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Studies on the development of wind set-up in the river Elbe - further analyses

Caroline Radegast, Thomas Strotmann & Ulrich Ferk

Hamburg Port Authority, Germany

Abstract

Hamburg, situated at the tidal Elbe River, has always been exposed to storm surges. Thus, reliable forecasts of water levels have always been of great importance for Hamburg´s flood protection, but also for navigational needs. In order to improve Hamburg´s own storm surge forecast system, the Hamburg Port Authority (HPA) analyzed the propagation of surges in the Elbe estuary. This study had been carried out within the joint research project 'OPTEL – Wind set-up Studies and Development of an Operational Model of the Tidal River Elbe'.

Although it has in general been known for a long time that surges are being deformed in the Elbe estuary, for instance by factors like the current bathymetry, the fresh water discharge or the height of the surge itself. By the OPTEL-studies, the influence of some parameters could be quantified for the first time. For instance, the investigations revealed that the local wind over the mouth of the estuary has in many cases a significant impact on the propagation of the surge and can increase its height by up to 50 cm. Thus, the possibility of a further improvement of high water forecasts for Hamburg is evident.

1 Motivation

Hamburg, situated 100 km upstream of the mouth of the River Elbe, is not only the second largest city in Germany but also one of the most important seaports worldwide. Because of the city´s location at the tidal Elbe River, constant and highly accurate forecasts of water levels have always been of highest relevance for Hamburg´s flood protection as well as for navigational needs.

Therefore the Federal Ministry of Education and Research is funding the research project 'OPTEL – Wind set-up Studies and Development of an Operational Model of the Tidal River Elbe' which aims at supplying constant information on water levels and currents of the River Elbe with operational models and at analyzing the propagation of surges in the Elbe estuary in order to improve the storm surge forecasts for Hamburg.

Within OPTEL two operational models will be developed: one run by the Federal Maritime and Hydrographic Agency (BSH, OPTEL-A) the other run by the Federal Waterways Engineering and Research Institute (BAW, OPTEL-C). The National Meteorological Service (DWD, OPTEL-B) provides the wind data for these models. Within the project, the Hamburg Port Authority (HPA) is responsible for empirical studies on storm surges in the Elbe estuary (OPTEL-D). After the severe storm surges of 1962 and 1976 Hamburg established its own storm surge forecast service – Hamburger Sturmflutwarndienst (WADI), which is a part of the HPA. The current forecast system is based on an empirical model which provides forecasts of water levels for Cuxhaven and Hamburg primarily based on observation of the wind set-up due to the wind development in the German Bight (Siefert & Christiansen 1983). In OPTEL the studies focus on empirical analyses of the propagation of wind set-up in the Tidal River Elbe from Cuxhaven to Hamburg.

This whole project is funded by the Federal Ministry of Education and Research (03KIS072) until March 2011.

2 Objectives

It is known from further scientific work (e.g. Siefert 1978, Bremer 2008) that the propagation of a storm surge in the Elbe Estuary is subject to many influences. The geometry and bathymetry of the estuary, the amount of fresh water discharge, the current water volume, local wind effects as well as the height of the surge itself and other factors lead to a deformation of the surge from Cuxhaven to Hamburg. As a result, the height difference of storm floods between Cuxhaven and Hamburg range between 70 and > 160 cm. Although the peak differences Cuxhaven – Hamburg normally grow with the height of the storm surge, the highest storm surges surprisingly do not have the biggest peak differences. Thus, the objective of the project is to determine and describe all factors influencing the surge propagation in the Elbe River. The local wind over the Elbe Estuary receives special attention in those studies. After all, the results of OPTEL-D focus on a further improvement of the empirical storm surge forecast system for the Tidal Elbe River.

The analyses are based on data from 152 storm surges between 1980 and today. A storm surge is defined as follows:

- the wind set-up in Cuxhaven exceeds 2.0 m during any time of the tide and/or
- the water level in Hamburg – St. Pauli is higher than + 4.0 m NN.

The data includes water levels of eleven gauges along the River Elbe and wind data of four wind recording stations.

Gauges:	(Elbe Station - km):	Wind data:
Cuxhaven	(724,0)	Scharhörn
Brunsbüttel	(696,5)	Neuwerk
Brokdorf	(684,2)	Cuxhaven
Glückstadt	(674,0)	Brunsbüttel
Grauerort	(660,6)	
Stadersand	(654,8)	
Schulau	(641,0)	
Hamburg - St. Pauli	(623,1)	
Bunthaus	(609,8)	
Zollenspieker	(598,2)	
Geesthacht (weir)	(585,9)	

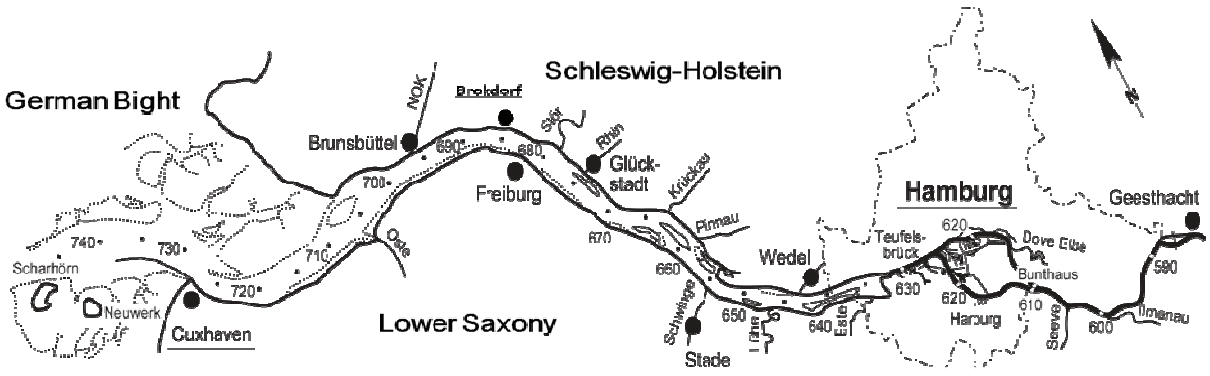

Figure 1: The Elbe Estuary (ARGE ELBE/FFG ELBE).

3 Results

The difference between an expected and an actually reached water level is defined as wind set-up (figure 2). The expected water level can be the astronomical or the mean tide. The BSH has been calculated the astronomical tide for a period from 1980 to 2008 for OPTEL. The mean tide has been calculated from the averaged water levels over five years.

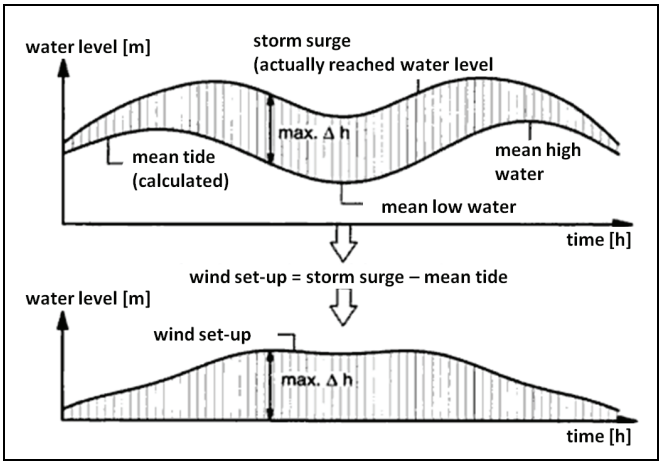

Figure 2: Definition of the wind set-up graph (Lecher, Zanke & Lühr 2001, translated).

The best approach to analyze the propagation of the storm surge through the estuary is to consider the wind set-up values at high water time in Cuxhaven and Hamburg-St. Pauli. Two other approaches to research the propagation had been tested also, but the results were not satisfying enough (Radegast et al. 2010).

Figure 3 shows the relation between wind set-up at high tide in Cuxhaven (x-Axis) and Hamburg (y-axis) for the 152 storm surges. It is apparent that some storm surges deviate more than 50 cm from the linear regression line (figure 3).

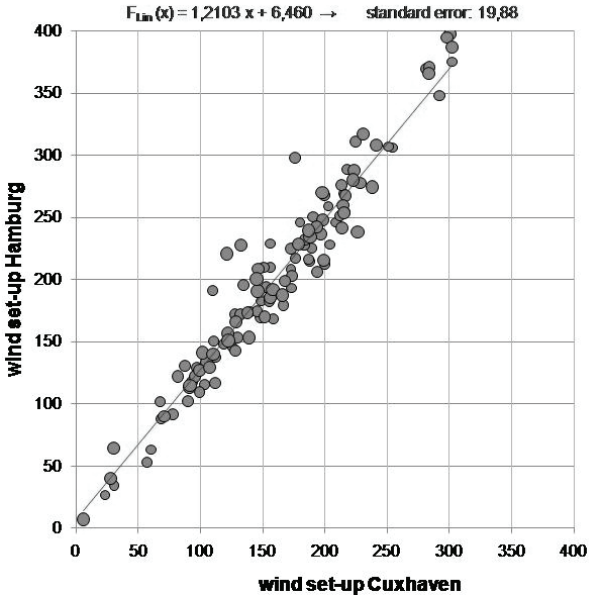

Figure 3: Scatter diagram for wind set-up between Cuxhaven and Hamburg.

In contrast, figure 4 shows the wind set-up-relation between Brokdorf and Hamburg. Brokdorf is located 30 km upstream of Cuxhaven in the inner estuary, where the funnel-shaped mouth narrows and

the river bed turns its direction by ca. 90 degrees. As figure 3 demonstrates, the progression of storm surges from Brokdorf to Hamburg along the inner estuary can be described as linear. According to this, effects causing increases of the wind set-up have to be located at the mouth of the estuary.

All those storm surges with a high deviation from the regression line (figure 3) were analyzed separately. It became clear that in most of the cases the local wind in Brunsbüttel has a high influence on the wind set-up.

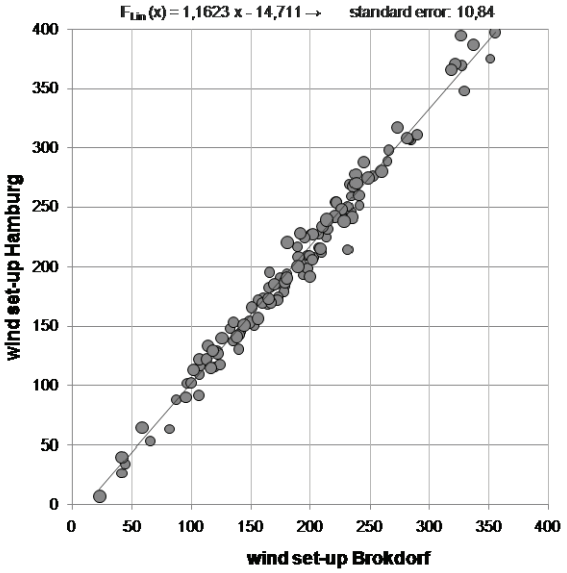

Figure 4: Scatter diagram for wind set-up between Brokdorf and Hamburg.

To find out which wind direction produces the highest wind set-up in the mouth of the estuary, an iteration method had been carried out. The wind data of the wind recording station Brunsbüttel, which is located between Cuxhaven and Brokdorf, had been used for this calculation. Furthermore the difference between the wind set-up in Cuxhaven and Brokdorf is part of the iteration.

$$\sum | \Delta Y - WV^2 \cdot cos^2 (WD - WD_0) |^2 = Min$$

ΔY Δ wind set-up between Cuxhaven and Brokdorf
WV wind velocity Brunsbüttel
WD wind direction Brunsbüttel
WD_0 wind direction that produces the highest wind set-up

The minimization of the mean square error (MMSE) of this equation leads to a wind direction of 260° (WD_0) that produces the highest wind set-up in the mouth of the Elbe estuary. In contrast, the most relevant wind direction in the inner German Bight is 280 – 285°.

Figure 5 shows the correlation between the projection of the wind and the increase of the wind set-up between Cuxhaven and Brokdorf. The wind data of Scharhörn (wind recording station in the German Bight) is represented by the red statistical series, the wind data of Brunsbüttel (wind recording station in the mouth of the estuary) by the blue one. A tolerance range of ± 20 cm is marked by the red lines.

One storm surge is highlighted. This specific event also stands out, because of the high deviation. With the wind data of Scharhörn (red) a deviation of ca. 60 cm from the regression line occurs, whereas, using the wind data of Brunsbüttel (blue), a remarkable shift into the tolerance range can be achieved. Compared to the red time series most of the blue data are inside the tolerance range. Accordingly the local wind in the mouth of the estuary has in many cases a great influence on the development of the storm surge level in the Elbe estuary.

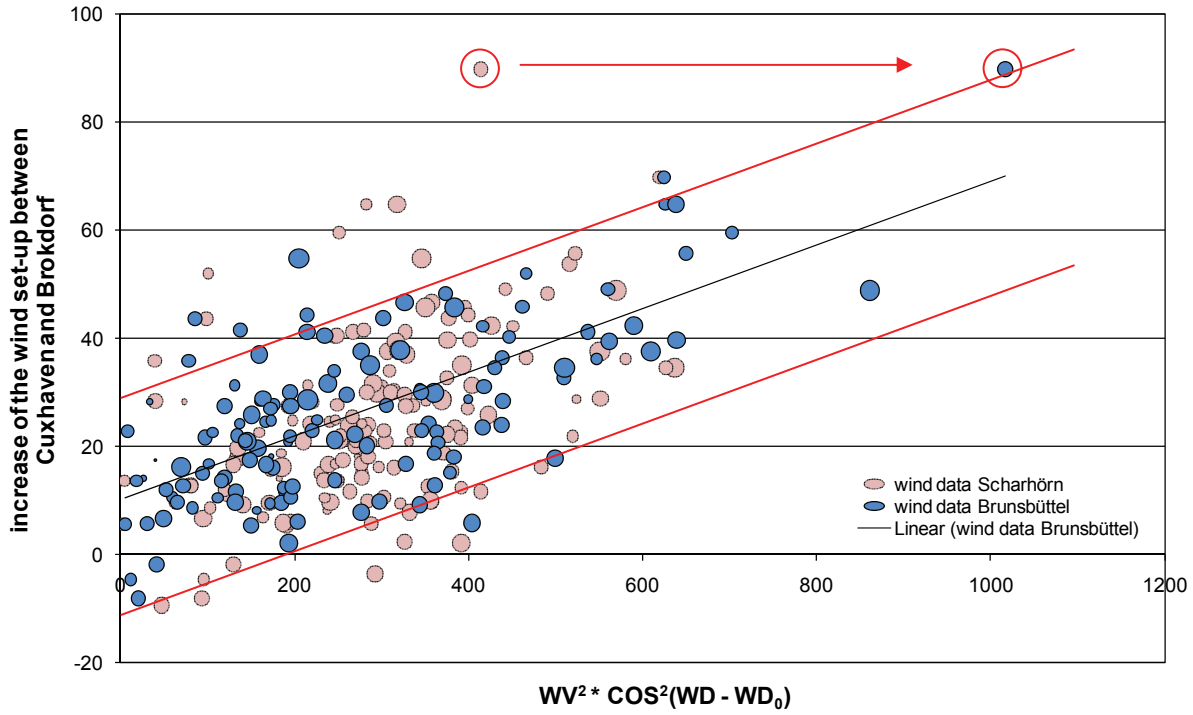

Figure 5: Influence of the local wind in the mouth of the estuary on the storm surge maxima.

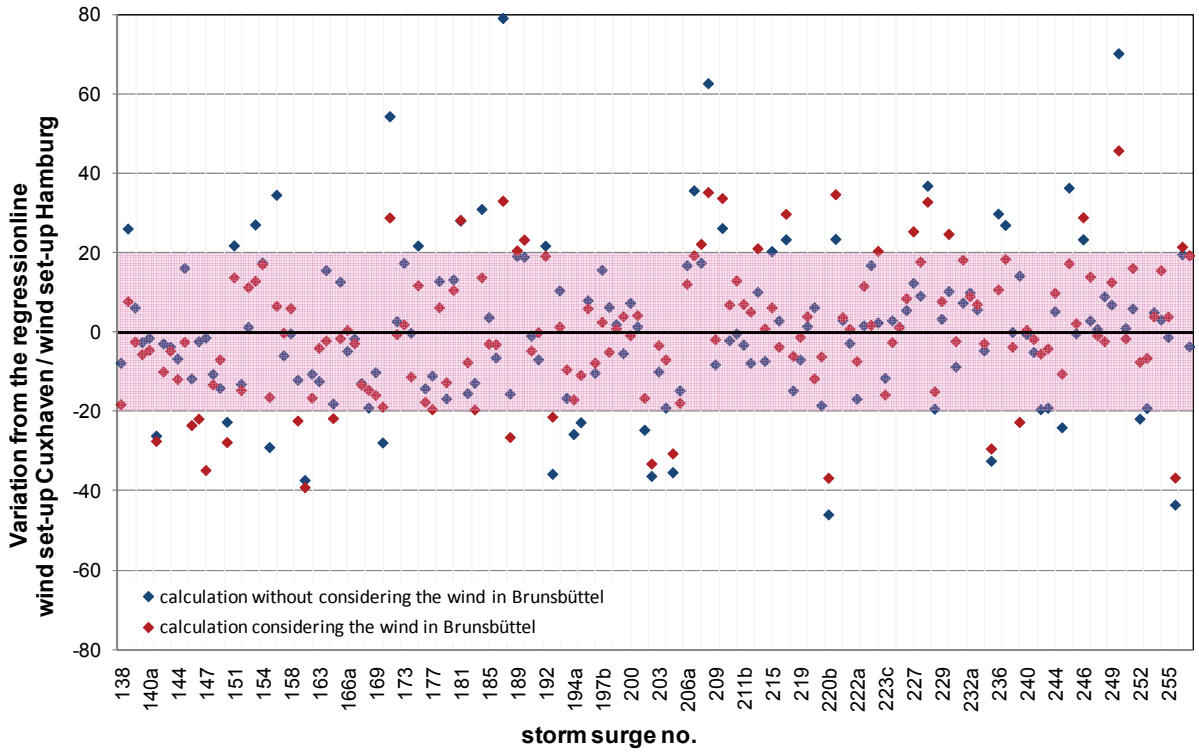

Figure 6: Comparison of wind set-up between Cuxhaven and Hamburg with and without consideration of the local wind over the mouth.

The significant influence of the local wind effects in the mouth of the estuary can be verified using a multiple regression. Its components describe the propagation of the wind set-up of storm surges from Cuxhaven to Hamburg.

$$\begin{aligned} \textit{wind set-up Hamburg} &= 1{,}158 \cdot \textit{wind set-up Cuxhaven} \\ &+ 0{,}010 \cdot f(Q) \\ &+ 0{,}061 \cdot (WV^2 \cdot \cos^2 (WD - 260°)) \end{aligned}$$

Q	fresh water discharge
WV	wind velocity Brunsbüttel
WD	wind direction Brunsbüttel

With this regression formula a significant improvement of the correlation between the wind set-up in Cuxhaven and Hamburg can be received. The calculation of wind set-up propagation from Cuxhaven to Hamburg can be improved by up to 45 cm, just by consideration of the local wind (figure 6).

Figure 5 shows the change for every storm surge calculation by applying the modified regression formula. Thus, the possibility of remarkable improvements of high water forecasts for Hamburg by considering the local wind over the outer Elbe Estuary is evident. On the other hand it is important to note, that the time period between high water in the mouth of the estuary and high water in Hamburg is only about 3½ hours in average. For appropriate high-water protection measures in Hamburg this period is rather short. So a further improvement of local wind forecasts not only for the German Bight, but particularly for the Elbe River itself is highly essential.

Besides the local wind there are still other factors that have a further influence on the development increasing of wind set-up in the Elbe estuary, for example the estuary´s filling level and the gradient of the mean water level. In addition, not only the height but also the form of the incoming surge is of great importance for its propagation upstream.

Although further analyses revealed certain relationships between some of these factors and the propagation of the surge in the estuary, these processes are hard to quantify and to describe empirically. Nevertheless, also these studies lead to a further knowledge of the development of storm floods in tidal rivers and thus to improve the local forecast systems.

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Address

Caroline Radegast
Hamburg Port Authority
Neuer Wandrahm 4
20457 Hamburg, Germany

caroline.radegast@hpa.hamburg.de