HARBASINS Report:

Reconstruction of the historical tidal regime of the Ems-Dollard estuary prior to significant human changes by applying mathematical modeling

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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 straightforward procedures for the objective identification of 'Heavily Modified Water Bodies' (HMWB) according to the water framework directive (WFD) of the European Community. The aim of the investigation is to identify such areas using the application of hydro-morphodynamical models as basis for the evaluation of comparable assessment criteria.

For the time being, 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 the immediate zone of impact.

The aim of work package 4 ("Hydro- and Morphological Pressures and Impacts") within 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.

To identify waterbodies that had experienced significant changes in their tidal regime due to anthropogenic interferences, it seems reasonable to compare prevailing hydrodynamical parameters to those of historical states. Continuous current measurements of historical states hardly exist or are temporally and spatially delimited in most cases.

For this reason, the hydrodynamic regimes in the Ems-Dollard estuary respectively before and after the main human impacts, i.e. streamlining and deepening of the Lower Ems, are modelled by applying on the one hand the bathymetry of the year 2005 and on the other hand the reconstructed bathymetry due to data of the period between 1923 and 1952. The aim is to evaluate and compare the physical parameters as i.e. current velocities and tidal volumes. Significant changes in between the mentioned states can then be assessed with respect to the ecological impact.

The preceding HARBASINS report "Set-up of a hydrodynamic model of the Ems-Dollard Estuary" (HERRLING, NIEMEYER 2007b) describes the set-up of the model for the actual state incorporating bathymetrical data of the year 2005. The report in hand focuses on the set-up of a 2DH hydrodynamical model that reconstructs the hydrodynamic regime prior to 1950. Main human impacts as the streamlining and deepening of the Lower Ems happened in the decades after 1950.

The set-up of the model comprises the reconstruction of the historical model bathymetry, the open boundary conditions and the setting of different input parameters. The model is calibrated by fine-tuning numerical and physical parameters, e.g. the bottom roughness. The quality of the modelled hindcast is compared and verified by available historical water level records at gauge locations along the estuary for a period in July 1937.

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. In the year 1898 this tidal barrage was built at about 50 km upstream of the Dollard Bay. 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).

In the 1930's, the mean tidal range in the Ems estuary had a bandwidth between 2.2 m at the island of Borkum increasing to its maximum of 3.0 m at Emden and decreasing upstream to 2.4 m at the tidal border at Herbrum (Fig. 2).

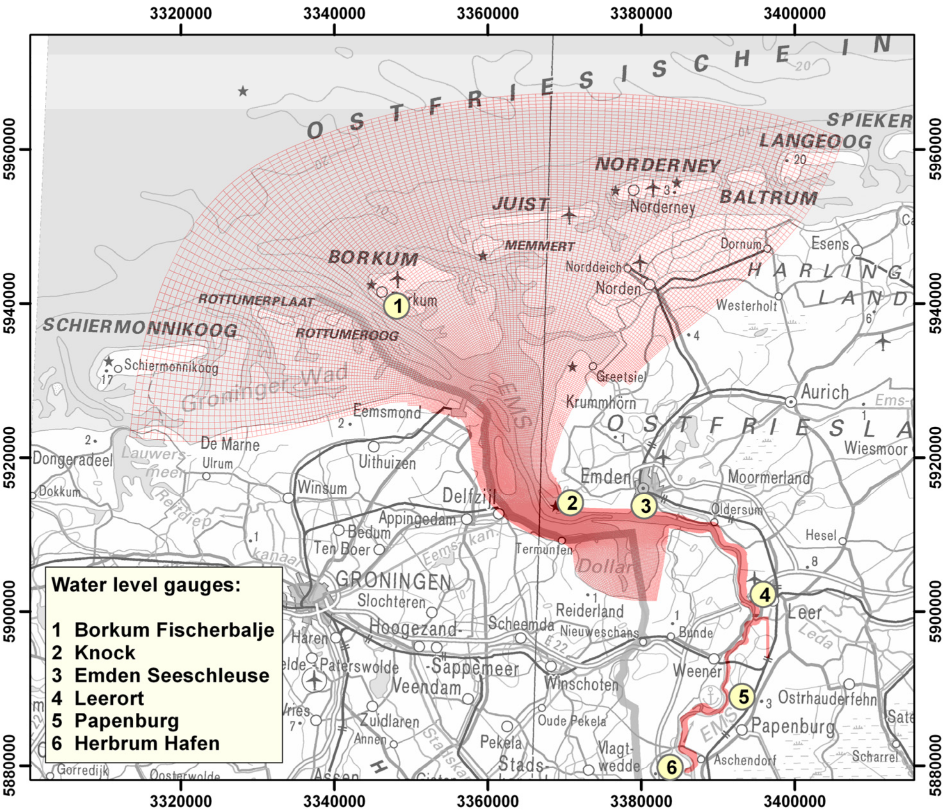


Fig. 1: Area of investigation (grid extent) and water level gauges

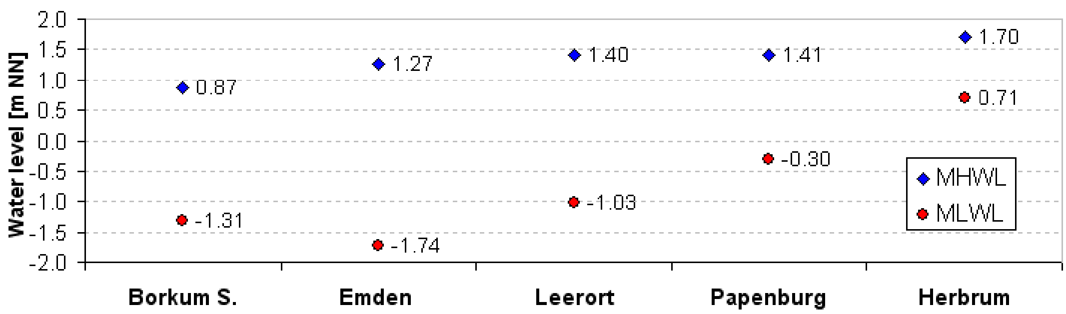


Fig. 2: MHWL and MLWL observed at Borkum Suedstrand, Emden, Leerort and Papenburg for the period from 1933 to 1937 and at Herbrum from 1936 to 1940

3 Set-up of the historical configuration of the model

3.1 Reconstruction of the historical bathymetry

3.1.1 Available bathymetrical data

Detailed bathymetrical information on the area of investigation is necessary to set-up the mathematical model. The aim was to reconstruct a model bathymetry representing the morphological state prior to significant human alterations in the Ems-Dollard estuary. Historical marine charts and maps due to topographic surveys have been required from authorities and local waterway agencies. The criteria for the final selection of the data is the date of origin and the density of the bathymetrical information. (Tab.1)

Solid constructions as the Geise training wall in the Dollard Bay or groins in the Lower Ems that are intended to stabilize the channel for navigational purpose had been constructed by end of the 19th and begin of the 20th century. Unfortunately, bathymetrical data prior to these flow alterations is not available or does not match the required quality.

The oldest data covering the whole model area is available for the period between 1923 and 1952, whereas most data is dated to the 1920's and 1930's (Fig. 3). The data is found to be adequate to model the hydrodynamical state prior to the main dredging activities starting by 1960 in the Lower Ems that caused significant changes in the system.

Depth contours and points were digitized manually in a very time consuming way from marine charts covering the Dollard, the outer estuary and the East Frisian Islands. Data formats of inconsistent reference and coordinate systems were converted and processed using GIS software to further implement an adequate bathymetry in the modelling system. All bathymetric data were structured and interpolated onto the computational grid applying different interpolation methods depending on the spatial density of the data points in relation to the spatial resolution of the computational grid.

Data in the Lower Ems is taken by soundings of the navigational channel in cross-sectional profiles successively at a non-uniform distance of 100 to 700 meters depending on the course of the channel (Fig. 4). The missing depth information in between the cross-sections is reconstructed by applying a linear interpolation method in longitudinal (flow) direction. The method uses the computational grid points as support points for the interpolation.

Tab. 1: Description and origin of historical topographic data

Area covered	Date of origin	Type of records	Recorded by	Provided by
East Frisian Islands	1912, corrected 1923	depth points & contours	German Marine	Federal Agency for Navigation and Hydrology
Outer Ems	1913, corrected 1926			
Mouth of Ems	1936, corrected 1941			
Dollard	1952	depth contours	Rijkswaterstaat Rijksinstituut voor Kust en Zee (Netherlands)	
Lower Ems (Papenburg to Pogum)	1933	cross-sectional profiles	Waterway Agency Emden	
Lower Ems (Papenburg to Herbrum)	1927	cross-sectional profiles	Waterway Agency Meppen	

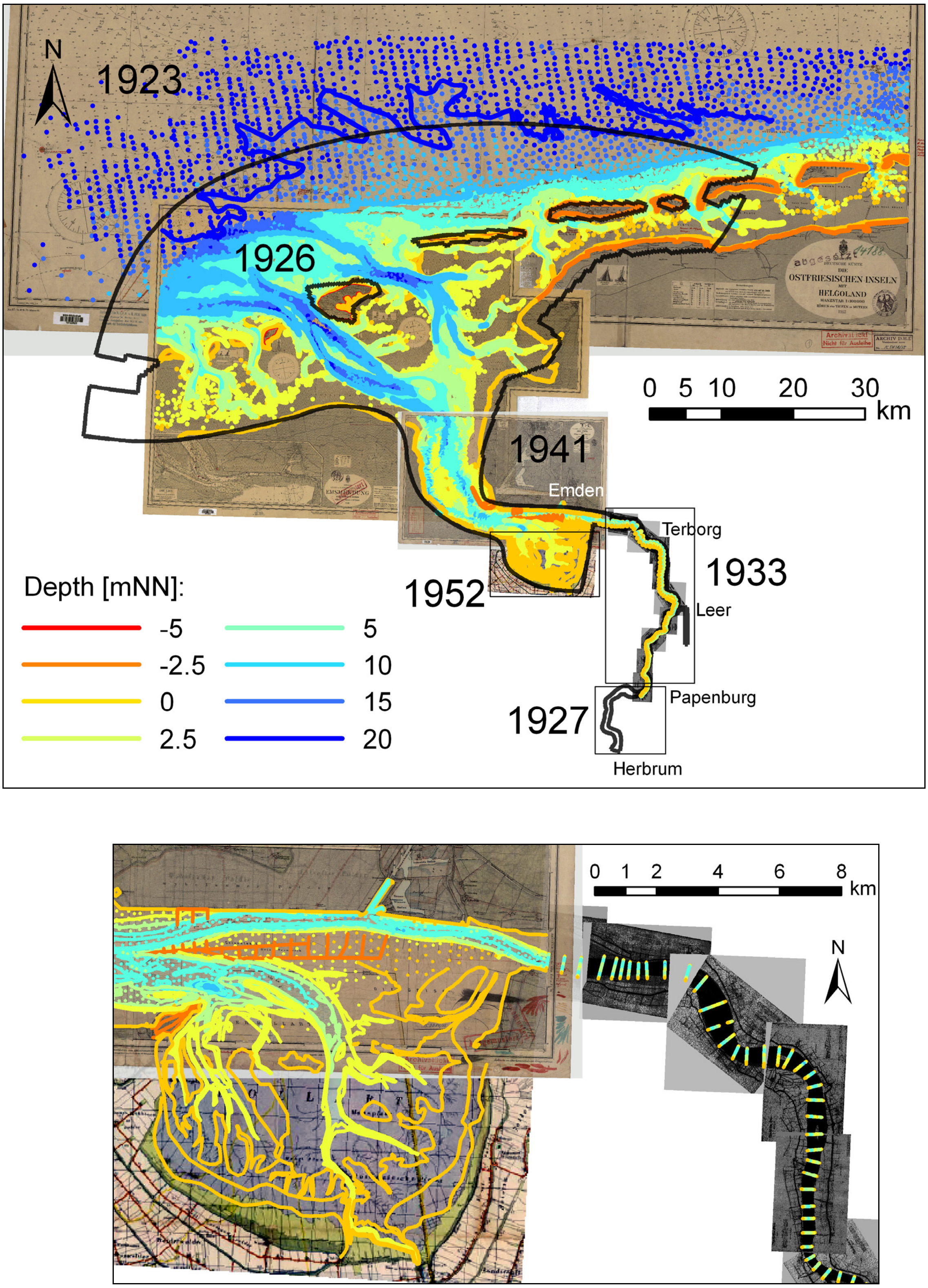


Fig. 3: Visualisation of topographic data digitized from historical nautical charts a) displayed for the whole model area b) highlighted for the Dollard Bay and parts of the Lower Ems

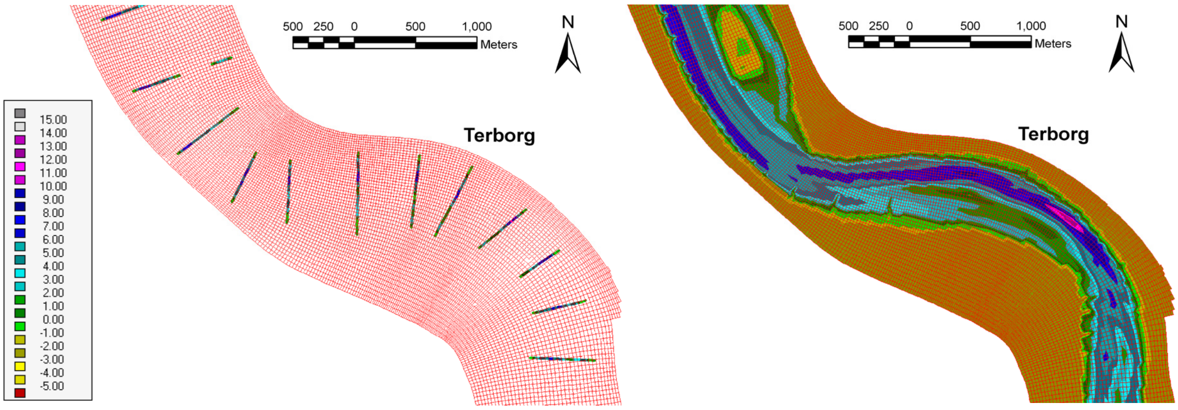


Fig. 4: Visualisation of cross-sectional data digitized from historical nautical charts a) on the computational grid before the interpolation b) after the linear interpolation along grid lines

3.1.2 Schematization of the bathymetry

Bottom depths range from about -25 mNN at the tidal inlets and the seaward boundary of the model to a fictive elevation of +9 mNN landwards of the main dykes (Fig. 5).

In the Lower Ems, the model bathymetry covers the sub- and intertidal areas, i.e. bottom depths below Mean High Water (MHW). The purpose of the soundings taken in former times was to survey the fairway. Data thus obtained do not cover supratidal areas. Mappings of only a few cross-sections show records above MHW. For this reason, unmapped supratidal areas in the model domain were set to a constant depth value of 3 meters over NN (~ 1.5 m over MHW). As a consequence, hydrodynamical investigations in the Lower Ems are restricted to the calculation of average tidal conditions. Simulations of storm surges that would cause the flooding of supratidal areas cannot be carried out.

The river Leda, a tributary stream of the Ems, is schematized up to its tidal limit by a rectangular channel. Reason for this schematization was the exceedance of the maximal number of computational points. The extension and the total volume of the channel are approximated by considering the representative tidal prism of about 3 millions cubic meters. The size and volume of the tributary system has been further adjusted in the calibration process.

Two former meanders located at Wilgen and Vellage in the section between Herbrum and Papenburg are still connected to the main stream and are affected by the tide. These sidearms function as polder areas and have a significant influence on the tidal regime in the upper estuary and have thus been substituted by representative basins in the model bathymetry.

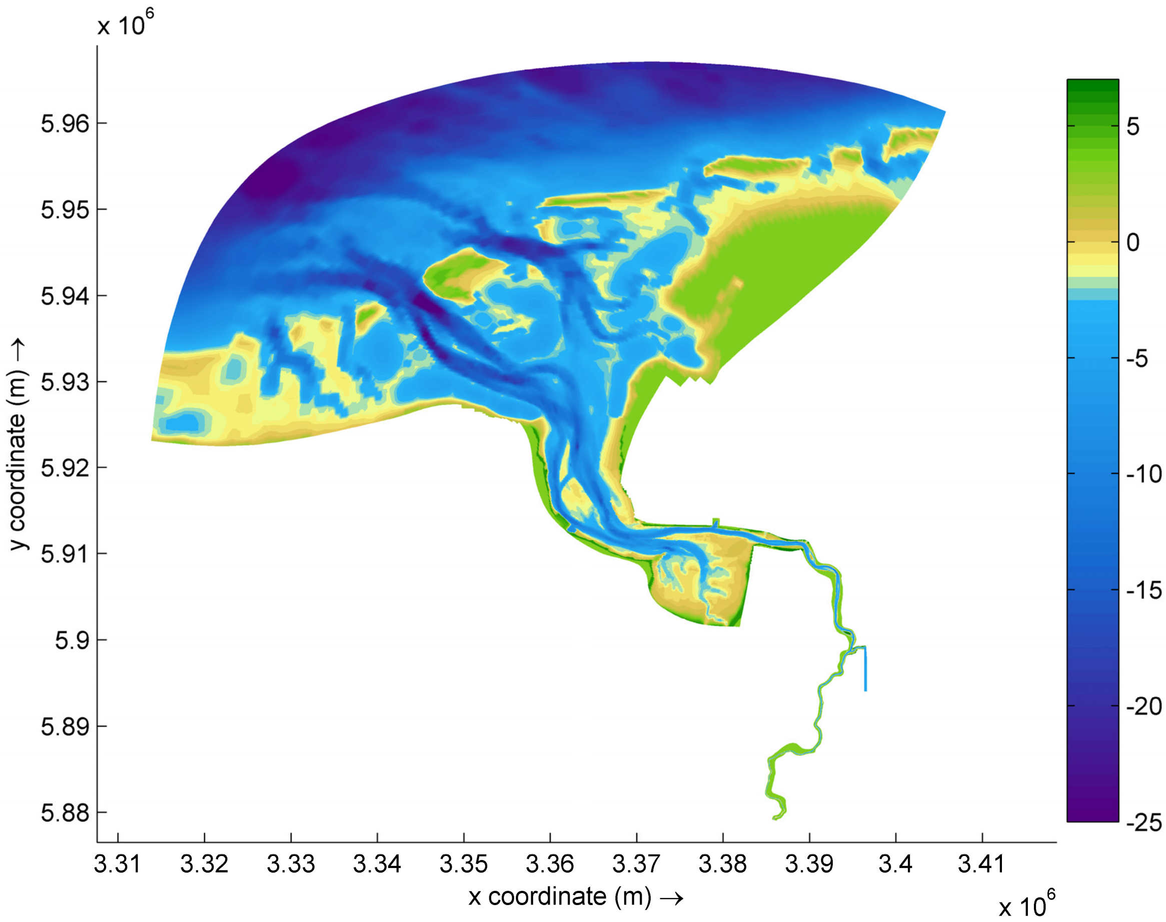


Fig. 5: Schematization of the historical model bathymetry

3.2 Open boundary conditions

3.2.1 Sea boundary conditions

To obtain the “historical” tidal forcing at the open offshore boundary of the Ems-Dollard Model, the model is nested into the existing “German Bight Model” (WL|DELFT HYDRAULICS 1997). This overall model covers the coastal waters from Terschelling in the Netherlands to North of Esbjerg in Denmark. The computational grid of the German Bight Model is presented by a blue grid; the extension of the nested Ems-Dollard Model is shown in red colour (Fig. 6). For a detailed description of the nesting methodology it is referred to the report: “Set-up of a hydrodynamic model for the Ems-Dollard estuary” (HERRLING, NIEMEYER, 2007 b).

The water levels at the sea boundary (pink line) of the German Bight Model are prescribed by 29 tidal constituents that in turn are gained from a nesting procedure with the larger “North Sea Continental Shelf Model” (VERBOOM et al. 1992). Generally, this model configuration will allow the computation of tidal predictions and hindcasts for any given time period. But the German Bight Model was set-up and calibrated due to prevailing boundary conditions of the 1990’s. The application for tidal hindcasts of the 1930’s would incorporate uncertainties. Errors might arise due to changes in morphology and the secular sea level rise. The effect of changes in the morphology might be insignificant as the sea boundary of the nested Ems-Dollard Model (where the boundary conditions are generated) is located in deep waters, where the morphology has minor effects on currents and water levels. But increased water levels due to the secular sea level rise can be estimated by approximately 0.15 meters from the 1930’s to the 1990’s. The water level boundary conditions for the year 1937, generated by the German Bight Model, are therefore reduced by 0.15 meters.

The selected type of boundary conditions, i.e. the tidal forcing obtained from the overall German Bight Model, only represents the astronomical tide without any meteorological effects. Thus the observed tide, i.e. measured water levels, will to some extend differ from the astronomical tide generated by the model due to the influence of wind, variation in atmospheric pressure, etc. According to this, the time period selected for tidal predictions in the calibration process is characterized by moderate meteorological conditions with low wind speeds of less than Beaufort 4.

It has to be noted, that simulations for extreme meteorological conditions resulting in local set-up or set-down due to wind forcing need a different approach for the sea boundary conditions.

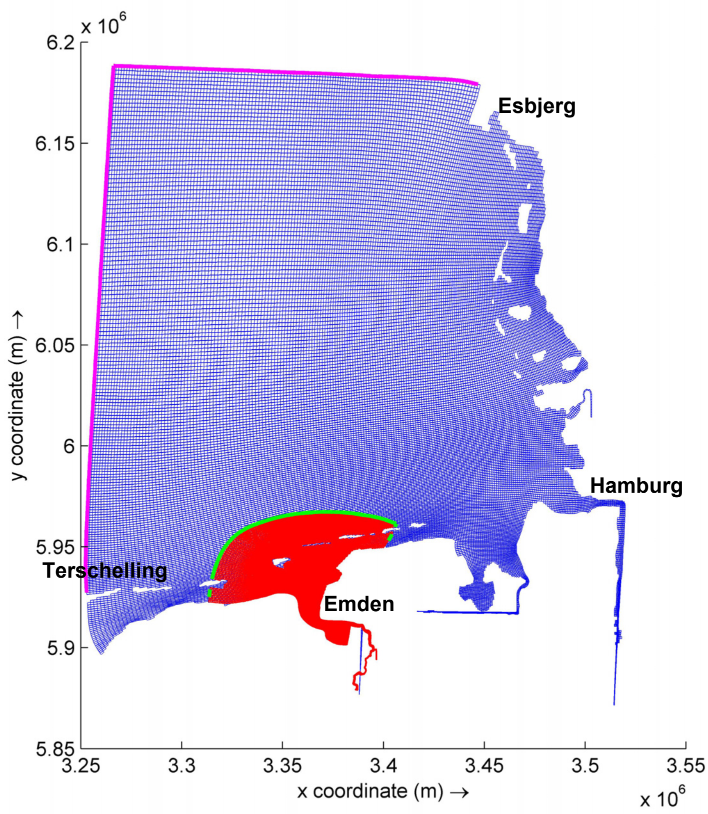


Fig. 6: Nesting of the Ems-Dollard model (red) into the overall German Bight model (blue)

3.2.2 River discharges

The upstream discharges of the rivers Ems, Leda and Westerwoldsche Aa were derived from general available data bases. The mean maximum, mean and mean minimum discharges of the river Ems are respectively 375 m^3/s, 81 m^3/s and 16 m^3/s based on averages of long-year measurements (German Yearbook of Hydrology, 2005). The mean yearly discharges of the river Leda and Westerwoldsche Aa are 25 m^3/s and 10 m^3/s, respectively.

For the calibration period from 06.07.1937 to 08.07.1937, the prevailing discharges are taken from observations. For this period the discharges of the Ems, Leda and Westerwoldsche Aa are respectively 19 m^3/s, 6 m^3/s and 2 m^3/s and hence much lower than the yearly averages.

3.3 Setting of model parameters

Part of the schematization process is the setting of various numerical and physical parameters. During the calibration process, some parameters, e.g. the bottom roughness and the time step were varied to check their impact on the calculated water levels. The following settings were assumed to perform best and are therefore applied for the Ems-Dollard Model:

- Water density: a uniform value of 1023 kg/m³, corresponding with a water temperature of 10°C and a salinity of 30 $^{0}/_{00}$
- Acceleration of gravity: 9.813 m/s²
- Corriolis parameter: corresponds to the latitude of 53.5° N
- Horizontal eddy viscosity: a uniform value of 2 m²/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 fixed Manning values are applied for specified blocks ranging from 0.016 to 0.026.
- Numerical time step: 30 seconds

4 Model calibration

The aim of the model calibration is to adjust the model setting in such a way, that the simulated magnitudes at specific locations in the model domain match as best as possible with observations at corresponding locations in nature. To achieve this objective, a number of physical and numerical model parameters have to be modified and tuned. The variation of the parameters has to be kept within realistic ranges and assumptions.

During the calibration process more than fifty simulations have been carried out with changes in bed roughness, model geometry and bathymetry, discharges and a number of other numerical and physical parameters and settings. The computational effort is high considering the computation time of about 8 hours for each calibration run.

A previous model calibration was carried out for the Ems-Dollard Model applying the bathymetry of the state of 2005 (HERRLING, NIEMEYER, 2007 b). Most settings of numerical and physical parameters have been adapted to the underlying model state. However, due to the application of a different bathymetry (state of the 1930's), the bottom roughness is partly adjusted.

The bottom roughness is implemented in the model by the Manning formulation. The model area was subdivided into adjoining sections with respectively constant roughness values. Sections more seawards were characterized by high Manning values, i.e. increased bottom roughness, and sections along the inner estuary by low Manning values, i.e. resulting in rather low bottom roughness. An extensive calibration was needed to figure out the most promising Manning value for each section.

To further improve the model outcomes, the bottom roughness values were related to the bottom depth. As a result, the bottom roughness values within each section vary spatially with the bottom depth. Deep water areas are exposed to lower roughness values than shallow water areas.

In the framework of the set-up of the historical and the actual model state, the bottom roughness has been adapted and calibrated separately for each state in order to achieve global agreement between modeled and observed water levels along the estuary.

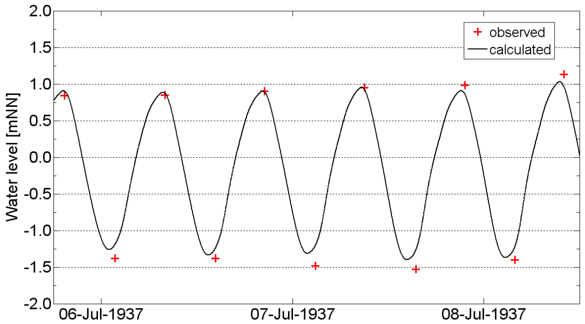
Comparing the spatially varying bottom roughness values between the model states, it turned out that both bottom roughness schematizations are generally similar in the outer estuary and on the intertidal flats, whereas in the Emder Fairway and along the Lower Ems the bottom roughness of the actual state is to some extent reduced. For the section from Herbrum to the Knock, the overall mean differences between the bottom roughness schematizations of 1937 and 2005 are in the order of 0.005 with respect to the Manning formulation, accordingly by a value of 30 referred to the formulation after Chézy.

The time period from 05. July 1937 18 p.m. to 08. July 1937 12 a.m. (60 hrs) was selected for the calibration process. This period is characterized by meteorological conditions with calm winds of less than Beaufort 4 to avoid as far as possible the influence of meteorological effects on the water levels.

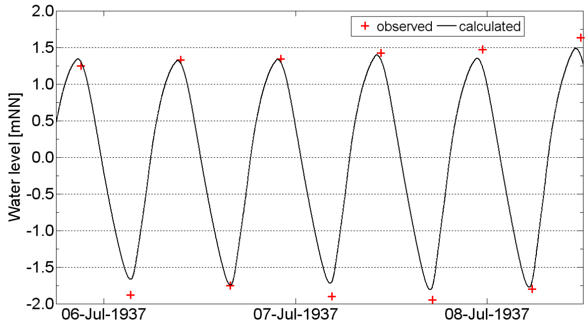
Only results of the simulation with the most promising setting of parameters are presented in order to delimit the total amount of figures. Computed and observed water levels are compared at seven tidal gauge locations along the estuary (Fig. 7a to 7g).

Average discrepancies between modeled and observed water levels are in the order of 0.1 meters with maximal discrepancies of up to 0.25 meters. The tidal phase of the computed tide shows generally a good agreement with the measured peak values.

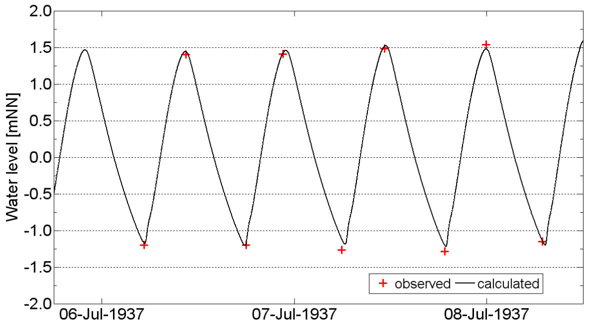
Relative discrepancies between the computed and the measured tidal signal at Borkum are found in a similar extent at other gauge locations along the estuary. This leads to the assumption, that most of the disagreement between the modeled and the observed tides is due to sea boundary conditions. Inside the estuary, the propagation of the tidal wave is satisfactorily.



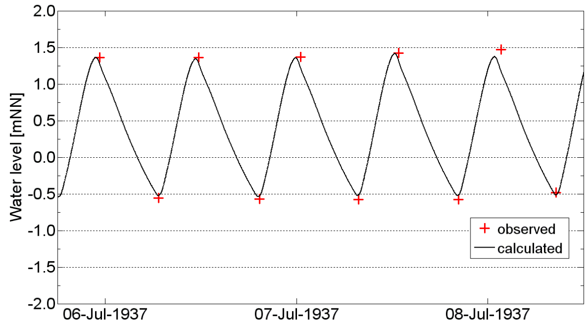
Borkum



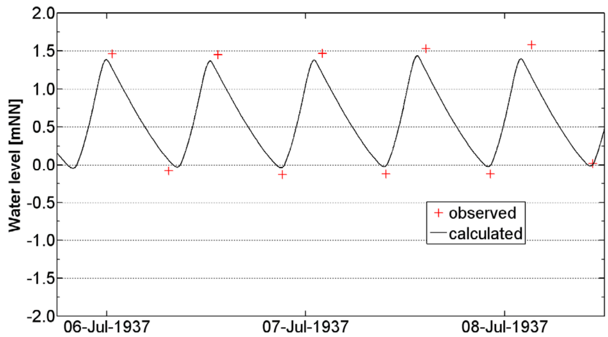
Emden



Leerort



Papenburg



Herbrum

Fig. 7: Comparison of observed and computed water levels at tidal gauge locations along the Ems-Dollard estuary for the period of 06. - 08. July 1937

5 Summary

The hydrodynamic model of the Ems-Dollard estuary is established by applying the vertically averaged version of the modeling system Delft3D (DELFT HYDRAULICS, 2006).

Historical data of topographic surveys and marine charts of the period between the years of 1923 and 1952 is used to reconstruct and implement a historical bathymetry in the model. The reconstruction represents the morphological state prior to the main human impacts like the deepening of the Lower Ems.

The Ems-Dollard Model is driven by water level and current velocity time series obtained by a nesting procedure with the existing overall German Bight Model. The sea boundary conditions having obtained by the nesting have been corrected accordingly due to common estimations based on the secular sea level rise. The imposed tidal signal representative for the year 1937 is selected due to the availability of water level measurements needed for the calibration of the model.

Hydrodynamic simulations have been performed and computed water levels were compared to historical observations of existing water level gauges along the estuary. The comparison with measured high and low water peaks showed good agreement for all available gauge locations. The discrepancies in the vertical tide are generally in the order of 0.1 meters with maximal differences of up to 0.25 meters.

The historical configuration of the hydrodynamic model of the Ems-Dollard estuary will be applied for hydrodynamical hindcasting, i.e. the reproduction of the hydrodynamic regime prior to the main human impacts, and the comparison of hydrodynamic parameters with respect to the model state of 2005.

6 Literature

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