EVALUATION OF DESIGN WATER LEVELS AT THE EMS-DOLLARD ESTUARY CONSIDERING THE EFFECT OF A STORM SURGE BARRIER

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In the Ems-Dollard estuary at the southern North Sea coast a revaluation of design water levels along the German dykes has become necessary, since the safety margin for sea level rise was increased by 25 cm due to a decision of the Lower Saxon Ministry for Environment and Climate Protection. The upstream part of the estuary is protected against high storm surges by a storm surge barrier. The closure of the barrier effects downstream surge water levels due to partial reflection. Deterministic-mathematical modeling is applied to evaluate design water levels and design wave run-up. Three severe storm surge events have been hindcasted by a cascade of three hierarchical models from the Continental Shelf over the German Bight into the area of interest. The models are forced by non-stationary and spatially varying data of atmospheric pressure, wind velocities and directions available of meteorological model investigations. The verification of the storm surge model with water level observations yields good agreements. With respect to legal boundary conditions, the single-value-method is applied to determine the highest expected high water level at Emden. Starting from this target water level, the wind velocities in the meteorological boundary conditions are increased with the aim to increase the surge level at the coast and to match the predetermined design water level at Emden. The responding water levels in the Ems-Dollard estuary assign the new design water levels.

Keywords: storm surge modeling; design water level; Ems-Dollard estuary; North Sea, single-value-method; storm surge barrier; Delft3D

INTRODUCTION

The requirement of the German federal state of Lower Saxony with respect to a new safety margin for sea level rise acceleration has been increased of formerly 25 to now 50 centimetres for a time horizon of 100 years as by the evaluation of design water levels. At open coastlines this supplement can be added to previously investigated design water levels, but in estuaries being subject to complex interactions a revaluation of design water levels is necessary. Furthermore, the upstream part of the Ems-Dollard estuary at the southern North Sea coast (Fig. 1) is protected from flooding by a storm surge barrier. At the closing of the barrier the storm surge is partly reflected and effects the downstream water levels. Deterministic-mathematical modelling is applied with respect to both technical state of the art and legal boundary conditions to evaluate design water levels and design wave run-up in order to verify the design height of the dykes along the outer Ems-Dollard estuary. In this paper, the full approach of the evaluation of wave run-up is omitted but the methodology is shortly mentioned.

STUDY AREA

The Ems-Dollard estuary with an area of about 500 km² is located at the southern North Sea coast (Fig. 1). The estuary can be divided into the Dutch-German Outer Ems from the East Frisian island Borkum to the mouth of the Lower Ems at Pogum with a length of 60 km and the Lower Ems about 70 km upstream until the artificial tidal barrier at Herbrum. In the year 1898 this tidal barrage was built for navigational purpose. The entire coast is lined by dykes preventing the lowlands against flooding in case of a storm surge. The study area is marked by all geomorphological features characteristic for this type of coastline: deep tidal inlets, tidal channels and intertidal flats. The surface sediment in the tidal channels and on the tidal flats consists mainly of sands with varying proportions of silt and clay. Water levels are recorded at several fixed tidal gauges along the estuary. The 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 in the upper estuary and decreases further upstream to 2.7 m at the tidal border. The mean maxima, mean and mean minima discharges of the river Ems are respectively 375 qm/s, 81 qm/s and 16 qm/s with respect to long time series. Regarding the course of storm surges, two impacts in the Lower Ems are of significance: The estuarine waterway had been deepened several times since 1984 and is maintained and dredged to allow the transfer of cruise ships being built by a shipyard at Papenburg on the one hand and the construction of the storm surge barrier on the other. The deepening of the waterway reduced the hydraulic resistance in the Lower Ems with the resulting effect of increased water levels during storm surges (Niemeyer 1997). Since 2001, the storm surge barrier at Gandersum turns high storm surge levels in the Lower Ems. The coast between Eemshaven and Nieuwe Statenzijl

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belongs to the Netherlands. The German dykes at the eastern coast of the Dollard Bay between Nieuwe Statenzijl and the storm surge barrier and northerly of the Dollard Bay between Knock and the storm surge barrier are subject of the revaluation.

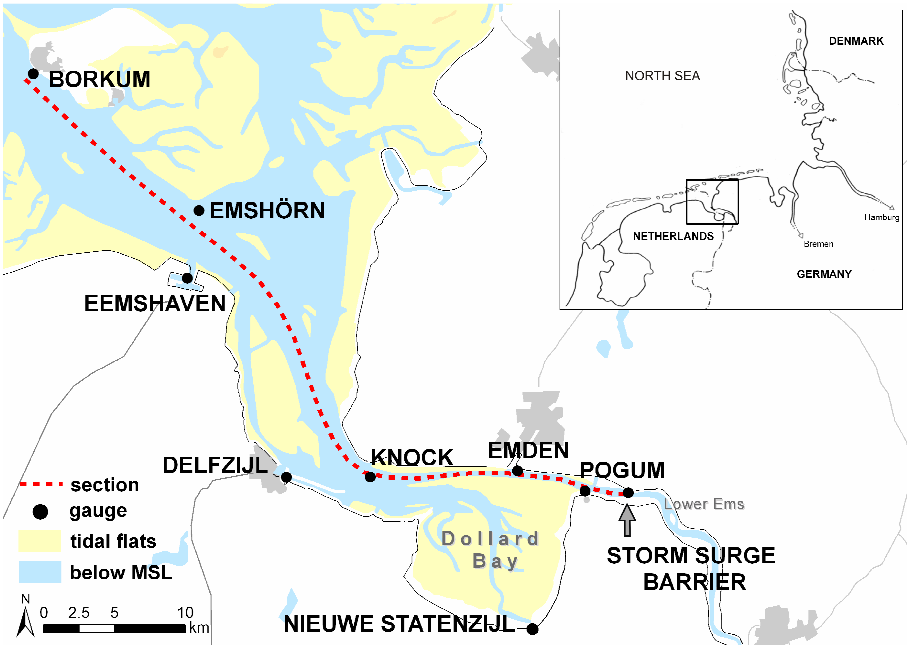


Figure 1. Investigation area in the Ems-Dollard estuary at the southern North Sea coast.

MODEL SET-UP

The software suite Delft3D (Deltares 2009) is applied to set-up and run high resolution process-based storm surge models in a two dimensional, depth-integrated configuration. The deterministic mathematical model solves the three-dimensional shallow water equations and the continuity equations by use of an implicit finite-difference-scheme. Non-stationary hydrodynamic processes driven by tidal forces and meteorological boundary conditions are solved on a staggered curvilinear model grid. Hereafter the model set-up and the boundary conditions are specified.

Hierarchical cascade of storm surge models

Storm surge modelling requires a hierarchical cascade of models starting far out of the area of interest with decreasing spatial dimension and increasing numerical resolution (Fig. 2). The largest model with a grid resolution of 8 km covers the Continental Shelf and parts of the North Atlantic Ocean. Harmonic constituents are applied to generate the astronomic tide at the sea boundaries of the Continental-Shelf-Model (Verboom et al. 1992). It embeds the German-Bight-Model with average grid sizes of 600 meters covering North Sea waters from the Dutch barrier island Terschelling in the South to the northern edge of the Wadden Sea at Esbjerg in Denmark. The German-Bight-Model, in turn, generates water level time series at the sea boundary of the smaller Ems-Dollard-Model. The most detailed model of the hierarchical cascade covers the entire Ems-Dollard estuary from the seaward limit at the 20 meter depth-line beyond the East Frisian barrier islands to the landward limit at the tidal barrier in the Lower Ems (Fig. 3). The curvilinear model grid consists of about 220.000 active grid cells with resolutions of 150 m offshore and up to 30 m in the upstream part, where strong topographical gradients along the estuarine cross-sections need to be sufficiently resolved for proper reproduction of processes. The bathymetrical data in sub- and intertidal areas has been gained by side-scan-sonar or by conventional sounding methods, whereas inter- and supratidal areas have been surveyed by high resolution airborne laser-scanning.

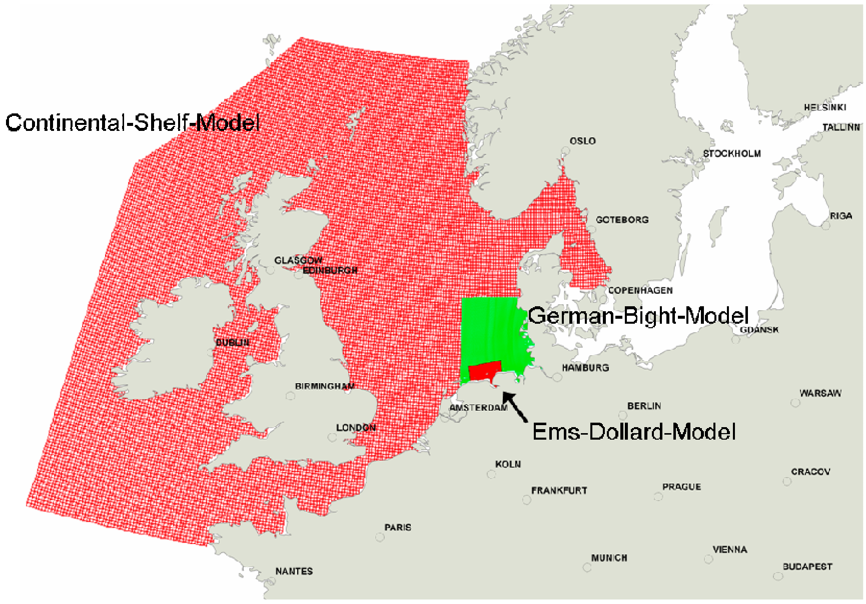


Figure 2. Hierarchical model cascade: Continental-Shelf-Model, German-Bight-Model and Ems-Dollard-Model.

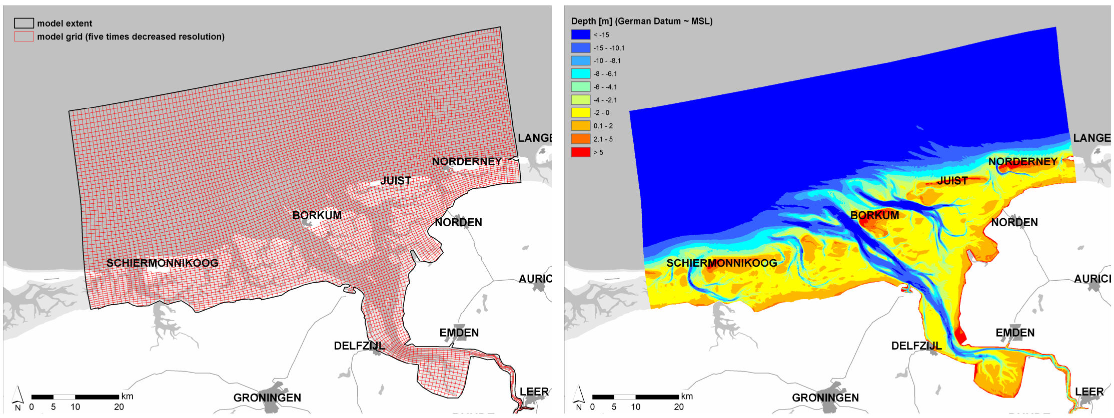


Figure 3. Model grid (five times decreased grid resolution for improved presentation) and model bathymetry of the detailed Ems-Dollard-Model.

Meteorological boundary conditions

In addition to the astronomic tides, storm surge generation involves wind stress terms and the horizontal gradient of atmospheric pressure at the sea surface. Modelled meteorological data; i.e. non-stationary and spatially varying data of atmospheric pressure, wind velocity and direction, of three severe storm events are available as meteorological forcing of the storm surge models. These storms are typical low-pressure areas moving from West to East across the central part of the North Sea, causing strong onshore winds combined with strong surge at the coast and in the estuaries. Exemplarily a wind field of the storm "Tilo" on Nov. 9th 2007 at 9 a.m. UTC is presented that covers the spatial extent of all three model areas of the model cascade (Fig. 4). In case of the Continental-Shelf-Model, the velocity components of the wind and the atmospherical pressure are interpolated directly onto the computational grid, whereas for the German-Bight-Model and for the local Ems-Dollard-Model the data is interpolated on a separate rectilinear grid with a spatial resolution of 5 km.

For the storm "Anatol" of Dec. 3rd 1999 data series with time-intervals of 3 hours on a rectilinear grid with a relatively coarse spatial resolution of 42 km are obtained of the synoptic PRISMA model (Mayerle & Winter 2002). At the island of Borkum the maximum wind velocities are about 25 m/s of westerly directions shortly before the occurrence of the tidal high water level at Emden (Fig. 5a, Tab. 1). The relatively low surge level due to the storm "Anatol" is explained by the circumstance that for a longer period at flood tide only south-westerly wind directions have prevailed. This wind direction is far less relevant with respect to the surge levels at the estuarine mouth than wind directions from the West to North-West.

The German Weather Service provided reanalyzed data of the local European forecast model (COSMO-EU) that covers a temporal resolution of 1 hour and a spatial resolution of about 7 km in North-South and 4 km in West-East orientation for the storm "Britta" on Nov. 1st 2006 (Fig. 5b, Tab. 1). The forecast-data has been reanalyzed in the area of the German Bight by meteorologists which improved the reliability but still shows underestimated wind magnitudes with respect to local wind measurements. The output of the storm surge model strongly depends on the quality of the applied meteorological boundary conditions. Thus, the wind velocities in the series of wind fields have been modified with respect to the measurements of six stations; the wind directions and the atmospheric pressure remained unchanged. The maximum wind velocity of the whole data set is in the order of 28 m/s at Norderney coming from North-North-West. These modifications within the wind fields improved the computations of the storm surge levels in comparison with water level observations considerably.

Forecast-data of the COSMO-EU-Model for the storm "Tilo" on Nov. 9th 2007 is made available by the German Weather Service (Fig. 5c, Tab. 1). The temporal and spatial resolution of the data is just the same as for the storm "Britta", but yields fair agreements with wind observations. Maximum wind velocities are in the order of 19 m/s from North-West - so significantly lower than for "Britta". However, the spatial extent of the area with high wind velocities over the North Sea is much larger in case of "Tilo" than for "Britta", where a strong gradient in wind velocities is observed westerly of the mouth of the Ems-Dollard estuary.

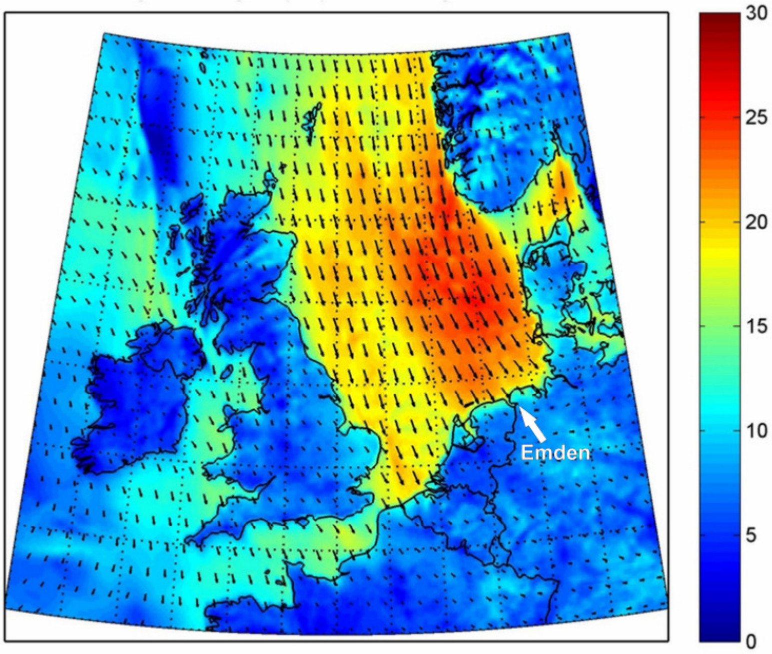


Figure 4. Modeled and reanalyzed wind velocities (m/s) and directions of the storm event "Tilo" on Nov. 9th 2007, 9 a.m. UTC provided by the German Weather Service (DWD).

Table 1. Specification of wind and atmospherical pressure data available of the storm events "Anatol", "Britta" and "Tilo".

	"Anatol"	"Britta"	"Tilo"
Date	Dec. 3rd, 1999	Nov. 1st, 2006	Nov. 9th, 2007
Resolution in time	3 hrs	1 hr	1 hr
Resolution in space	42 km	North-South 7 km and West-East 4 km	
Predom. wind direction	West	North-North-West	North-West
Maximum wind velocity	~ 25 m/s	~ 28 m/s	~ 19 m/s
Source of data	PRISMA (Mayerle & Winter 2002)	COSMO-EU-Model; German Weather Service (DWD)	

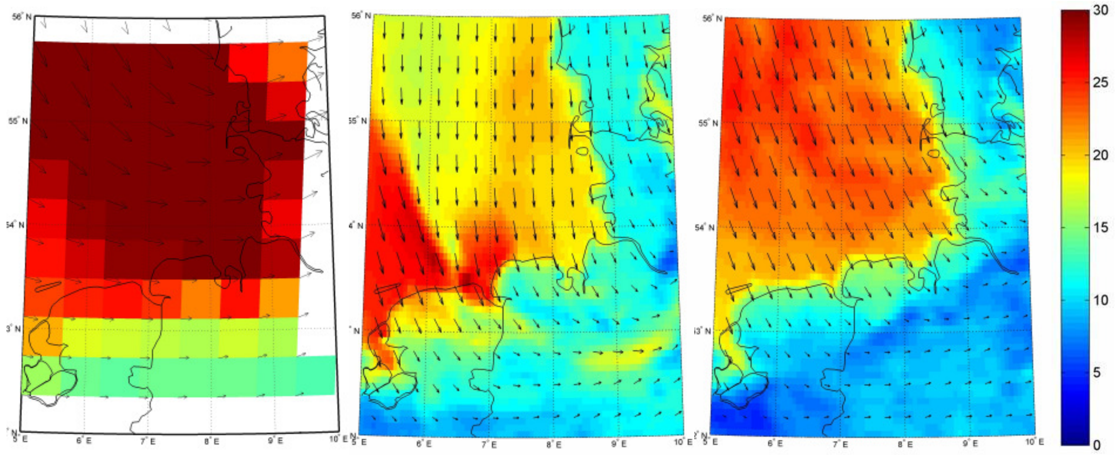


Figure 5. Comparison of maximum wind velocities (m/s) and directions in the modeled wind fields of the storms: a) "Anatol" Dec. 3rd 1999 (PRISMA data), b) "Britta" on Nov. 1st 2006 and c) "Tilo" on Nov. 9th 2007 (forecast-data provided by the German Weather Service).

Modification of the wind drag coefficient

Besides the reliability of modelled wind data, the wind shear stress over the water surface is of significance with respect to the effected surge. The wind shear stress can by evaluated by:

$$|\tau_s| = \rho_a C_d U_{10}^2 \quad (1)$$

with τ_s wind shear stress, ρ_a air density, C_d wind drag coefficient and U_{10} wind velocity at 10 meter over the water surface. The influence of waves on the surface roughness is parameterized in the wind drag coefficient. Within a certain range of wind velocities, the wind drag coefficient increases linearly with the wind velocity, as the surface roughness increases, too. Typically, the formulation of the wind drag coefficient after SMITH & BANKE (1975) is applied. But recent investigations (Bruss & Mayerle 2009) have shown, that for shallow seas as the Baltic Sea or the North Sea with limited fetch and at very high wind velocities different wind drag coefficients should be applied. The comparison of computed water levels of the hindcasted storm surge "Britta" with measurements at the gauge of Borkum (Fig. 6) shows that the adapted approach of the formulation of the wind drag coefficient after data of BRUSS & MAYERLE, here, yields better agreements than the application of the formulation after SMITH & BANKE (1975).

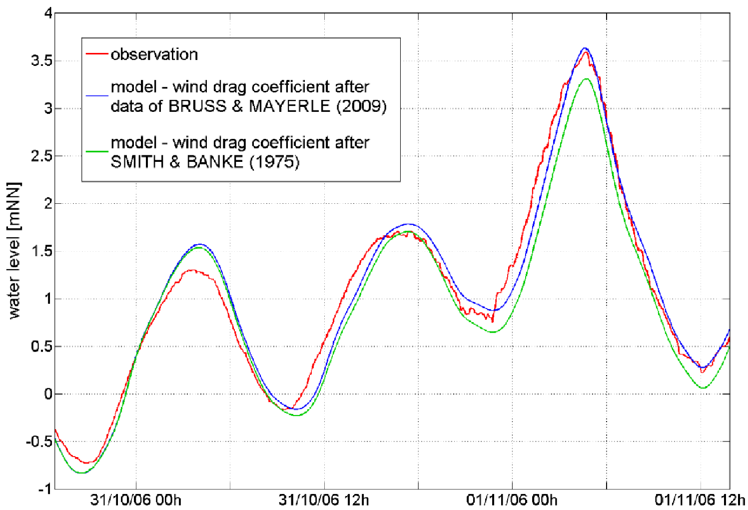


Figure 6. Effect of different formulations of the wind drag coefficient on the modeled water levels at the island of Borkum.

Storm surge barrier

In 2001 the storm surge barrier at Gandersum with a width of 476 meters started its operation. Storm surges with an expected peak water level of more than NN +3.7 m (NN = German Datum) are blocked by the closing barrier and prevented of entering the Lower Ems. In case of such an event, the barrier is closed hydraulically effective at a level of NN +3.5 m. The closing of the gates takes about 30 minutes, the opening 45 minutes. Once it is closed, the storm surge wave is partly reflected at the barrier and travels on a stretch of about 5 km downstream to the Dollard Bay, where its crest decreases due to the cross-sectional expansion. The operation of the continuously closing storm surge barrier is schematized in the model by a stepwise narrowing of the cross-section in three intervals. The simulations are run discontinuously. By the time of the initiation of the closing procedure, the simulation is stopped and restarted with the previously saved conditions, but with a partially blocked cross-section. This is repeated two times, while for the last time the simulation continues until the end of the event, but with a blocked barrier. The time-schedule of the closing procedure is adapted with respect to the procedures reported by the barrier personnel.

HINDCAST OF STORM SURGES AND MODEL VERIFICATION

The model is verified against observed water levels of three storm events: "Anatol" (Dec. 3rd, 1999), "Britta" (Nov. 1st, 2006) and "Tilo" (Nov. 9th, 2007). The storm surge peak of "Britta" is one centimetre below the highest ever measured surge level at the gauge of Emden in 1906, whereas the set-up is significantly smaller due to the sea level rise since then. Water level time series of the gauges at Borkum, Emshörn, Eemshaven, Delfzijl, Knock, Emden, Pogum and at the storm surge barrier are used for the calibration and validation of the model. Exemplarily, the comparisons of modeled and observed water levels are shown at the station Borkum for "Britta" and at the station Emden for "Tilo" in the time domain (Fig. 7 and 8).

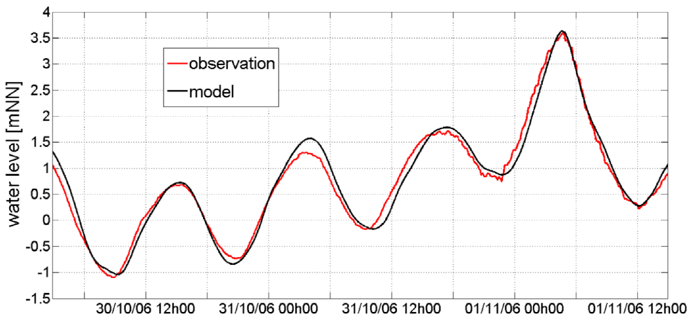


Figure 7. Hindcasted versus observed water levels at the tidal gauge of Borkum on Oct. 30th to Nov. 1st, 2006 during storm "Britta".

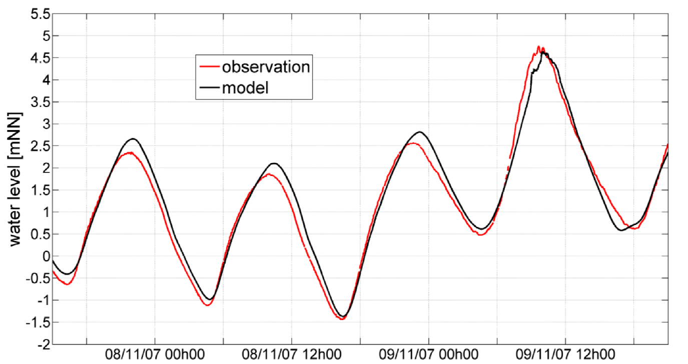


Figure 8. Hindcasted versus observed water levels at the tidal gauge of Emden on Nov. 7th to 9th, 2007 during storm "Tilo".

Good agreements are obtained in the tidal amplitude, whereas at Emden in the inner estuary a phase lag of about 20 minutes occurs with respect to the storm surge peak. The comparison of modeled and observed peak water levels along a stretch following the waterway from the island of Borkum to the storm surge barrier at Gandersum shows the different intensity of the three selected storm surge events (Fig. 9). At the gauge of Emden NN +3.75 m are modelled for "Anatol", NN +4.65 m for "Tilo" and NN +5.42 m for "Britta". The measured water level peaks of “Anatol” are consequently underestimated by the model in the order of 15 to 20 cm. This is probably explained by the fairly low resolution of the non-stationary wind-fields, both in time and in space. The modeled peak water levels of "Tilo" and "Britta" show good to very good agreements with observations; solely in case of the simulation of "Britta" the peak water levels at Emden and at the storm surge barrier are overestimated by 22 cm and 33 cm in the computations.

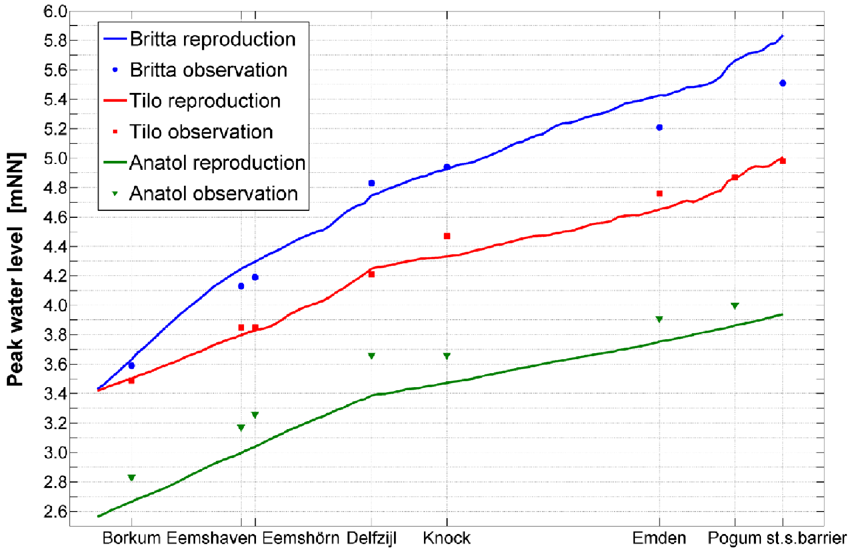


Figure 9. Hindcasted and observed peak water levels of the storm surge events “Anatol”, “Tilo” and “Britta” for the stretch following the waterway from the island Borkum to the storm surge barrier at Gandersum.

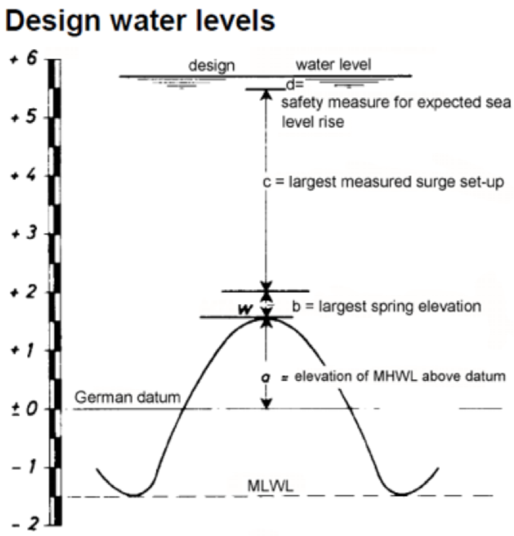
EVALUATION OF DESIGN WATER LEVELS

Determination of the highest expected high water level at Emden

The evaluation of design water levels for sea dykes in Lower Saxony is carried out by use of the ”single-value-method” (Lüders & Leis 1964). The method is generally not applicable for the evaluation of design water levels for estuarine dykes as the effects of geometrical changes of the estuary, i.e. waterway deepening and widening, the storm surge barrier or strong upstream discharges are not considered. But at the location of the gauge in Emden at the mouth of the estuary, the effects on water levels due to the deepening of the Ems or due to strong riverine discharges are negligible. The design water level for Emden with an open storm surge barrier is determined by the single-value-method and in compliance with the Lower Saxon Dyke Act to NN +6.39 m (Fig. 10).

Methodology and results

After verification of the model, simulations for the evaluation of the design water levels under consideration of the design upstream discharges of 770 qm/s and increased wind velocities have been undertaken. The model boundary conditions are modified for each storm surge scenario respectively, i.e. the wind velocities in the wind fields are increased with the aim to achieve agreement with the predetermined design water level at Emden for the model state with an initially opened storm surge barrier (Fig. 11). The wind velocities are increased spatially constant in all three models of the cascade but by applying adapted multiplication factors for the different storm events, respectively. The wind velocities of the modified wind fields do not reach magnitudes that have to be rated as unrealistic. All modeled storm surge peaks match the aimed value of NN +6.39 m at the Emden gauge for a model state with an open storm surge barrier, but over the entire estuary different peak water levels do respond.



a) Mean High Water Level (MHWL) of the 5 year-period 2003 to 2007:	**1.48 mNN**
b) largest spring tide elevation:	**0.49 m**
c) largest surge set-up measured in 1906:	**3.92 m**
d) new safety margin for sea level rise acceleration:	**0.50 m**

Design Water Level at Emden gauge for the year 2108:	**6.39 mNN**

Figure 10. Determination of the highest expected high water level at Emden with an open storm surge barrier by “Single-Value-Method" (Lüders & Leis 1964) and in compliance with the Lower Saxon Dyke Act.

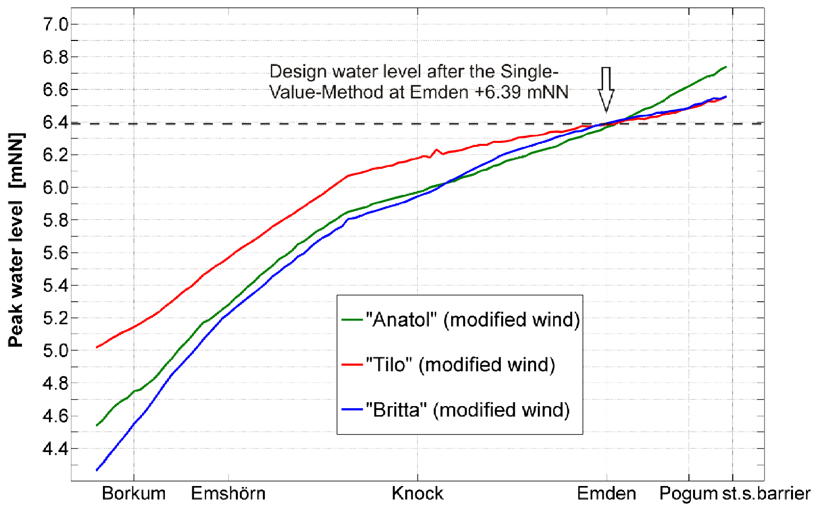


Figure 11. Peak water levels of the modeled storm surge scenarios with increased wind velocities and an opened storm surge barrier for the stretch between Borkum and the storm surge barrier.

In a following step, the barrier is closed according to the practised procedure. The variation of the model results can be explained by both the shape of the tidal wave as a consequence of the development of the underlying storm event and the associated effect of the reflection at the closing storm surge barrier (Fig. 12).

In compliance with the Lower Saxon Dyke Act and in order to meet safety requirements, the design water level is a combination of the overall maximum peak water levels: in the outer estuary the peak water levels of the scenario “Tilo-modified" are maximal, while upstream of Knock the scenario of “Britta-modified" produces the highest water levels (Fig. 13). Thus, the design water levels along the inner estuary are evaluated by NN +6.25 m at Knock, NN +6.77 m at Emden, NN +6.93 m at Pogum and NN +7.05 m at the storm surge barrier.

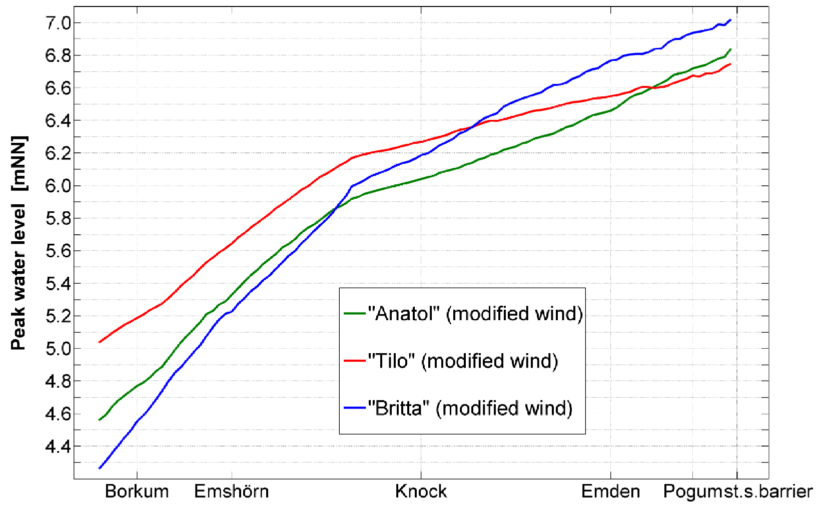


Figure 12. Peak water levels of the modeled storm surge scenarios with increased wind velocities and after the closure of the storm surge barrier for the stretch between Borkum and the storm surge barrier.

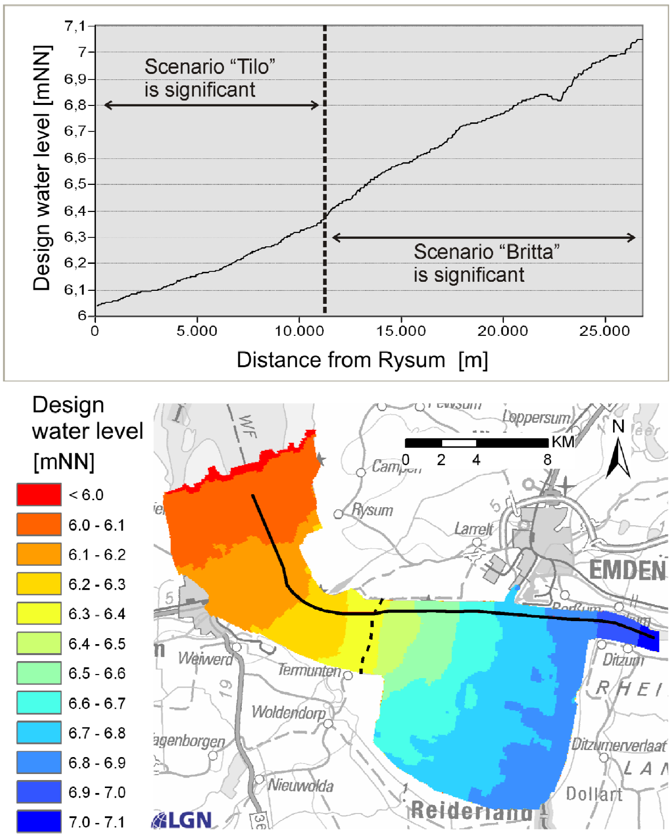


Figure 13. Combination of the design water levels in the Ems-Dollard estuary: the scenario "Tilo" (modified) westerly and the scenario "Britta" (modified) easterly of the dashed line are significant.

Modeled water levels and current velocities are applied as spatially differentiated and non-stationary boundary conditions to run the spectral wave model SWAN (Booij et al. 1999). Based on the modeled wave parameters at the dykes, the design wave-run-up is computed by empirical formula (Elsebach et al. 2010). The sum of the design water level and the design wave-run-up determines the new crest heights of the dykes.

CONCLUSIONS

A hierarchical cascade of three storm surge models has been set-up to simulate the tide- and wind driven dynamics from the Continental Shelf over the North Sea into the Ems-Dollard estuary. The model is successfully verified against water level observations of three severe storm events. Model simulations are run with increased wind velocities for the evaluation of design water levels in the Dollard Bay. Every storm development is different and so is the propagation of the storm surge wave into the estuary, particularly if reflected by a storm surge barrier. In case of the Ems-Dollard estuary, therefore it was necessary to model more than one significant storm surge event and evaluate the overall highest peak water levels as design water levels. The variation of the model results can be explained by both the shape of the tidal wave as a consequence of the development of the underlying storm event and the associated effect of the reflection at the closing storm surge barrier. The partly reflected storm surge wave at the closing barrier effects the downstream design water levels in the Lower Ems and the Dollard Bay; in the outer estuary the effect is negligible.

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