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Studies on the Development of Wind set-up in the River Elbe

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Abstract

Storm surges are often the reason for crevasses, flooding, damages and if it comes to the worst fatal casualities. To minimize damages the construction of stable and high dikes is one of the necessities. Another important issue is to understand the physical processes causing storm surges and the application of this knowledge to forecast water levels. These forecasts can save life and protect areas like ports or lower laying areas where portable flood protection measures can be installed. In Hamburg an approach to forecast water levels of storm surges exists already.
Within a research project the main objective is to improve the forecasting water levels along the tidal River Elbe. Additionally Hamburg Port Authority deals with the analysis of physical processes contained by empirical and statistical research especially on storm surges, while partners in the project generate numerical models to forecast water levels induced by tides. The validation for storm surges is also based on statistical interpretation.

1 Background and Motivation

Hamburg Port is the most important port of Germany and one of the most important ports in Europe. Bulk cargo and containers reach Hamburg by vessel via the River Elbe. Increasing economy during the last centuries resulted in growing length and width of vessels and of course deeper draughts. As the River Elbe is subjected to the tide it is necessary to forecast the water levels of all gauges along the fairway as exactly as possible.

To improve the prognoses for storm surges, Hamburg Port Authority (HPA) is a member of the research project OPTEL – Wind set-up Studies and Development of an Operational Model of the tidal River Elbe – funded by the Federal Ministry of Education and Research. The main intention of this project is the development of an operational numerical model which supplies continous information on water levels and currents of the River Elbe. OPTEL receives scientific support by the German Coastal Engineering Research Council.

The Federal Maritime and Hydrographic Agency (BSH) and the Federal Waterways Engineering and Research Institute (BAW) generate the models for the forecasts (OPTEL – A & C), the German weather Forecast Agency “Deutscher Wetterdienst” (DWD) handles wind data for the models (OPTEL – B) and the HPA assumes the collection and preparation of all required data and focuses on storm surges, their causes and characteristics (OPTEL – D).

In this article first studies and results on the main topic of HPA - the storm surges are presented.

2 Objectives

In 1962 a storm surge caused many crevasses and more than 300 casualities. Since then HPA is working on the research of storm surges. During this storm tide the water level reached a value which was never recorded before. After 1962 the research on storm surges headed to the establishment of the Hamburger Sturmflutwarndienst (WADI). This service alerts the port and the citizens of Hamburg in case of a storm surge. An empirical and statistical approach provides forecasts of the water level in Hamburg. In most of the cases these forecasts are precise, but there are of course some storm surges, where forecasted and measured water levels differ more than 20 cm. Results of OPTEL – D hopefully lead to further improvement of that approach to reduce such rough results.

Storm surges are mainly caused by wind. In detail the aim of OPTEL – D is to define more precisely the influence of wind in the German Bight and the Waddensea. Are there similarities between wind directions, constancy of the wind and duration of wind velocities? Where is the major influence on the water levels by the wind: from the mouth of the River Elbe up to Hamburg, in the German Bight or further offshore in the North Sea? The analysis of the development of the rising water levels from the North Sea to Hamburg is another important component of OPTEL – D.

Another topic is the analysis of the upstream water discharge of the River Elbe, measured in Neu Darchau upstream of the weir of Geesthacht. The standardization of the water levels can show the influence of discharge on storm surge water levels.

3 Location and Approaches

The first step by the project team was to agree on the main gauges to analyse the water levels, the wind recording stations to investigate the wind set-ups and to define other important data necessary for the studies besides the upstream water discharge.

The collected data for OPTEL and its storm surges refers to the period from 1980 to 2008. In addition to this period the storm surges, defined in OPTEL, needed to have the following characteristics:

- the water level in Cuxhaven exceeds more than 2.0 m above high water (mean high water in Cuxhaven: + 1.5 m NN) and
- the water level in Hamburg – St. Pauli is higher than + 4.0 m NN.

Both characteristics are independent of the phase of the tide. These basic principles lead to approximately 150 storm surges.

In the proposal of OPTEL the names of different gauges of the River Elbe which are the basic for the research, are mentioned:

Table 1: Gauges of the River Elbe considered in OPTEL

Gauge	Short	River Elbe Station [km]
Cuxhaven	CUX	724
Brunsbüttel	BRU	697
Brokdorf	BRO	684
Glückstadt	GLÜ	674
Grauerort	GRA	661
Schulau	SCH	641
Hamburg – St. Pauli	STP	623
Bunthaus	BUN	610
Zollenspieker	ZOL	598
Geesthacht (weir)	GST	586

To analyse the wind blowing from the North Sea to Hamburg the project team agreed to use the following wind recording stations: Borkum (located north of the Ems Estuary, border between Germany and the Netherlands), Scharhörn and Neuwerk (located outside of the mouth of the Elbe Estuary) and Cuxhaven, Brunsbüttel, Ruthenstrom and Finkenwerder all along the River Elbe.

Figure 1 gives an overview of all relevant gauges and wind recording stations.

Figure 1: Review of the River Elbe, position of the gauges, wind recording stations and upstream water discharge (www.google.de)

Wind set-up is defined as the difference between an expected and an actually reached water level. This difference is mainly produced by wind and leads to higher water levels. To estimate the difference the astronomical or the mean tide is required. The astronomical tide has been calculated by the BSH for the period from 1980 to 2008. The mean tide is calculated from the averaged water levels over five years. The discrepancy of the results will be analysed for both wind set-up graphs.

To identify the causes for wind set-up is the main aim of the analysis in OPTEL – D, especially to improve the forecasts. To survey a status quo for analysis of storm surges three different statistical and empirical approaches were used. All of them exclusively consider the peak values in Cuxhaven and Hamburg – St. Pauli at high water time.

The first approach is a comparison between the forecasted water level and the measured water level for Hamburg – St. Pauli by WADI and its empirical statistical method at the moment of high tide in Cuxhaven. This comparison gives information about the accuracy of the forecast by this method.

The difference between low water tide and the following high water tide is the second approach. This difference, called tidal rise, from Cuxhaven and Hamburg will be set in contrast with each other in a scatter diagram.

To obtain a relation between the wind set-up during high tide (independent of high water time) of Cuxhaven and Hamburg is the third approach.

Figure 2 shows two outlines to explain the calculation of the wind set-up and the tidal rise.

The relation for wind set-up and tidal rise between Cuxhaven and Hamburg is presented in scatter diagrams in figure 3. The values of Cuxhaven are shown on the x-axis while on the y-axis the values of Hamburg – St. Pauli are presented. The first diagram displays the results of the wind set-up. The second diagram shows the result of tidal rise comparison as well as the linear regression.

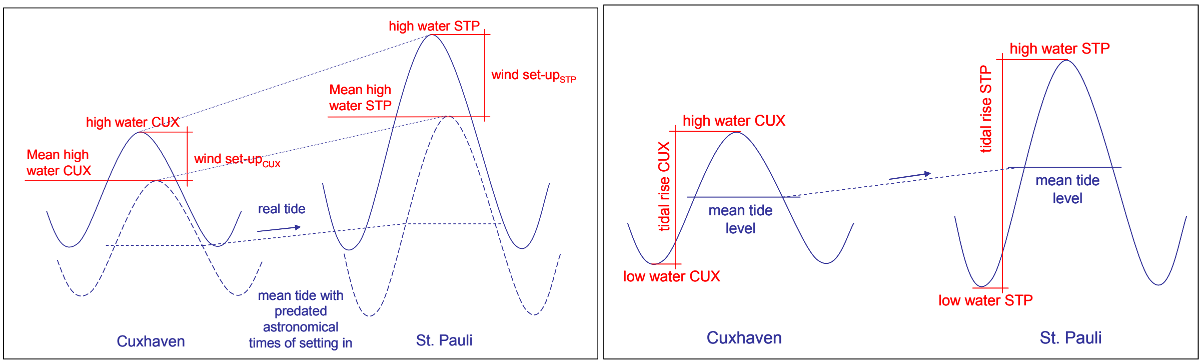

Figure 2: Outlines for the explanation of wind set-up (left) and tidal rise (right)

At first glance the results of the tidal rise look much better than the results of the wind set-up comparison. However, the different scaling of the axis and the standard error of these two approaches indicates that the wind set-up comparison provides better results.

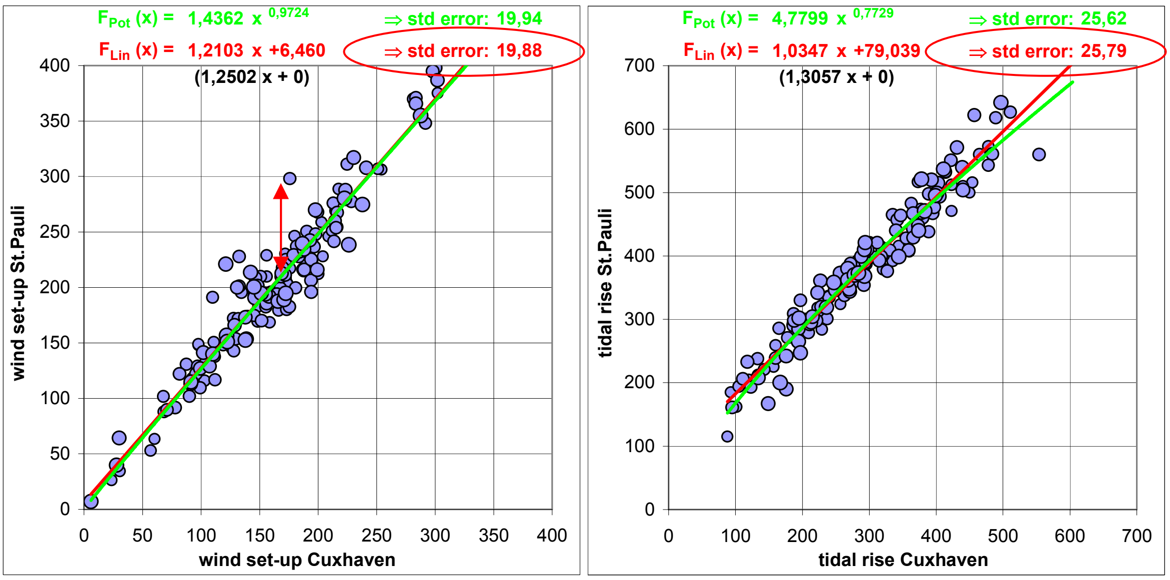

Figure 3: Scatter diagrams for wind set-up s (left) and tidal rise (right)

Another form of presentation for these scatter diagrams is a chronological order of the storm surges and their results of wind set-up / tidal rise. The difference between function value and regression line is labelled by the pink scatters in figure 4 – only shown for the wind set-up approach.

Additionally it is possible to show the correction of the upstream water discharge in this figure. By means of a multiple regression the effect of the upstream water discharge can be described. The white scatters show the dimension of the effect. The mean deviation for wind set-up averages here about ± 7.6 cm / 1000 m^3. For the tidal rise approach the discharge shows an influence of ± 16 cm / 1000 m^3.

It can be seen that the influence of the discharge in case of storm surges is not critical. The means are less than 20 cm which is the boundary value. This boundary value results of the WADI – approach. The forecast error should be less than 20 cm for storm surges.

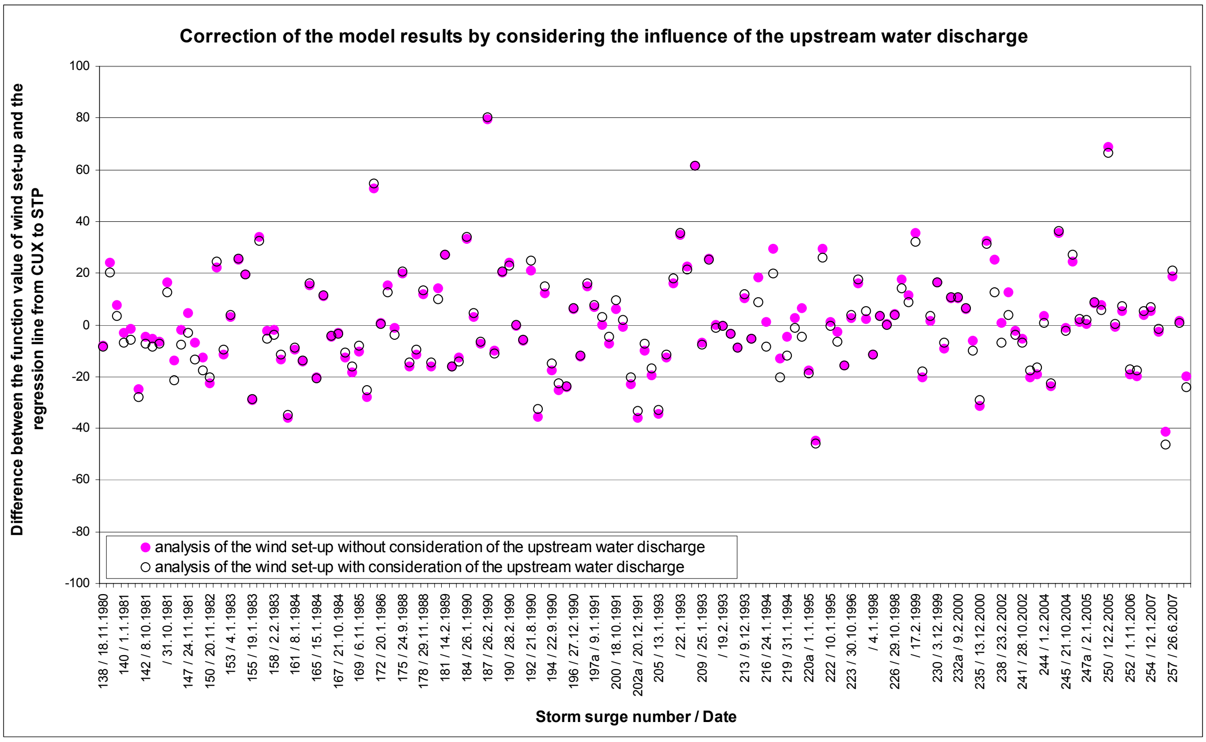

Figure 4: Difference between the function value of wind set-up and the regression line as well as the influence of the upstream water discharge

The same form of presentation demonstrates the results of all three approaches (wind set-up, tidal rise and the WADI – approach) for every storm surge in figure 5. Wind set-up and tidal rise are available for every event; unfortunately the results of the WADI – approach are incomplete. Due to the enlargement of the lists of events there is no WADI – data for every storm surge. If there has not been made a forecast by WADI, no data have been stored and it is very complex to reproduce the missing data. Therefore some gaps in data appear which will be filled contemporary.

None the less one tendency is obvious. Since 1993 – the last optimisation after the beginning of the development in 1978 – the WADI-approach supplies very good results, except a few. The continuous advancement of this approach shows that many influencing factors are already considered in this empirical and statistical procedure.

The spreading of the tidal rise approach and the wind set-up approach are clearly larger than the spreading for WADI. Especially the values of the tidal rise seem to be very discontinuous, but the standard error is nearly the same as that of the WADI – approach. The standard error of the wind set-up is a bit lower. To conclude, the wind set-up between Cuxhaven and Hamburg appears to be the best approach for further analysis.

The next step was a research along all gauges of the River Elbe to show the development of the tidal wave in the estuary. The two different approaches, tidal rise and wind set-up, were used to analyse this effect. The tidal wave runs from Cuxhaven along Brunsbüttel, Brokdorf, Glückstadt, Grauerort and Schulau to Hamburg – St. Pauli. Figure 6 shows the relation of the wind set-up between every gauge to Hamburg – St. Pauli exemplarily for both approaches.

Red circled black values give information about the forecast error. From Cuxhaven and Brunsbüttel to St. Pauli the forecast errors are about 25 and 14 cm. Upstream Brokdorf the errors are less than 10 cm, which is a very good result. Therefore the progression of the storm surges from Brokdorf to Hamburg along the inner estuary can be described quite well as linear.

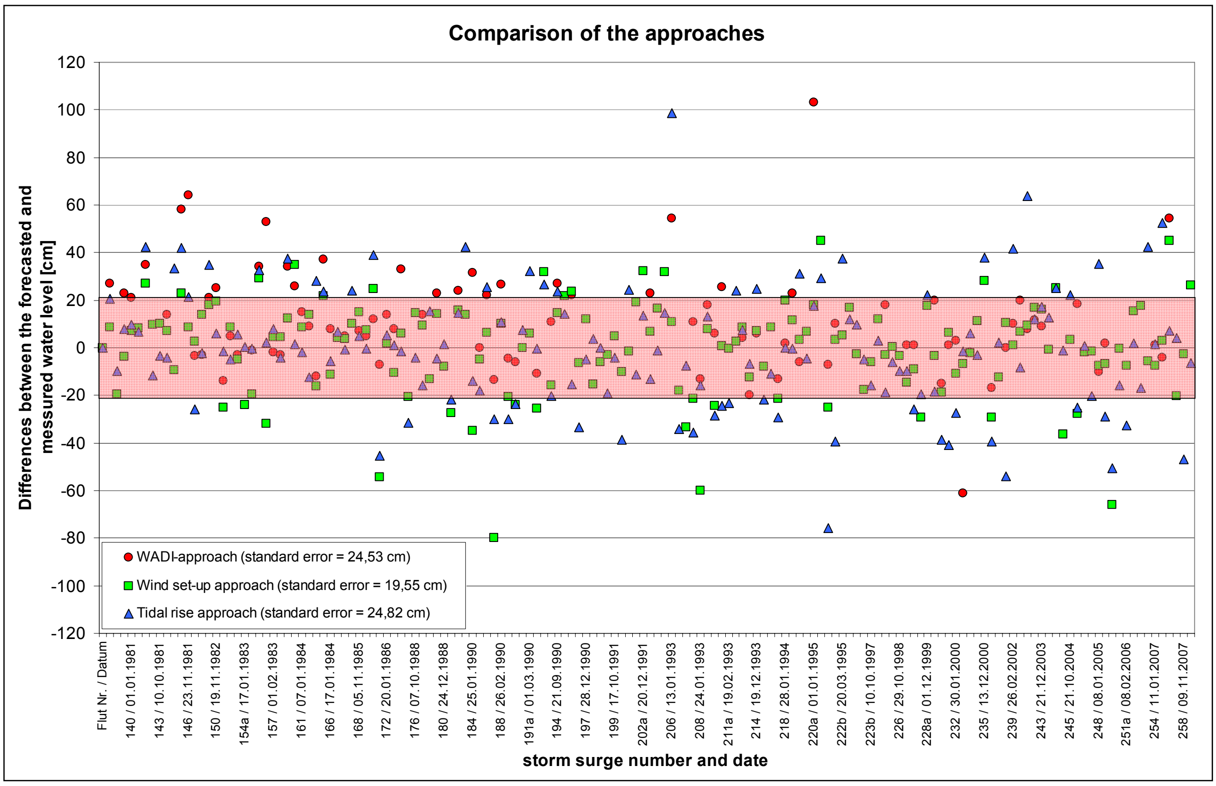

Figure 5: Comparison of the three analysing approaches and their standard error

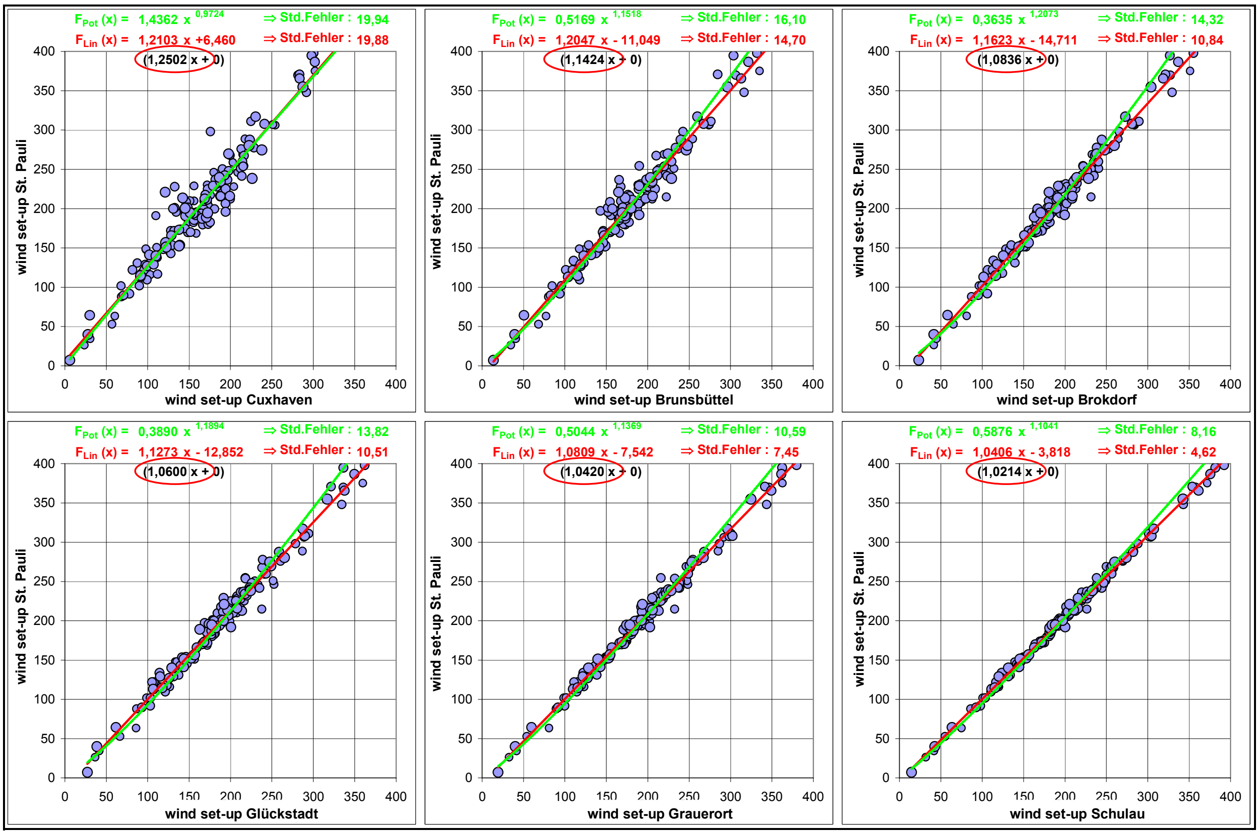

Figure 6: The run of the tidal wave from the mouth of the River Elbe to Hamburg – St. Pauli for the tidal rise approach

The results of this effect are a very important result. This implicates that the influences on the water levels are located outside the mouth of the River Elbe. Certainly this fact is just a little help for the forecasts. The tidal wave needs about 2-3 hours from Cuxhaven to St. Pauli and it would be too late for an alert. But this knowledge can be used for a specification of the forecasts and about ceasing the handling of cargo or not.

The wind is probably the most important influence on water levels, because it causes the wind set-up. Therefore it is necessary to research the main factors on that. There are three important parameters: wind direction, wind speed and the difference of wind set-up between Cuxhaven and Brokdorf. The aim is to find the main wind set-up causing direction and period of time. Is there a time period before high tide in Cuxhaven that has a great influence on the wind set-up heights and would the consideration of this result lead to better forecasts? Research of this fact is still at the beginning. Wind data from Scharhörn are currently used but probably there will be a concentration on the wind data of Cuxhaven and Brunsbüttel too.

4 Results

At the beginning data collection, controlling and validation were the main part of OPTEL - D. The following data are collected: water level, wind speed and direction, degree of salinity, flow velocity and direction, water temperature, upstream water discharge, mean and astronomical tide.

The water level data were used for the analysis of three different approaches. The evaluation of the approaches showed, that the wind set-up approach gives the best results. But to minimise the standard errors the understanding of the physical effects causing the increasing water levels is necessary.

The factor of the upstream water discharge is not responsible for high variations between expected and measured water level. There is an influence but it is not essential. Another factor is the linear describable movement of the tidal wave from Brokdorf through the estuary up to Hamburg - St. Pauli. There is evidence to imply, that all influences causing the wind set-up are located in the German Bight and the mouth of the River Elbe. The wind along the River Elbe is not that important for the water levels, which are reached in Hamburg - St. Pauli. This increase is created by the narrowing shape of the River Elbe.

At least the wind outside the estuary is the main cause for the height of the wind set-ups. But it is very difficult to apportion the different elements of the wind as direction, speed, duration and produced wind set-up height. Therefore - as a next step - all storm surges are needed to be analysed individually.

5 Discussion and conclusion

Further analyses for improved statistical and empirical models for storm surges are still necessary. Other appendages for the research in OPTEL - D are for example the variation of the gradient of the individual tide or the filling degree of the estuary, when a storm surges is expected.

The co-partners of OPTEL are dealing with other components.

OPTEL - A establishes a model of the River Elbe based on BSHcmod and designed by BSH. BAW also works on a model, but based on UnTRIM. This part is OPTEL - C. Both partners need to calibrate and validate their models. They also need to accomplish an interface to transfer hydrodynamic parameters like water levels, flow and degree of salinity from the model of the North Sea to the model of the River Elbe.

DWD computes the roughness of the surface and the topography along the River Elbe up to the weir Geesthacht. Additionally the production of coefficients for the correction of wind speed dependent on the direction is required. The coefficients are part of the meteorological models COSMO-DE and COSMO-EU.

The work proceeds very well. DWD has almost finished. BSH and BAW are arranging the parameters for each model to get comparable results. In the near future the first test runs will start. The validation and calibration of the models will proceed with six scenarios of different hydrological situations of the River Elbe. For example: outstanding low water levels caused by longer lasting southeast wind, two storm surges with different wind set-up curves and a period with high upstream water discharge.

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