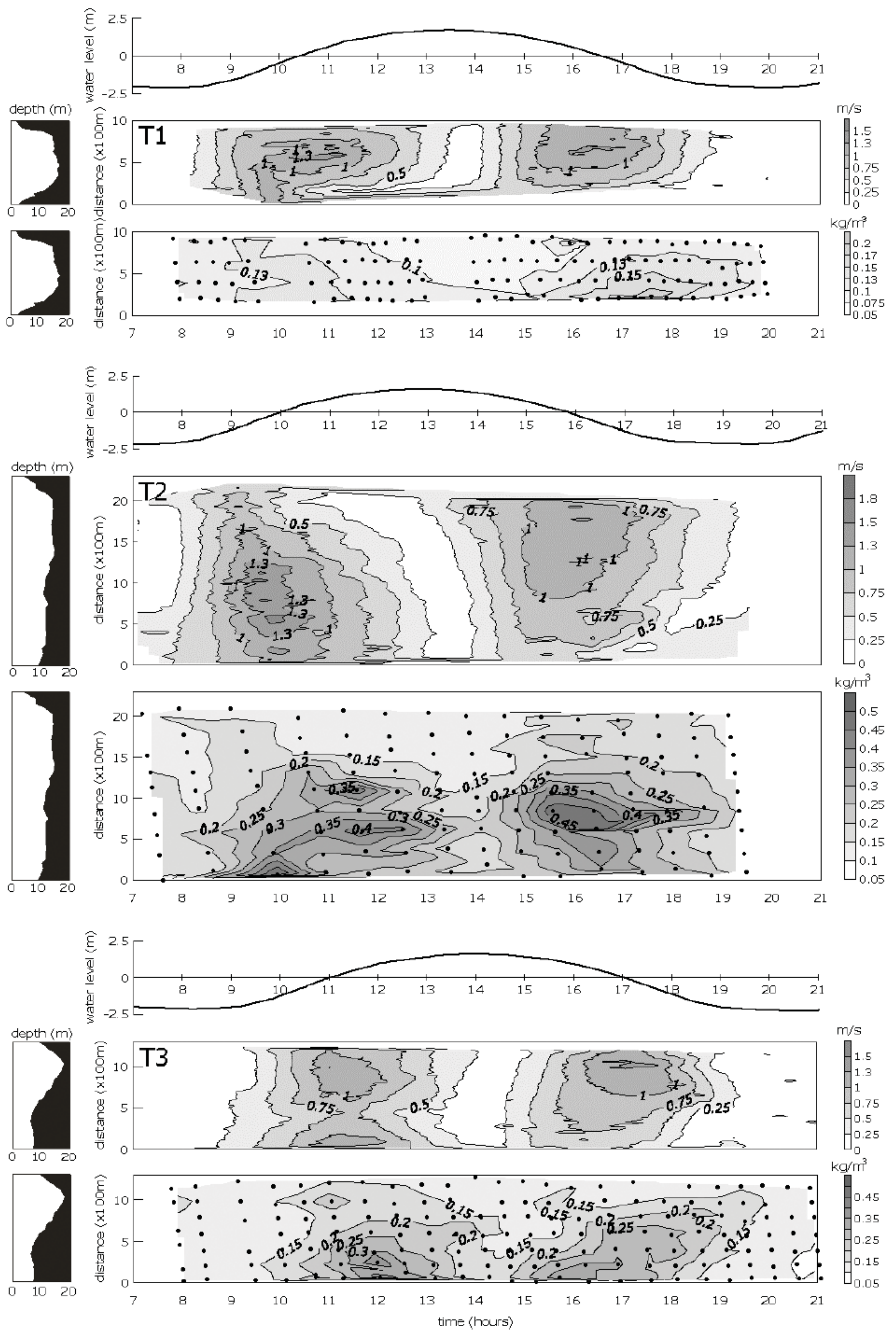

Fig. 2: Depth-integrated velocity and suspended sediment concentration over tidal cycles at the cross-sections T1, T2 and T3. Dots represent the stations of vertical optical transmission profiles

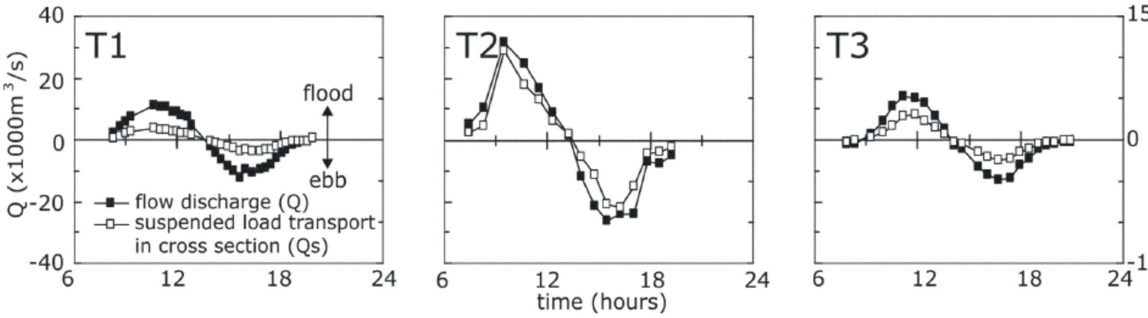

Fig. 3: Measured flow discharge and suspended transport load at the cross-sections T1, T2 and T3 on March 21 to 23, 2000

3. Numerical Model

For a further analysis and understanding of the suspended sediment dynamics and spatial and temporal extrapolation of measured data, numerical models for the simulation of hydrodynamics, sediment dynamics and morphodynamics have been set up. The set of field data, obtained from measurement campaigns within the research project, was used for an extensive calibration and validation of the models. The process-based coastal area model solves the mathematical equations describing the relevant physical processes on a computational grid. Driven by specified conditions at the open model boundaries (e.g. wind on the surface, waterlevels and sediment concentration at the lateral boundaries) the advective and diffusive processes within the model domain are simulated.

3.1 Modelling System

The process-based Delft3D modelling system has been applied. It comprises computational modules for the simulation of currents, waves, sediment transport and morphological evolution. These modules can be interlinked for the simulation of wave-induced currents, sediment transport and resulting morphological changes (ROELVINK et al., 1994). Here a quasi-stationary coupling of the computational modules is performed, where the bed is assumed immobile throughout the hydrodynamic and sedimentdynamic computations and the influence of the sediment concentration on the flow is neglected. This allows a successive simulation of the hydrodynamics, the sediment transport and the bed evolution in separate modules.

The set-up, calibration and validation of the hydrodynamic models are described in detail in PALACIO et al. (in this volume), PALACIO (2002) and PALACIO et al. (2001). All computations have been performed using two dimensional depth integrated (2DH) models. A curvilinear computational grid with quadrangular elements, covering the Meldorf Bight and the adjacent tidal channels has been used. About 43000 elements, with grid spacing ranging from 60 to 200 m were considered to discretise the domain with acceptable accuracy. Bathymetric data from recent echo soundings was interpolated on the grid using linear triangulation.

Water levels specified along the western open sea boundaries of the model have been derived from larger models covering the German Bight (WL|DELFT HYDRAULICS, 1997) and the European Continental Shelf (VERBOOM et al., 1992) using a nesting scheme (MAYERLE et al., in this volume, and WINTER, 2003). PALACIO (2002) gives long-term RMS-errors around

0.15 m/s in the Piep and Norderpiep and circa 0.25 m/s in the Suederpiep for the depth-integrated current velocities. The RMS-error of the water levels was between 0.02 and 0.04 m for high tide and between 0.05 and 0.12 m during low tide, based on the maximum and minimum water levels of a two-month period.

For the periods considered here, the differences between measured and computed water levels at the position Norderpiep are below 0.1 m at high-water and about 0.3 m at low water which corresponds to approximately 3 % and 8 %, respectively, of the maximum tidal range (3.6 m). At the gauge Büsum differences in water level remain below 0.15 m at high water and 0.4 m at low water giving about 4 % and 10 %, respectively, of the maximum tidal range (3.9 m). Although covering climatically mild periods only, a wave model (HISWA) was used to compute the wave field. At the open sea model boundaries, constant wave heights of 0.4 m and mean periods of 2 s were used. This model computes on a rectilinear grid with element sizes of 200 x 400 m covering the domain of interest. Model results indicate that the effect of small waves on the current velocities is moderate on the tidal flats and negligible in the tidal channels.

3.2 Sediment Transport Model

The transport module computes the sediment dynamics for a 2D horizontal area taking into account the flow and optionally wave parameters derived by the hydrodynamic models. As shown above, high velocity gradients and small grain sizes of the sediments transported in suspension cause considerable lag effects between local current velocities and the suspended sediment concentration. Thus the advection and diffusion of suspended sediment dynamics are computed by the numerical solution of an advection-diffusion equation. The bedload transport is separately derived from algebraic formulations. In this study two algebraic total load formulas, which distinguish between bed load and equilibrium suspended load, have been applied, being the BIJKER (1971) and the VAN RIJN (1984) formulation.

The BIJKER (1971) total load formula $S = S_b + S_{se}$ separately accounts for bed load (S_b) and the instantaneous equilibrium suspended load (S_{se}). The bed load relation is a modified version of the bed load formula by FRIJLINK (1952), for which a wave term was added. This formula has been initially verified with wave basin data with fine sand (D_{50} = 220 µm). It is commonly used in comparative and applied studies (e.g. DAVIES et al., 2002; BAYRAM et al., 2001; CAMENEN and LARROUNDÉ, 2003). It reads:

$$S_{bBIJKER} = b_1\, D_{50} \frac{u}{C} \sqrt{g}\, \left(1-p\right) \exp\left(\frac{-0.27(s-1)\, D_{50}\, \rho g}{\mu \tau_{b,wc}}\right) \tag{3.1}$$

With:
- b_1 = empirical coefficient
- C = Chezy coefficient, based on D_{50}
- D_{50} = median particle diameter
- u = current velocity
- g = acceleration of gravity
- p = porosity
- s = $(\rho_s - \rho)$ relative sediment density

μ = $(C/C_{90})^{1.5}$ ripple factor
C_{90} = Chezy coefficient, based on D_{90}
$\tau_{b,wc}$ = shear stress at the bed

The original reference assigns $b_1 = 5$. However the formula has been found to overestimate measured transport rates (BAYRAM et al., 2001). Thus in practice it is considered to range between 1 and 5 depending on local conditions. The distribution of the suspended load is based upon the EINSTEIN (1950) approach:

$$S_{seBIJKER} = 1.83 S_{bBIJKER} \left(I_1 \ln\left(\frac{33.0\,h}{r_c}\right) + I_2 \right) \tag{3.2}$$

With: I_1, I_2 = Einstein integrals (Einstein, 1950)
h = water depth
r_c = bottom roughness

The Van Rijn (1984) total load equation is a widely used formulation for situations without waves. This total load formulation $S = S_b + S_{se}$ also separately defines bed load (S_b) and suspended load (S_{se}). The formula for the bed load transport reads:

$$S_{bVANRIJN} = \begin{cases} 0.053\sqrt{s\,g\,D_{50}^3}\; D_*^{-0.3} T^{2.1} & \text{for } T < 3.0 \\ 0.1\sqrt{s\,g\,D_{50}^3}\; D_*^{-0.3} T^{1.5} & \text{for } T \geq 3.0 \end{cases} \tag{3.3}$$

With: T = $(\mu_c\,\tau_{b,c} - \tau_{bcr})/\tau_{bcr}$, dimensionless shear stress parameter
τ_{bcr} = critical bed shear stress according to Shields
τ_{bc} = the effective shear stress
D_* = dimensionless particle diameter

The suspended sediment load is given as:

$$S_{seVANRIJN} = 0.015\, f_{cs}\, u\, h\, b_2 \frac{D_{50} T^{1.5}}{r_c D_*^{0.3}} \tag{3.4}$$

With: f_{cs} = $((r_c/h)/(1 - r_c)/h)^{1.2} \cdot \ln(r_c/h)$ shape factor
b_2 = empirical coefficient (O(1))

The expressions for the instantaneous equilibrium suspended load S_{se} as given above may be directly used for the calculation of suspended sediment concentrations if lag effects between hydrodynamics and sediment dynamics are small. However, if the adaption length of the suspended sediment is larger than the computational grid size, the entrainment, deposition, advection and diffusion of the suspended sediment must be determined by an advection-diffusion equation:

$$\frac{\partial hc_s}{\partial t}+\frac{\partial huc_s}{\partial x}+\frac{\partial hvc_s}{\partial y}-\frac{\partial}{\partial x}\left(\varepsilon h\frac{\partial c_s}{\partial x}\right)-\frac{\partial}{\partial y}\left(\varepsilon h\frac{\partial c_s}{\partial y}\right)=\frac{w_s\left(c_{se}-c_s\right)}{T_{sd}} \quad (3.5)$$

With:
- u,v = current velocities along the horizontal directions x and y
- ϵ = horizontal dispersion coefficient
- w_s = settling velocity
- T_{sd} = dimensionless adaptation time for the vertical concentration profile (GALAPPATTI and VREUGDENHILL, 1985)
- c_{se} = S_{se}/uh local equilibrium concentration
- S_{Se} = equilibrium suspended sediment transport rate

This equation is solved for the depth-integrated suspended sediment concentration c_s where the source/sink term is proportioned to the instantaneous equilibrium concentration c_{se}, derived from one of the algebraic sediment transport formulas. The suspended sediment components in x and y directions then are calculated:

$$S_{sx}=q_xc_s-h\varepsilon\frac{\partial c_s}{\partial x} \qquad S_{sy}=q_yc_s-h\varepsilon\frac{\partial c_s}{\partial y} \quad (3.6)$$

With: q_x, q_y = local discharge in x,y direction.

3.3 Model Set-Up and Sensitivity Analysis

The set-up of a numerical model comprises the spatial discretisation of physical parameters which characterise the domain of interest. This includes a large amount of data reduction and generalisation, as input data is averaged over grid-cells or even considered uniform over the whole computational domain. Also some processes which certainly are of an instationary nature are treated as constant in time. As shown above, some empirical parameters in the transport formulas also have to be specified. Finally, there are also physical input parameters that only can be estimated by the modeller, as field data may be not sufficient or not available at all. All this brings about the necessity of a thorough analysis of the model sensitivity to input parameters when setting up the numerical model.

The transport module uses the same curvi-linear grid and bathymetric information as the flow module. Hydrodynamic quantities such as the wave-forces, depth averaged current velocities and water levels are read in from previous simulations. The numerical algorithm requires the definition of initial conditions describing the suspended sediment concentration at start-up time and suspended sediment concentration information at the open model boundaries throughout the simulation period. In order to avoid discontinuities in the initial conditions, every computation is started with a full tidal cycle spin-up, which is not taken into account for further analysis. For inflow conditions at the open model boundaries (e.g. flood current at the western boundaries) local equilibrium concentrations or specified time-series of concentrations are to be prescribed. For outflow conditions (e.g. ebb current at the western boundaries) the upstream computational cell concentration is imposed by setting the derivative of the suspended sediment concentration in stream-wise direction to zero. The influence of the prescribed boundary conditions on the computed suspended sediment dynamics was found to be limited to a region, not farther than five kilometres from the open model boundaries (RIZZO, 2003).

The observed suspended sediment dynamics show pronounced lag effects. In that respect the direct application of the instantaneous equilibrium suspended sediment concentration derived from algebraic formulations would produce unrealistic results. Instead the advection and diffusion of suspended sediment concentration has been simulated by the numerical solution of equation 3.5.

As shown above the suspended sediment concentration derived from the solution of the advection diffusion equation is highly dependent on the algebraic formulations which describe the equilibrium suspended sediment transport. Thus a sensitivity analysis has been performed to critically ascertain the response of the computed concentrations to variations in grain sizes and settling velocities, empirical coefficients and the bottom roughness. Based on these studies, preliminary settings to be considered in the later calibration as well as their ranges are defined.

Simulations considering the Bijker formula, which accounts for the effect of waves, showed that the effect of local waves on the suspended sediment concentrations in the tidal channels is negligible for significant wave heights less than 0.3 m. Computed sediment concentrations with and without waves differed less than 0.01 kg/m^3, which is less than the measured background concentration. Certainly the importance of waves is expected to be more pronounced in storm situations.

Simulations were carried out considering uniform bed grain sizes with D_{50} varying from 40 to 160 µm. These computations should clarify if the transport formulae produce reasonable results for particle sizes outside the ranges of derivation of these equations. For the range of particle sizes considered here, computed sediment concentrations differ within a factor 2.

A range of settling velocities from 0.1 mm/s to 4 mm/s (considering suspended sediment particle sizes from 10 to 80 µm) was also considered. The effect on the sediment concentration is mainly pronounced during slack water. As expected, computed concentrations are lower with higher settling velocities in periods with smaller current velocities. Maximum concentrations differ within 30 %.

The variation of the calibration parameters b_1 in the Bijker formula and b_2 in the Van Rijn formula proportionally affects the computed concentration. Thus this coefficient may be considered as a linear tuning factor for computed depth averaged suspended sediment concentrations.

The bottom roughness term r_c is delicate in the sense that it influences the computed suspended transport magnitude profoundly and at the same time it is difficult to measure or estimate in engineering practice. MAYERLE et al. (2002) found that bed forms in the domain vary significantly during a tidal cycle ranging from less than one millimetre (flat bed) to several decimeters (rippled bed). Computations were carried out covering the range of r_c from one millimetre to 0.5 m. Fig. 4 exemplarily shows the resulting sediment concentrations which range within three orders of magnitude. Bed roughness values of a few centimetres to decimetres provide sediment concentrations within the range of the measured values.

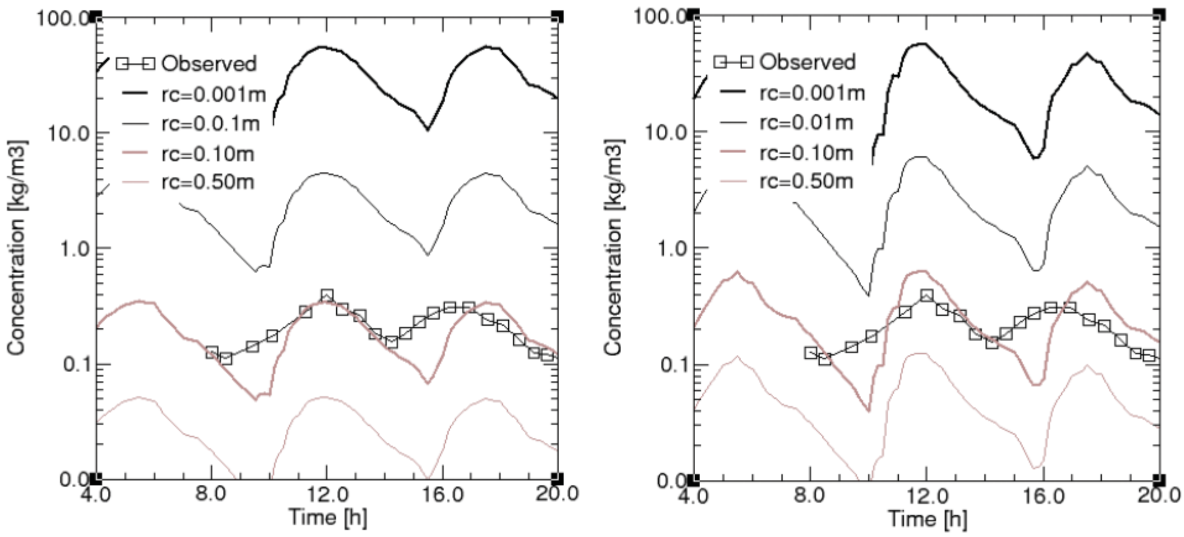

Fig. 4: Computed suspended sediment concentrations at Position 4 of cross-section T2. Modified bottom roughness r_c using the BIJKER (1971) (left) and VAN RIJN (1984) (right) equation

Initial computations with an estimated bottom roughness r_c = 0.1 m, grain sizes of D_{50} = 100 µm and D_{90} = 150 µm, and the empirical coefficients b_1 = 5 for the BIJKER formula and b_2 = 1 for the VAN RIJN formula result in differences between the two approaches up to factor 3, depending on the location. In this case the VAN RIJN formula leads to an underestimation of the suspended sediment concentration, whereas the BIJKER formula overestimates the measured values (Fig. 5).

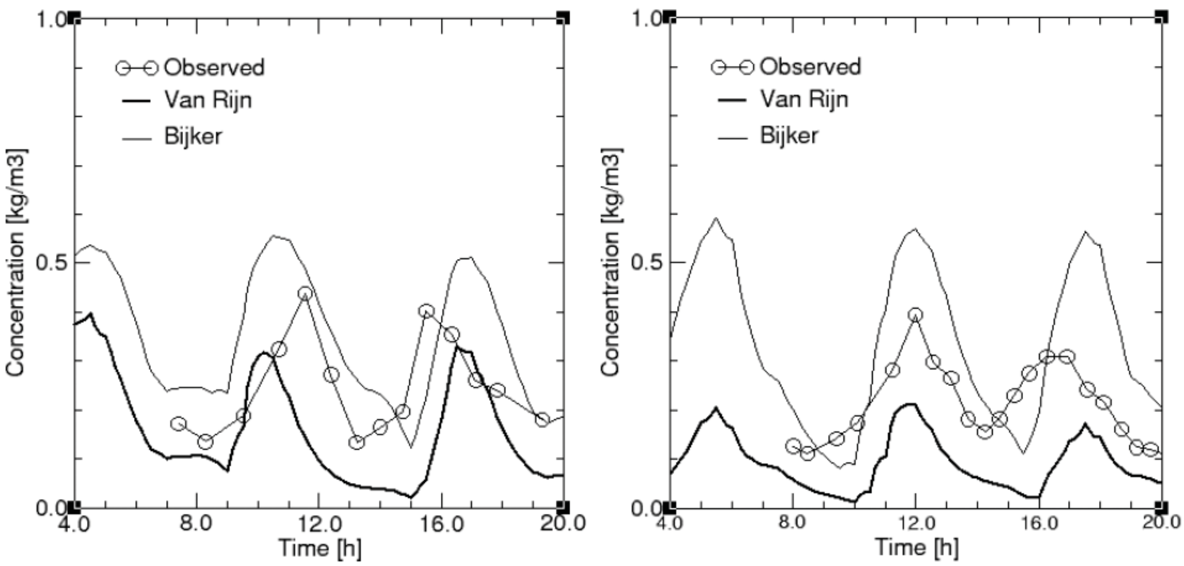

Fig. 5: Computed suspended sediment concentrations for initial settings at position 4 of cross-section T2 (left) and position 4 of cross-section T3 (right)

3.4 Evaluation Parameters

The calibration and validation of models are based on comparisons between field measurements and model simulations. To overcome purely descriptive and qualitative evaluations, statistical parameters are used to quantify the model quality. Yet, model evaluation still lacks universal and commonly accepted methods for an objective assessment of the model quality. However certain types of presentation seem to have formed a habit:

Generally the evaluation with field measurements is based on discrete data series of measured (c_m) and computed (c_c) values. Recent publications on intercomparisons of sediment transport models (e.g. DAMGAARD et al., 2001) tend to assess the model performance on the basis of the discrepancy ratio, i.e. the percentage of computed versus observed values that range within a certain distance from parity ($c_m/c_c = 1$). The distances typically are taken as factor 2 ($0.5< c_m/c_c<2$) or factor 5 ($0.2< c_m/c_c<5$).

VAN RIJN et al. (2002) proposed a quantitative measure to evaluate the performance of numerical wave and current models based on the Adjusted Relative Mean Absolute Error (ARMAE). This procedure has been adopted for the sediment transport simulations described here. The ARMAE is preferred above the Mean Square Error (MSE) as it is more robust against outliers and takes into account the accuracy of the measuring device. The formula reads:

$$ARMAE = \frac{< |c_c - c_m| - \Delta c_m >}{<| c_m |>} \tag{3.7}$$

With: c_c = computed value
c_m = measured value
Δc_m = device accuracy
$|..|$ = absolute value
$<..>$ = average over time

The expression $<|c_c-c_m|-\Delta c_m>$ is set zero for negative values, as it indicates that the difference between measured and computed values is smaller than the device accuracy. An appraisal by results for suspended sediment concentrations is not provided; however, the qualifications given in VAN RIJN et al. (2002) for wave heights and current velocities are cited in Table 2.

Table 2: Qualification of error ranges of the process parameters according to VAN RIJN et al. (2002)

Qualification	Waves : ARMAE [m]	Velocity : ARMAE [m/s]
Excellent	<0.05	<0.1
Good	0.05–0.1	0.1–0.3
Reasonable	0.1–0.2	0.3–0.5
Poor	0.2–0.3	0.5–0.7
Bad	>0.3	>0.7

4. Model Calibration

The survey of March 2003 provides a comprehensive set of suspended sediment concentration data at twenty positions on three cross-sections. Although the data and the calibration of the optical device cannot be completely free of errors because of the nature of the measurements carried out, they still offer a unique possibility of calibrating the model in space and time. Measured values and model results were compared at twenty cross-sectional positions during three tidal cycles (WINTER and MAYERLE, 2003).

A uniform and constant bed composition of fine sand with D_{50} and D_{90} values equal to 100 µm and 150 µm, respectively, was assumed. The calibration focused primarily on the bed roughness r_c and coefficients b_1 and b_2 in the algebraic equations. Uniform values of bed roughness ranging from 0.08 to 0.5 m, and coefficients in the algebraic equations varying from 1 to 5 were considered.

Comparisons of measured and computed values for the ranges of bed roughness are shown in Fig. 6. Three stations (station 4 on cross-section T1, station 4 on cross-section T2 and station 4 on cross-section T3) were selected to exemplify the change in model performance. It can be seen that uniform bed roughness values ranging from 0.1 to 0.3 m give results in the order of magnitude of the measured ones. Also the empirical coefficients b_1 and b_2 were adapted to correct for the under-estimation of the VAN-RIJN and the over-estimation of the BIJKER formula.

The magnitude of calculated suspended sediment concentrations can be adjusted to the measured values at single positions. However, the low background concentration around slack water mostly is under-predicted. Since the target of the project is the simulation of coastal morphodynamics which are governed by high loads, no further correction for this underestimation has been performed. Best parameter settings differ according to location and time. In order to select uniform and constant parameters that lead to the best possible agreement with measurements throughout the entire domain and at all times, approaches which enable a quantitative assessment of the model performance were considered. First, the discrepancy ratio, i.e. the percentage of computed versus observed concentrations that range within a factor of 2 and 5 has been chosen as a skill score. A number of different model runs with different settings has been evaluated based on dataset 1 (March 21 to 23, 2000):

Fig. 7 shows the discrepancy ratios of simulations after calibration: Best results using the BIJKER formula in the transport model set-up, with constant and uniform settings throughout the whole model domain, respectively resulted in 74 %, 74 % and 75 % for the cross-sections T1, T2 and T3 (all: 75.1 %) of the computed concentration values at the three cross-sections within a factor 2 compared to the measured. At the cross-sections T1 and T3 100 % and at cross-section T2 97 % (all: 98 %) are within a factor of 5. It shall be pointed out that outliers mostly belong to positions at the channel banks such as position 4 in cross-section T1, positions 1, 8 and 9 in cross-section T2, and position 7 in cross-section T3.

Best results applying the Van Rijn formula in the transport model set-up result in 61 %, 51 % and 58 % for the cross-sections T1, T2 and T3, respectively (total: 57 %) of the computed concentrations within a factor 2 compared to the measured. At the cross-sections T1, T2 and T3 94 %, 95 % and 91 %, respectively (all: 93 %) are within a factor of 5. Again outliers, underpredicting the observed concentrations mostly belong to positions near the channel banks such as position 4 in cross-section T1, positions 1, 8 and 9 in cross-section T2, and position 7 in cross-section T3. The ascertained settings are specified in Tab. 3.

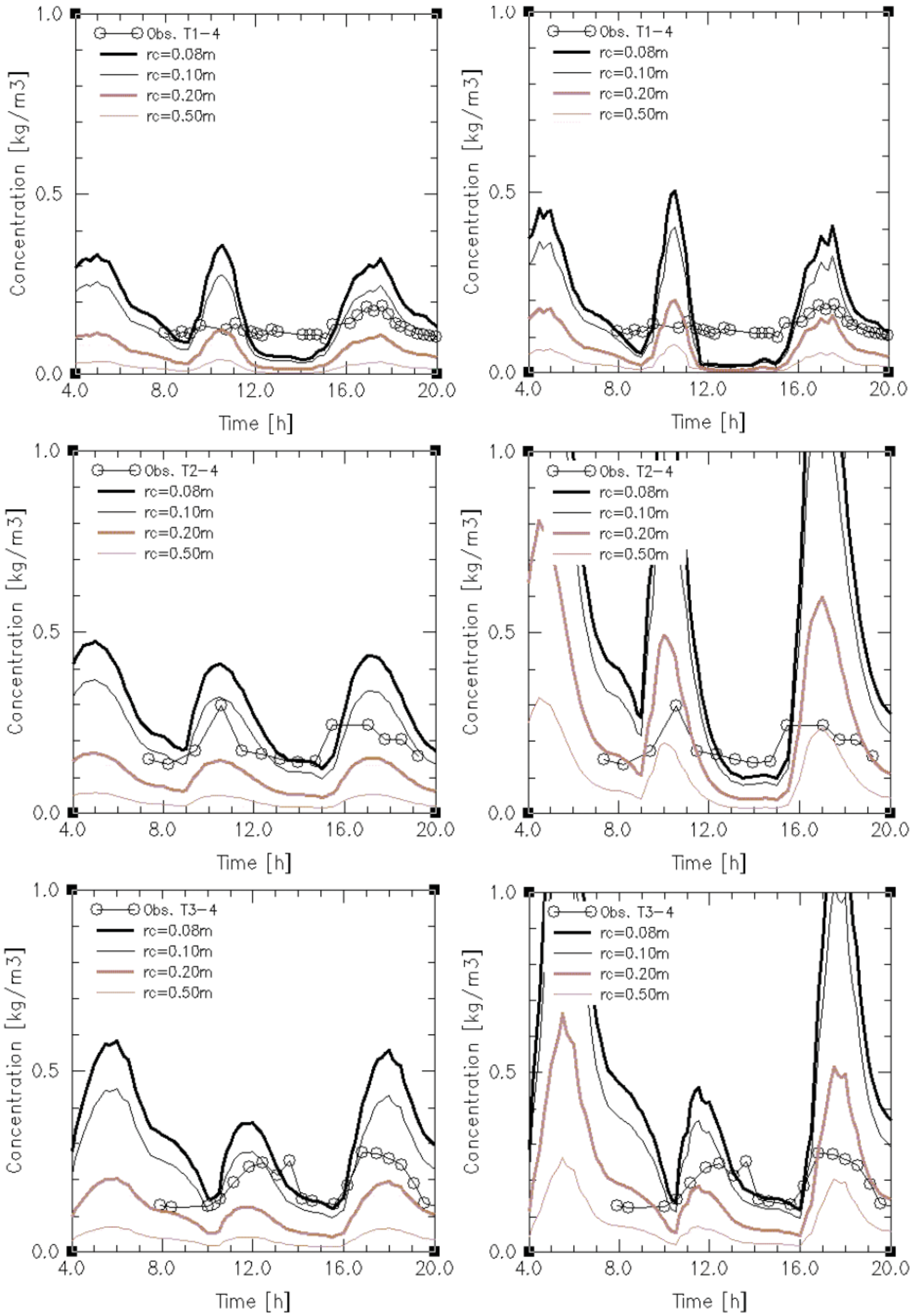

Fig. 6: Calibration with respect to bottom roughness r_c (Dataset 1). Measured (o-o) vs. computed (---) depth averaged suspended sediment concentrations at position 4 of transect T1 (upper), at position 4 of transect T2 (middle), at position 4 of transect T3 (lower). Results from simulations using the BIJKER (left) and the VAN RIJN (right) approach

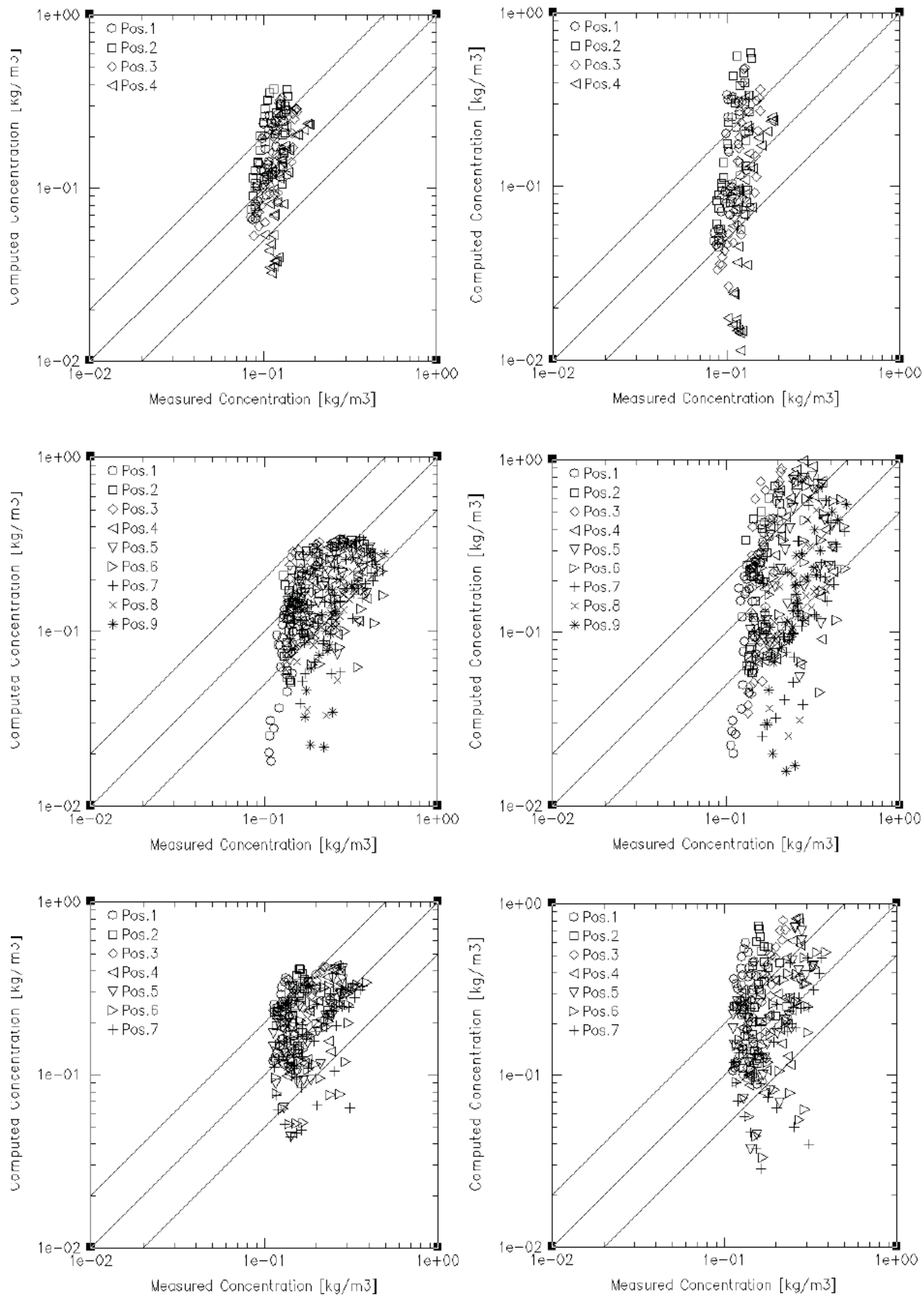

Fig. 7: Computed versus measured concentrations at cross-sections T1 (upper), T2 (middle), T3 (lower) using BIJKER (left) and VAN RIJN (right) formula. Solid lines indicate the range of factor 2

Table 3: Model settings after calibration

	$D50$ [µm]	$D90$ [µm]	b [–]	r_c [m]	w_s [mm/s]
BIJKER	100	150	3	0.2	0.1
VAN RIJN	100	150	2	0.2	0.1

To provide a quantitative measure of the model quality after calibration, which takes into account the accuracy of the measuring device, the mean ARMAE value for the twenty stations along the three-cross-sections were obtained with the same model settings used above. Assuming 30 % accuracy, the mean ARMAE for all twenty stations resulted to 0.17 kg/m³ for the Bijker formula and 0.28 kg/m³ for the VAN RIJN formula.

The computed variations of the depth-integrated velocity and concentration over the tidal cycle at the three cross-sections are shown in Fig. 8 for comparison with Fig. 2. Simulations were carried out using the BIJKER formula and the model settings given in Table 3. Apart from the concentrations computed for the flood phase in cross-section T1 which show far too high values, the observed characteristics could be reproduced reasonably well. Maximum concentrations can be computed at the right times and locations. The model is also capable of determining phase lag between maximum currents and concentration.

5. Model Validation

5.1 Validation of suspended sediment concentration

A meaningful evaluation of the model quality must be performed with independent datasets, which have not been used for calibration. Thus field data of suspended sediment concentrations from sets 2 to 4 (see Tab. 1) were used here. Data set 2 measured on June 5 and 6 (spring tidal range of 3.9 m) and dataset 3 measured on September 5 and 6, 2000 (average tidal range of 3.1 m) are chosen. Model validation was performed for computed suspended sediment concentrations and cross-sectional loads which are shown in the following sections. No additional tuning of model parameters was done.

The model quality in terms of depth averaged suspended sediment concentration is exemplarily shown for single positions at the three cross-sections in Fig. 9. In contrast to the results that were obtained for the calibration period the model overpredicts the marginally fluctuating concentration values at cross-section T1 for both periods (Fig. 10). Simulation results applying the BIJKER formulation are within the ranges of accuracy of the measuring device at the cross-sections T2 and T3. The VAN RIJN approach tends to over-estimate the maxima and under-estimate slack-water low values. Statistical parameters for these simulations are given in Table 4.

Table 4: Validation of simulated suspended sediment concentrations for datasets 2 and 3

	Mean ARMAE	Mean Absolute Error	Mean Relative Error	Data within Factor 2
BIJKER	0.12	0.05 kg/m³	41 %	75 %
VAN RIJN	0.40	0.08 kg/m³	73 %	52 %

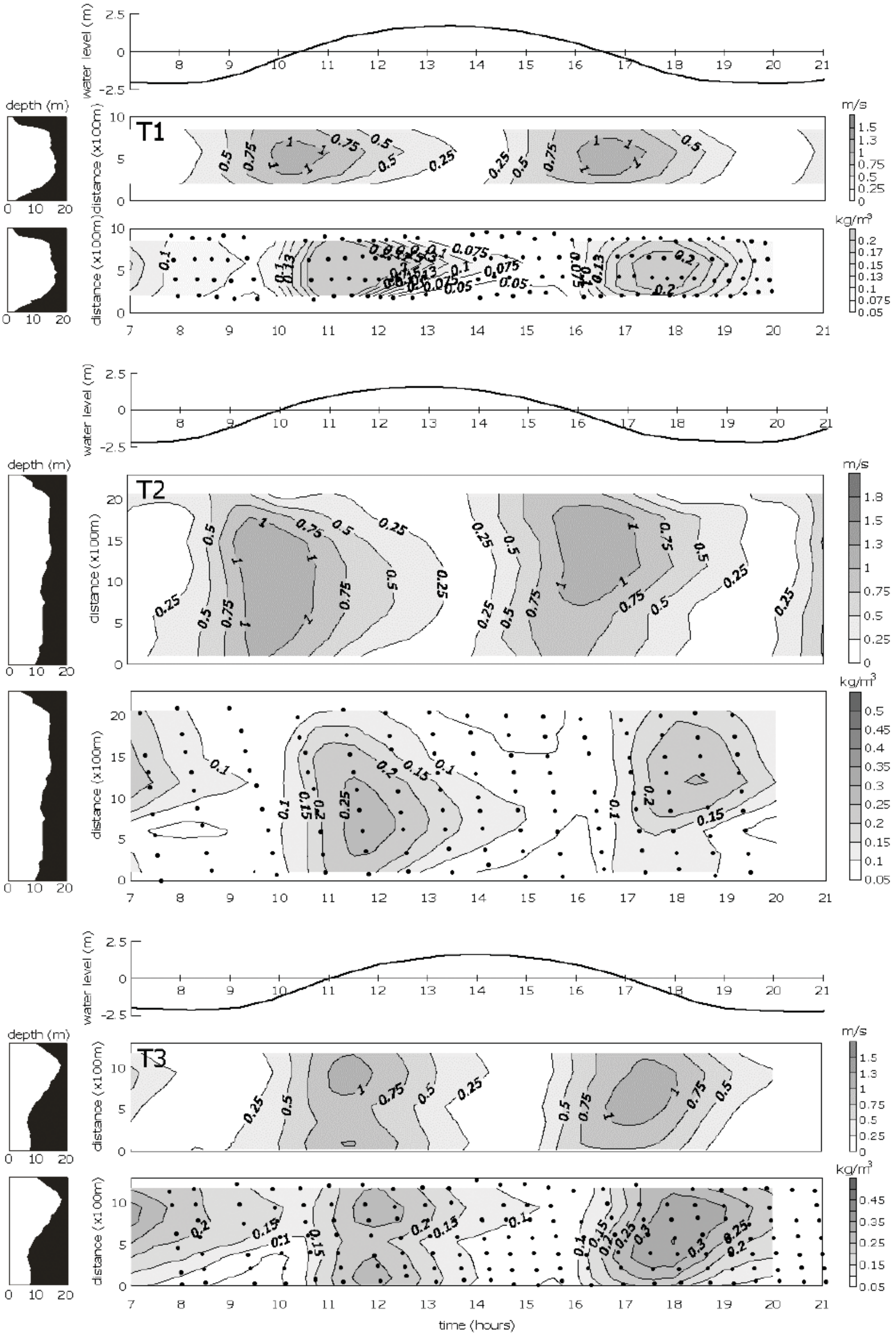

Fig. 8: Computed water levels, depth-integrated velocity and suspended sediment concentration hindcasting dataset 1 (March 2000) at the cross-sections T1, T2 and T3. For comparison see Fig. 2

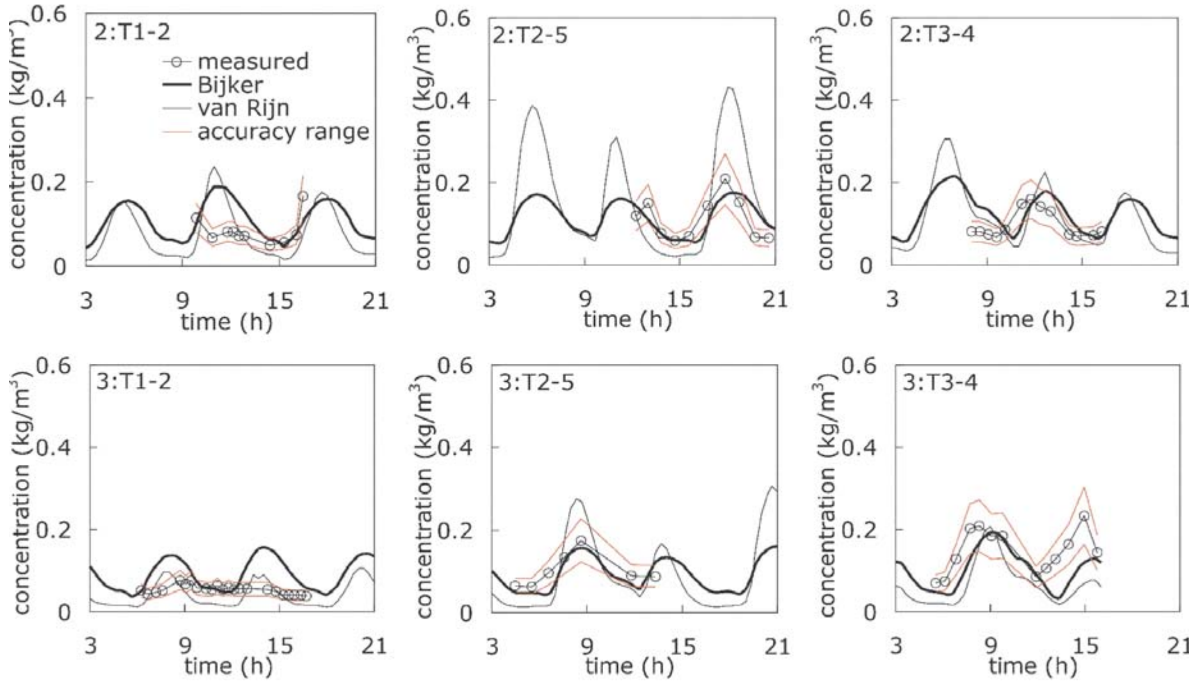

Fig. 9: Comparison of measured and predicted depth integrated concentration for datasets 2 (upper) and 3 (lower). Results for selected stations at cross-sections T1 (left), T2 (middle), and T3 (right)

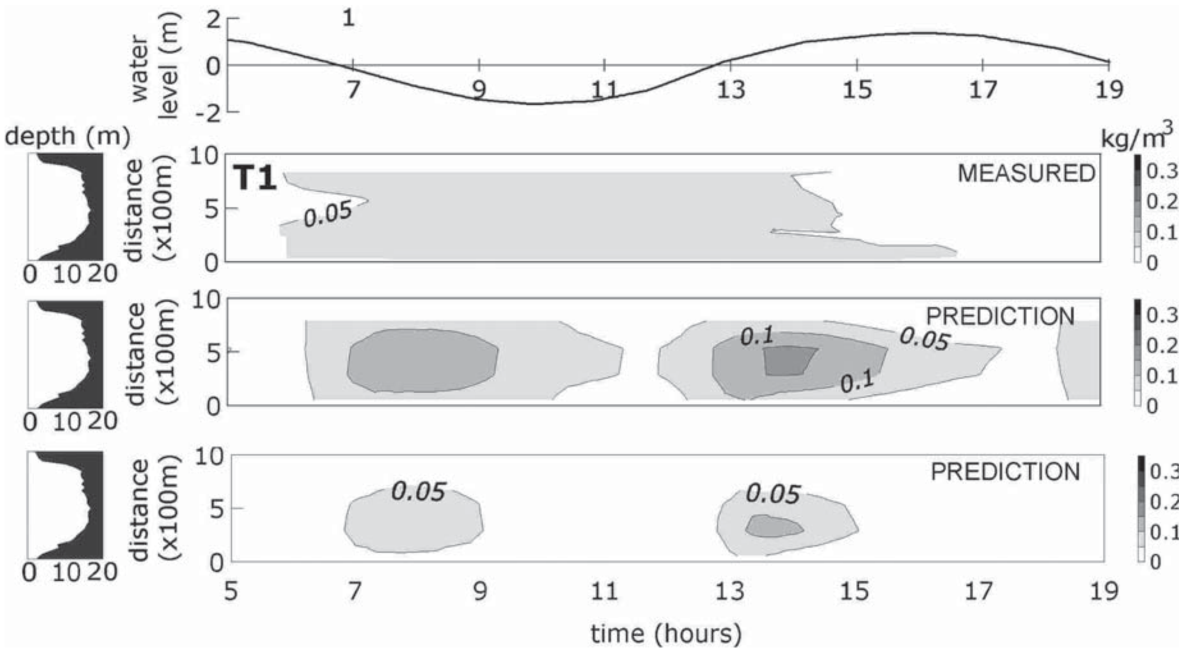

Fig. 10: Measured (upper) vs. computed (BIJKER: middle, VAN RIJN: lower) variation in suspended sediment concentration at cross-section T1 (Norderpiep) for dataset 3 (September 5, 2000)

The Suederpiep channel (cross-section T2) has been found to have the largest variation in depth-integrated concentration. In this cross-section, a clear response to the increasing tidal range can be observed. During this campaign the depth-integrated concentration varied between 0.06 to 0.33 kg/m^3. Unfortunately, due to technical reasons measurements could not cover the entire flood phase. The prediction results generally follow the dynamic pattern of the depth-integrated concentration magnitudes (Fig. 11). The time of occurrence of maximum concentrations is captured well by both model approaches. However, the absolute values are under-estimated. The corresponding deviation is up to a factor of 2. Using the Van Rijn formula leads to a closer fit to the measured data.

The Piep (T3) channel's bed morphology and sediment characteristics influence the transport behaviour in a sense that the ebb currents mobilise material mainly in the shallow and sandy southern part (Fig. 12). Two hours later than in the southern region a weaker concentration peak of sediment – brought into suspension in the tidal flats upstream – is also observed in the northern part, which features a rigid bed of consolidated cohesives in the vicinity of the cross-section. The suspended sediment concentration during flood shows a twofold maximum from the southern and slightly later from the northern channel. The model is able to reproduce significant features of depth-integrated concentration dynamics in this cross-section: These are the twofold concentration maxima during flood and the lagged response of the northern channel. However the prediction of the absolute magnitudes generally tends to be underestimated by both model approaches.

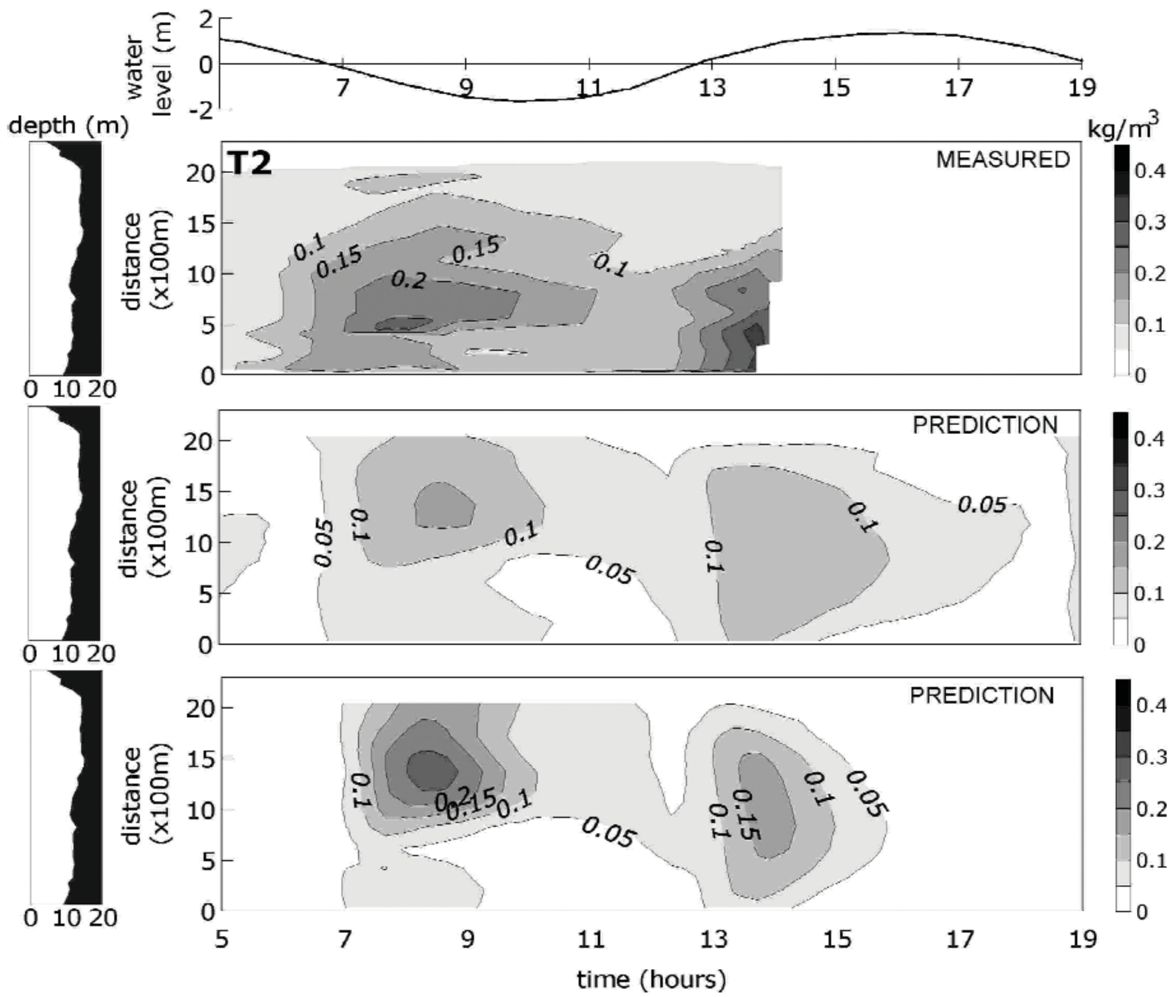

Fig. 11: Measured (upper) vs. computed (BIJKER: middle, VAN RIJN: lower) variation in suspended sediment concentration at cross-section T2 (Suedererpiep) dataset 3 (September 5, 2000)

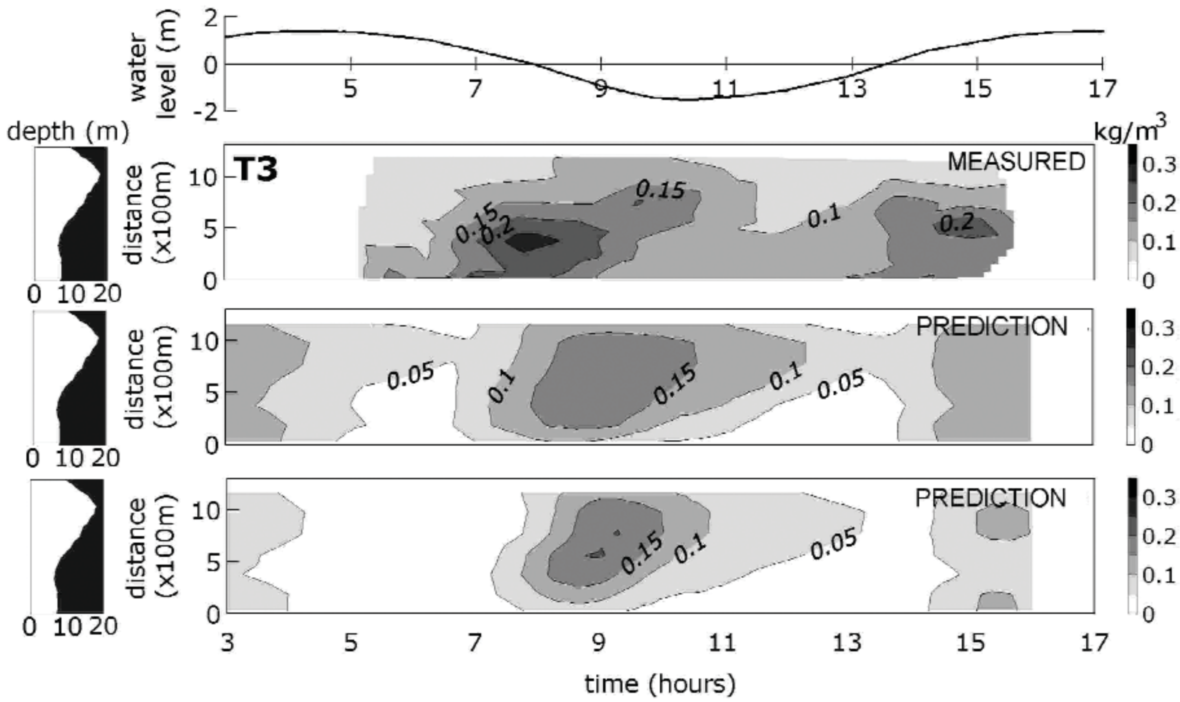

Fig 12: Measured (upper) vs. computed (BIJKER: middle, VAN RIJN: lower) variation in suspended sediment concentration at cross-section T3 (Piep) for dataset 3 (September 5, 2000)

5.2 Validation of cross-sectional transport load

As shown above the calibrated model is able to hindcast prominent characteristics of suspended sediment concentration during a tidal cycle. However considerable disagreement is observed in terms of local concentration magnitudes. In order to further assess the model quality with respect to the overall aim of the research project, being the simulation of morphodynamics, the prediction of total load transport at cross sections is investigated hereafter. By comparison with measured values an evaluation of the models ability to simulate the right amount of material transported over time is possible. The total load transport at a cross-section was integrated over time from the product of current velocity and suspended sediment concentration at all measuring stations. Data sets 1 (spring tide), 4 (mean tide) and 5 (neap tide) are chosen to represent different tidal conditions. The computed values generally are within the order of magnitude of the measured ones. The pattern of total load transport over a tidal cycle and the dependency of the amount of material transported on the tidal range is also captured (Fig. 13).

Acceptable agreement is generally achieved in cross section T1 (Norderpiep) for all tidal cycles. Here the average deviation of the predicted values with respect to those measured in the field is about 0.3 ton/s. About 50 % of data ranges within a factor 2. The model approach using the Bijker formula generally performs slightly better. At cross section T2 (Suederpiep) all simulations underestimate the measured values. Here major disagreement occurs for maximum tidal range; here the corresponding deviation is up to a factor of 4. The average deviation of the predicted values is about 1.5 ton/s. The average percentage of data within a factor of 2 is about 30 %. Simulated cross-sectional transport loads at cross section T3 show again a higher degree of conformity with measured values. The spring tide event is captured with a slight underestimation, whereas the values for the mean and neap tide are overestimated. The average deviation of the predicted values is less than 1 ton/s. The average percentage of data within a factor 2 is of about 35 %.

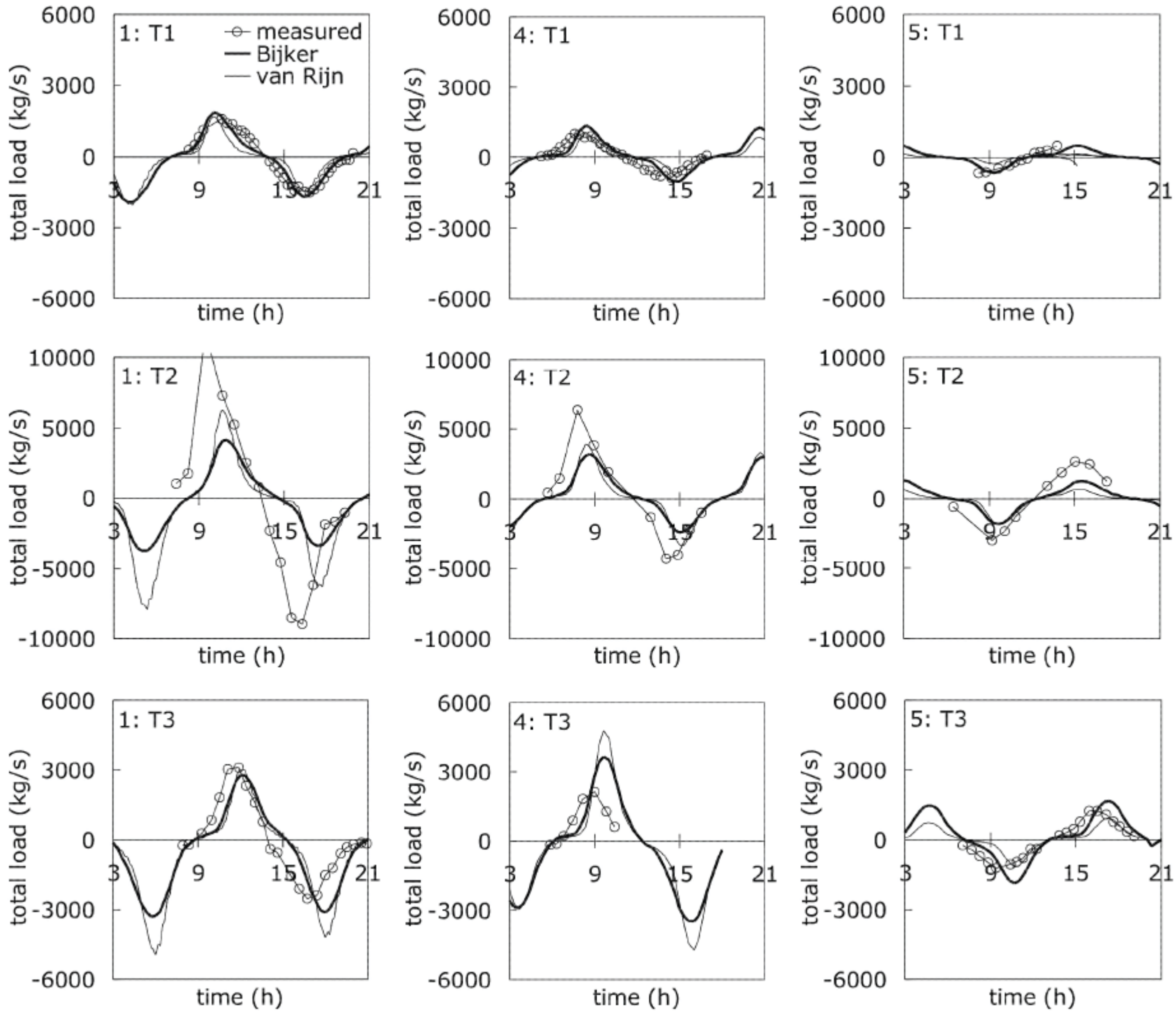

Fig 13: Validation of cross-sectional flux at the three cross-sections T1 (upper), T2 (middle) and T3 (lower row) for tidal cycles of dataset 1 (left), 4 (middle) and 5 (right column)

6. Conclusions

The set-up, calibration and validation of a numerical model for the simulation of sediment transport in the tidal channels of Dithmarschen Bight on the German Wadden Sea are described. In order to capture the complex suspended sediment dynamics the numerical solution of an advection diffusion equation has been applied, where the sink/source term is proportioned to the equilibrium suspended sediment concentration derived from algebraic formulations by BIJKER (1971) and VAN RIJN (1984). Sensitivity studies show the effect of input parameters on the calculated suspended sediment concentrations: The variation of the bed mean particle size within the range of samples from tidal channels resulted in differences in computed sediment concentrations within a factor 2. A clear effect of modified settling velocities from 0.1 mm/s to 4 mm/s was limited to periods around slack water. The empirical coefficients in the algebraic formulations may be considered as linear tuning factors as they proportionally influence the computed suspended sediment concentration. The bottom roughness term profoundly influences the computed suspended transport magnitude and is considered as a calibration parameter within its physical range. Bed roughness values of a few decimetres provide sediment concentrations within the range of the measured values.

It became clear that a pointwise model calibration to single position data could result in a high similarity between simulation and measurements at that specific location. However an over-calibration of models to single positions and periods might involve significant deviations for different conditions. In this case also the quality of underlying hydrodynamics has to be taken into account. As expected the model quality is reduced when uniform and constant parameters are applied throughout the domain. Generally the low background concentration around slack water is under-predicted and the maximum concentrations may be over-estimated by the model. A physical explanation can be given based on the analysis of instationary bed forms and bottom roughness of the domain (MAYERLE et al., 2002). They report that bed form dimensions vary throughout the tidal cycle from a smooth bed after slack water to bed forms of several decimetres after maximum tidal currents. As the numerical model used here applies a constant bottom roughness, it under-predicts the suspended concentrations at slack water and may over-estimate concentrations at times of high current velocities. However, the definition of spatially varying roughness requires rather extensive and costly surveys of the whole domain of interest and does not necessarily lead to better results (SUTHERLAND et al., 2004). Also the implementation of bed roughness predictors into transport models has not led to satisfactory results yet (DAVIES and VILLARET, 2003). It was therefore decided to apply uniform settings that produce best mean results at all measuring stations: A uniform bed roughness of 0.2 m was derived. Further improvement was achieved by the adaption of empirical coefficients in the algebraic formulations. The coefficient in the BIJKER formula, originally set to 5 to account for wave conditions was reduced here to a value of 3. The VAN RIJN formula, initially derived from flume experiments with coarser material (D_{50} > 200 µm) was adapted to the physical setting by increasing the relevant coefficient to a value of 2.

To overcome purely descriptive and qualitative evaluations, the model performance is assessed on the basis of the discrepancy ratio as proposed by recent publications: BAYRAM et al. (2001) give results of transport rates of six formulas at two locations of which 62 % to 84 % of the results are inside a factor of 5. Also CAMENEN and LARROUNDÉ (2003) compare calculated transport rates of five formulas to field data. In current-only situations they range from 60 % to 84 % inside factor 2. In situations with waves and currents only 18 % to 48 % yield this score. DAVIES et al. (2002) evaluated four non-calibrated sand transport models: Suspended sediment concentrations were hindcasted within a factor of 2 in 22 % to 66 % of the measured values, depending on the model formulation used. The model presented here resulted in 75 % of suspended sediment concentration data at all stations within factor 2 if using the Bijker formulation for datasets 1 to 3. This is more accurate than using the Van Rijn formulation, for which 57 % of data are within factor 2 for dataset 1 and 52 % of data are within factor 2 for dataset 2 and 3. Similar accuracy was achieved for the calibration data and independent data-sets used for validation. Thus the derived model set-up ranges well within published model quality. It should be noted that a large part of the deviations from parity is due to the under-prediction of the background concentration. This is of no relevance considering the application to morphodynamic simulations.

Also the Adjusted Relative Mean Absolute Error (ARMAE) of model results has been calculated to allow for future comparative studies. The mean ARMAE value for the twenty stations along the three-cross-sections, assuming 30 % accuracy, resulted to 0.17 kg/m³ for the Bijker formula and 0.28 kg/m³ for the Van Rijn formula.

It has to be pointed out, that all times and all sampling stations have been taken into account without weighting for the calculation of discrepancy ratios and errors: Highest discrepancies appear during slack-water times because of the under-estimation of the background concentration and generally at the channel banks.

In order to further assess the model quality the prediction of total load has been evaluated for different tidal conditions. The models ability to simulate the right amount of material transported over time leads to acceptable agreement in cross section T1 (Norderpiep) for all tidal cycles. The average percentage of data within a factor of 2 is about 50 %. At cross-section T2 (Suederpiep) all simulations underestimate the measured values. The average percentage of data within a factor of 2 is reduced to only about 30 %. Simulated cross-sectional transport loads at cross section T3 again show a higher degree of conformity with measured values. The average percentage of data within a factor of 2 is of about 35 %.

As profiling ship based measurements of hydro- and sediment dynamics are only practical in fair weather conditions, this study had to be restricted to those. It is understood that suspended sediment characteristics differ during higher energy conditions.

However, despite the somewhat basic model set up in terms of two-dimensional, depth averaged formulations and uniform and constant grain size and bottom roughness distributions, the model proved to be able to reproduce the main characteristics of suspended sediment transport across tidal channels of the Dithmarschen Bight using both BIJKER and VAN RIJN approaches.

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