HARBASINS Report:

Set-up of a morphodynamic model for the Ems-Dollard estuary

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1 Introduction

In coastal areas and particularly in estuaries or areas such as the Wadden Sea, there is a lack of procedures for the identification of ‘Heavily Modified Water Bodies’ (HMWB) according to the water framework directive (WFD) of the European Community. Aim of the investigation is to identify water bodies by comparable standardized methods, e.g. by applying mathematical models.

Currently, the assessment criteria concentrates on the area of impact, but this approach may be insufficient when alterations to current regimes may affect salinity levels and sediment transport in areas outside of the direct impact zone.

Aim of work package 4 “Hydro-morphological Impacts and Pressures” in the HARBASINS project is to generate process-based knowledge on these effects by high-resolution mathematical modelling in combination with the analysis of hydro- and morphodynamical parameters. Ultimately, it is intended to establish a modelling strategy to identify the spatial scale of potential HMWBs.

The Ems-Dollard estuary covering the area from the East Frisian Islands as far upstream as the tidal barrier at Herbrum in the Lower Ems is selected as the study area for this purpose.

The preceding HARBASINS report ‘Set-up of a hydrodynamic model of the Ems-Dollard Estuary’ (HERRLING, NIEMEYER 2007b) describes the set-up of the 2DH hydrodynamic model that serves as a basis for the calculations of sediment transport and bottom evolution. This report focuses on the implementation of the morphodynamical module into the existing hydrodynamical model.

The composition of the sediment bed is established based on available bottom sediment mappings. First, the initial distribution of different sediment fractions is determined. In a second step, the sediments are sorted and relocated in a preliminary simulation as a functioning of the exposure to tidal currents.

Some morphological and numerical input parameters are adopted of similar modelling investigations in literature, others are subject to a sensitivity analysis. The most influential parameters are tested and tuned to assess the influence of individual process refinements on the overall morphological behaviour.

The regular application of the morphodynamical model of the Ems-Dollard estuary and the evaluation of the spatial effect of solid structures, e.g. training walls, on the hydro-morphodynamics is subject of a subsequent report.

2 Area of investigation

The investigation area is located at the Dutch-German North Sea coast and covers the Ems-Dollard estuary as a whole. The seaward limit is close to the 20 meter depth-line in the outer estuary; the landward limit is at the tidal barrier at Herbrum in the Lower Ems. The study area is marked by all geomorphological features characteristic for this type of coastline: deep tidal channels and inlets, inter-tidal flats and the inner estuarine environment (Fig. 1). The morphology in the Ems-Dollard estuary is not stable. Natural and anthropogenic processes induce continuous sedimentation and erosion or the migration of tidal channels and gullies.

The actual mean tidal range in the Ems estuary has a bandwidth between 2.4 m at the island of Borkum increasing to its maximum of 3.5 m at Papenburg and decreasing upstream to 2.7 m at the tidal border at Herbrum (Fig. 2).

The salinity remains nearly constant at Borkum for mean tidal and freshwater conditions. Further upstream it reduces gradually up to Leer (Fig. 3). Contradictory, the concentration of suspended matter increases upstream of Borkum reaching its maximum of about 400 g/m³ between Jemgum and Leer (JONGE, 2000).

The bed sediment composition in the Ems-Dollard estuary varies between very high mud contents (> 75%) on the intertidal flats and the margins of the Dollard Bay to very low cohesive sediment contents (< 2%) in the estuarine inlet and the offshore areas. The content of cohesive sediments is strongly dependent on the degree of exposure to currents and waves. The remaining sediment percentage mainly consists of fine to coarse sands, while larger grain sizes are found in the tidal channels and the estuarine inlet.

In the section between Knock and Leerort fluid mud occurs in the near-bottom layer leading to density and viscosity variations over the vertical. The state of aggregation of fluid mud, changing between rather solid and fluid, and thus its viscosity are a function of the shear stresses exerted by the currents.

Bioconsolidation, has an important influence on the stability of the top sediment layer of the intertidal flats. Different biological organisms and their secretions affect the erosion behaviour by binding the top sediment layer.

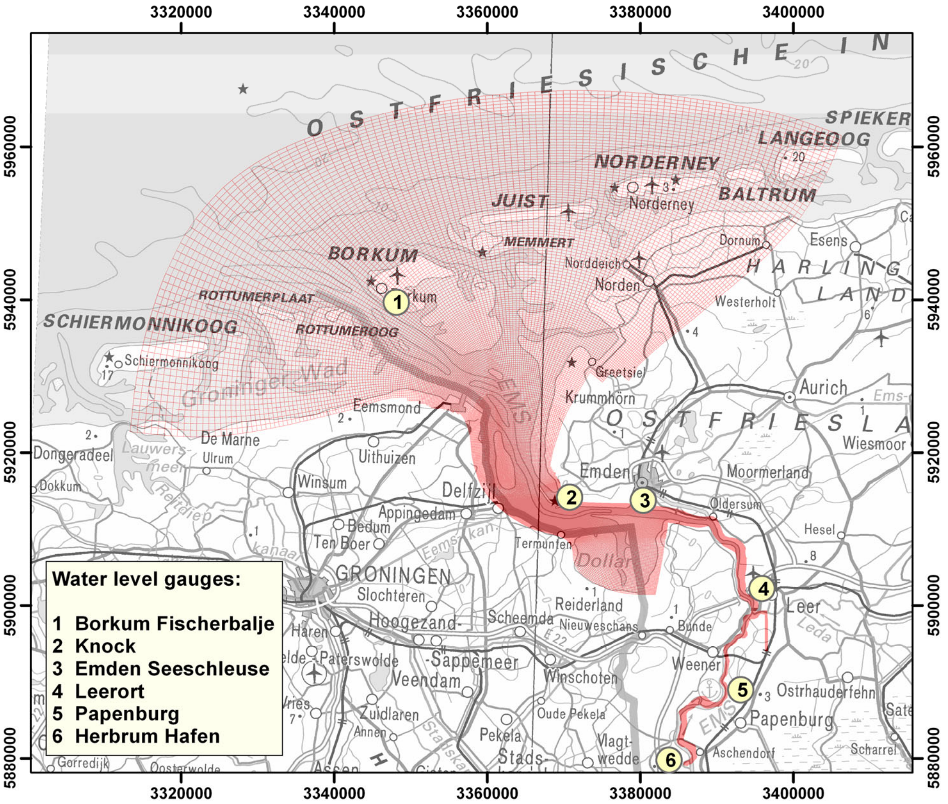

Fig. 1: Investigation area and location of water level gauges

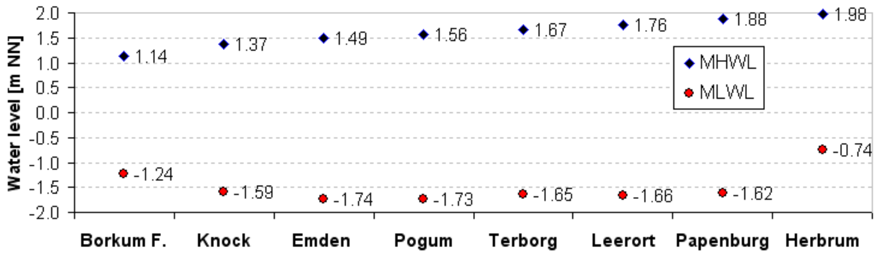

Fig. 2: Mean high water and mean low water levels (MHWL and MLWL) at gauges along the Ems-Dollard estuary for the period from 2001 to 2005

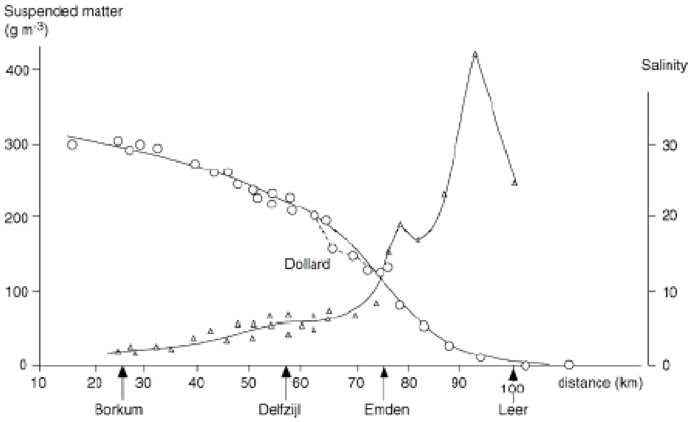

Fig. 3: Longitudinal gradient in suspended matter (mg/l) and salinity (ppt) (JONGE, 2000)

3 Set-up of the morphodynamic model

3.1 General

3.1.1 Conventions and definitions

The coordinate system used for the model generation and any horizontal positioning in the report is the German Gauss Krueger coordinate system, zone 3° E. The x-axis is pointing East, the y-axis is pointing North. The bottom depths are given in meters with reference to Normal Null (mNN), which is approximately Mean Sea Level (MSL). All time data in the report is referred to Greenwich Mean Time (GMT) based on conventions in the modeling system.

3.1.2 Modeling system and morphodynamical approach

The deterministic-mathematical model is set-up with the modeling system Delft3D (DELFT HYDRAULICS, 2006). The applied hydrodynamic module Delft3D-Flow is able to simulate two- or three-dimensional unsteady flow and transport phenomena resulting from tidal or meteorological forcing, including the effect of density differences due to a non-uniform temperature and salinity distribution. The program is based on three dimensional shallow water equations, the continuity equations and the transport equations for conservative constituents. The set of partial differential equations in combination with appropriate initial and boundary conditions are solved with a finite difference scheme on an orthogonal-curvilinear grid.

For this study, the hydrodynamical model is applied in the two-dimensional, horizontal mode, i.e. the modeled current velocities are depth-averaged and density driven flow in the vertical is neglected. Wave effects and meteorological boundary conditions, i.e. wind forcing, are neglected, too.

Sophisticated morphodynamical mechanisms as flocculation processes in the estuarine turbidity zone, bioconsolidation on intertidal flats affecting the resistance of the top sediment layer against erosion or the complicated fluid mud behaviour are not incorporated in the applied morphodynamical module.

For transport calculations of cohesive and non-cohesive sediments the additional system module Delft3D-SED (DELFT HYDRAULICS, 2006) is applied by its online-mode. It means that the movable sea bed is dynamically updated at each computational time step and the hydrodynamic flow calculations are always carried out with an updated bathymetry.

The transport of non-cohesive sand (e.g. clastic material of diverse grain sizes) and cohesive mud (e.g. clay and silt particles) is calculated by the use of different approaches. Bed-load transport processes of non-cohesive sediments, i.e. the transfer of sand fractions between the bed and the flow, are modeled using sink and source terms acting on the near-bottom layer. The implemented transport formula goes back to VAN RIJN (Van Rijn, 1993 in DELFT HYDRAULICS, 2006). Erosion and deposition of cohesive sediments characterized by very fine grain sizes smaller than 63 µm, i.e. the fluxes between the water phase and the bed, are modeled using the PARTHENIADES-KRONE formulations (Partheniades, 1965 in DELFT HYDRAULICS, 2006). Each time-step the source and sink terms model the quantity of sediment mass entering the flow due to upward diffusion and the quantity dropping out of the flow due to sediment settling. This change in mass is then translated into bed level change based on the dry bed density of each sediment fraction treated separately.

For calculating the morphodynamical evolution, a bed composition model approach different from the default is used. The default approach assumes a single layer uniformly mixed of different sediment fractions. This sediment column has no vertical discretisation of sediment contents; hence no difference in the availability of sediment fractions is made over time. The default approach is limited in intertidal areas, where in addition to the horizontal sediment differentiation, a vertically stratified bed composition is found. The bed composition approach used for the study at hand, the so called “layered bed stratigraphy”, makes use of multiple sediment layers and is described as following:
“A user-defined number of bed composition bookkeeping layers may be included to keep track of sediment deposits. When sediments are deposited, they are initially added to the top-most layer. After mixing in the top layer, sediments are pushed towards the bookkeeping layers beneath it. The bookkeeping layers are filled up to a user-defined maximum thickness, if this threshold is exceeded a new layer is created. If the creation of a new layer would exceed the maximum number of layers specified by the model user, layers at the bottom of the stratigraphy stack will be merged. Only sediments in the top-most layer are available for erosion. After erosion, the top-most layer is replenished from below” (DELFT HYDRAULICS, 2006).

3.2 Schematisation of the morphology in the Ems-Dollard estuary

3.2.1 Schematisation of the model bathymetry

Detailed bathymetrical information on the area of investigation is necessary to set-up the mathematical model. Data of recent topographic surveys has been required from the Federal Waterway Agency Emden and from the survey data base of the Coastal Research Station. The available data had been taken by different measuring methods such as common echosounding, side-scan-sonar and airborne laserscan. Data thus obtained was based on different reference and coordinate systems that had to be converted and processed using GIS software to further implement an adequate bathymetry in the modelling system (Fig. 4).

Basic data have been gained by side-scan-sonar in 2005 and by sounding in 2004 for sub- and intertidal areas in the inner and outer estuary. Whereas inter- and supratidal areas of the Lower Ems and parts of the Dollard Bay have been surveyed by airborne laser-scanning in 2005. Airborne laser-scanning produces data with an original resolution of 1 x 1 meters. The enormous amount of data had to be reduced by decreasing the data resolution to 5 x 5 meters in order to increase the effectiveness in data handling.

All bathymetric data was structured and interpolated onto the computational grid applying different interpolation methods depending on the spatial density of the bathymetric data in relation to the spatial resolution of the grid (Herrling & Niemeyer, 2007).

3.2.2 Schematisation of the sediment distribution and composition

The bed composition model follows a stratified multi-layer approach with sediment layers parallel to the bed surface. Three sediment fractions, one cohesive (silt) and two non-cohesive (fine to medium and coarse sands), are implemented by considering a spatial and vertical discretisation.

Available data of bottom sediments provide information about the spatial distribution and the content of cohesive sediments (< 63 µm) in the model area. The silt content of the outer estuary and the Dollard Bay is documented in the Sedimentatlas Rijkswaterstaat (2007). Bottom samples were taken and analysed between 1990 and 1996 in the Dutch Wadden Sea and the Dollard. On the stretch between Emden and Papenburg data was gained by a monitoring campaign of the Waterways and Shipping Board (WSA) Emden in June 2005 (Fig. 5).

Percentages of silt, representative for the cohesive sediment content, are extracted of available data and implemented in the sediment composition model. Due to the lack of sediment data upstream of Papenburg, the silt content is assumed to be in the order of 40% being in agreement with existing data at Papenburg. Offshore areas are set to a constant silt content of 3%.

The upper two sediment layers are composed of a thickness of two meters each and of a diverse mixture of cohesive and non-cohesive sediments accounting the mentioned cohesive contents. Non-cohesive sediments are assumed to have a median grain size of D50 = 350 µm matching with a medium grain size of sands found in the tidal inlet and the channels. Together with the upper-most transport-layer that is exerted to the current, these layers interact in the moment when sediment is pushed to or replenished from layers beneath. The sediment stock beneath these layers is a uniform sand-mixture of medium (D50 = 350 µm) and coarse (D50 = 800 µm) grain sizes with equal mass percentages. The coarse sand allows stabilizing the bed against maximal shear stresses, for instant in the tidal inlet, and prevents unrealistic erosion pattern.

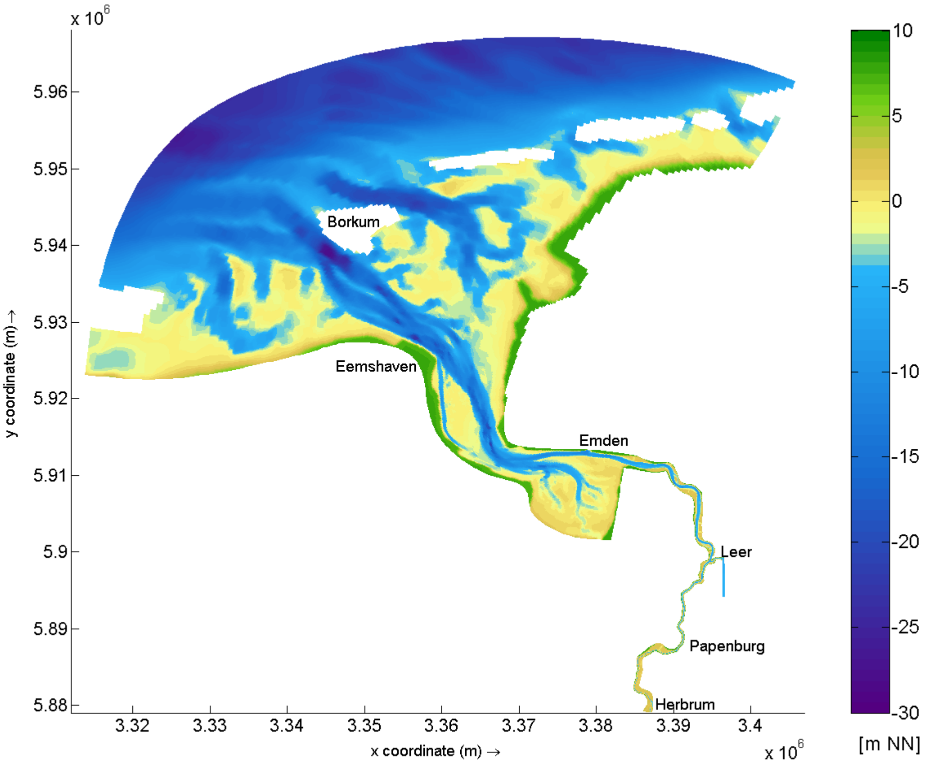

Fig. 4: Overview of the model bathymetry [m NN]

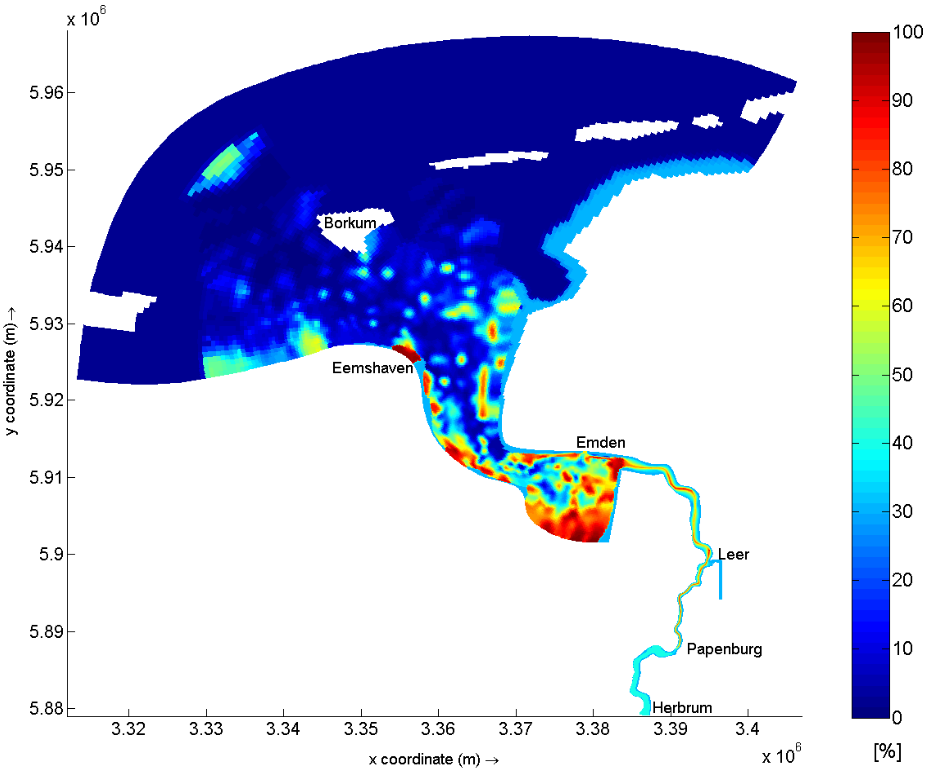

Fig. 5: Cohesive sediment distribution [%] applied for the initial model set-up based on silt contents of bed samples (Sedimentatlas Rijkswaterstaat, 2007 & WSA Emden, 2005)

3.2.3 Redistribution of sediments

The determination of the initial spatial distribution as well as the content of cohesive sediment fractions is originally based on point bottom samples. The area in between the sampled locations is spatially interpolated to obtain an overall mapping. This might be in disagreements with respect to the natural sorting of sediment grain sizes as a functioning of the bottom shape and hydrodynamic energy exposure.

A preliminary run of the duration of three simulated months has been performed to allow the redistribution and resorting of the initially composed sediment fractions according to the exerted influence of current velocities and bathymetrical gradients (Fig. 6). The redistributed sediment pattern point out that the cohesive sediment is relocated more towards the elevated margins of tidal channels and inlets, while the sand content increased in areas of high energy exposure (Fig. 6b).

Consecutive model runs are adapted for the newly gained bed composition of redistributed sediment fractions, but are applied by the original bed level, i.e. the original model bathymetry. The intention is to prevent unrealistic bottom evolutions in succeeding morphodynamical simulations.

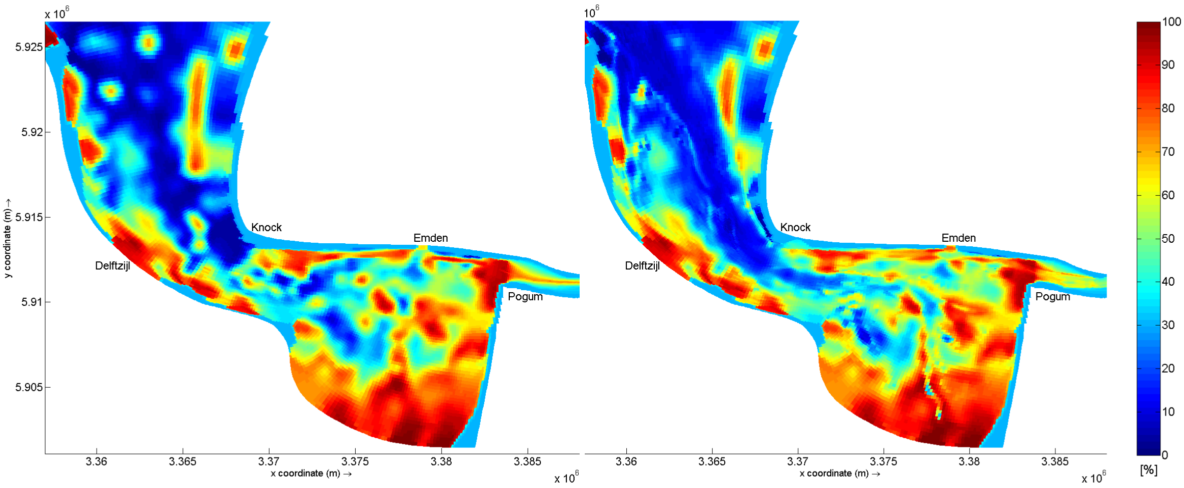

Fig. 6: Content [%] of cohesive sediment at (a) start of the preliminary simulation and (b) after the spatial redistribution of cohesive and non-cohesive bottom sediments being adopted for consecutive simulations as initial distribution

3.3 Setting of parameters in the morphodynamical model

Part of the schematization process is the setting of various numerical and physical parameters that control the sediment movement. A sensitivity analysis has been performed to determine the effect of the most influential morphological parameters. During this analysis, some parameters, e.g. the settling velocity or the critical shear stress for erosion have been varied to check their impact on the morphology. Following settings were assumed to perform best with respect to a reasonable relocation of sediments in the investigated area of the Dollard Bay and the Geise training wall (* sensitivity analysis is executed on these parameters):

General and hydrodynamical parameters:

- Horizontal eddy viscosity: a uniform value of 1 m^2/s
- Horizontal eddy diffusivity: a uniform value of 20 m^2/s
- Bottom roughness: according to the Manning formulation depth varying values are used ranging from 0.018 to 0.026 in the outer estuary and 0.012 to 0.019 in the Dollard embayment; along the Lower Ems depth varying Manning values are applied for particular blocks ranging from 0.011 to 0.015.
- Morphodynamical scale factor*: 20 [-]

Morphological parameters with respect to cohesive sediments:

- Settling velocity*: 0.47 mm/s
- Dry bed density: 380 kg/m^3
- Specific density: 2650 kg/m^3
- Critical shear stress for resuspension/ erosion*: 0.25 N/m^2 in the Dollard Bay and seawards, whereas a value of 0.5 N/m^2 in the Lower Ems to prevent undesired erosion.
- Critical shear stress for sedimentation: By using a uniform value of 100 N/m^2 a continuous sedimentation is allowed.
- Resuspension flux or erosion parameter*: 7E-05 $kg/m^2/s$

Morphological parameters with respect to non-cohesive sediments:

- Dry bed density: 1600 kg/m^3
- Specific density: 2650 kg/m^3
- Median sediment diameter for fine/medium sand fraction*: $D50 = 350$ μm
- Median sediment diameter for medium/coarse sand fraction*: $D50 = 800$ μm

4 Summary

The existing hydrodynamic model of the Ems-Dollard estuary is extended by the system module Delft3D-SED (DELFT HYDRAULICS, 2006) to enable further morphodynamical investigations.

The configuration applied is based on three sediment fractions, one cohesive (< 63 µm) and two non-cohesive. The latter have a median grain diameter D50 of respectively 350 µm (fine to medium sand) and 800 µm (coarse sand). The bed composition model follows a stratified multi-layer approach that allows a discretisation of sediment characteristics on a spatial as well as vertical scale.

The implementation of the morphodynamical module contains the setting of different morphological input parameters, e.g. the initial spatial distribution and the content of sediments in the model area. The initial settings are based on available sediment mappings. A preliminary simulation is performed to allow the spatial redistribution and sorting of the initially composed sediment fractions with the purpose to prevent unrealistic bottom evolutions within succeeding simulations.

Relevant morphological parameters as the settling velocity, the critical shear stress for erosion and the resuspension flux are determined and fine-tuned by a sensitivity analysis in order to reproduce reasonable sediment movements. The model area covers the entire Ems-Dollard estuary, but it is focused on the individual process refinement in the area of the Dollard Bay and the Geise training wall, because this spot is focused in subsequent investigations.

The established model is limited by sophisticated hydro-morphodynamical interactions in the Lower Ems and in particular in the turbidity zone. Here, deeper insight is necessary to improve the overall morphodynamical prediction.

5 Literature

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