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Improvements for the Estimation of Design Water Levels with Historical and Modeled Data

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Abstract: Design water level definitions for coastal engineering applications rely on robust statistical analyses of observed extreme water levels. Since tide gauge data only cover the past decades, statistical estimations lack the information of historical events. Furthermore, mathematically correct but physically implausible extreme water level estimations should be avoided. A projection of past storm surges, like the storm surge of 1717 at the German North Sea coast, on today's conditions as well as upper limit estimations of recent research projects will be presented, explaining the importance of a large data base for the improvement of extreme value statistics-based studies. Both methods, the projection as well as the simulation, allow an improvement of design water level estimations, since previously disregarded events can now be incorporated in statistical analyses.

Keywords: design water level, extreme value statistics, storm surge, historical events, water level projection, numerical simulation, reconstruction, coastal protection

1 Introduction

The design height of flood protection measures is mostly based on observed hydrological data by estimating design events with extreme value analyses (EVA). In coastal engineering, tide gauge observations are used in EVA to estimate extreme water levels to assure protection with an acceptable low probability of failure, e.g. 1% annual exceedance probability. On a double logarithmic probability scale, distribution functions which describe extreme water levels can take shape of a progressive line (Gumbel Typ II or Frechét), a straight line (Gumbel Typ I) or a degressive line (Gumbel Typ III or Weibull) (Coles, 2001). Only the latter has an upper limit, both other functions increase steadily. Using functions with a progressive or straight line to estimate extremes with very small probabilities may yield an overestimation, which is, however, in clear contrast to the physics behind most meteorological or hydrological processes (see Fig. 1).

Therefore, historical data and a physically based upper limit are helpful for the estimation of a more reliable distribution function resulting in plausible flood protection design heights. In addition, EVA studies generally use observed data, which only go back a few decades for most tide gauges. This also limits the chances of a reliable extrapolation and, in return, low probability events can only be roughly estimated. A proper EVA should include observed extreme water levels (i.e. annual maxima or peaks over threshold), levels of historical events, upper or physical limits (e.g. by simulations, model results), and aspects on dealing with uncertainties in risk analysis approaches. The uncertainties will additionally increase by using climate change scenarios and by considering changes in coastal morphodynamics, since these processes interact and affect further developments. The challenge is to transfer historical storm surge heights to the current state of the flood protection systems (e.g. dikes, dunes, etc.) in order to improve the EVA performance.

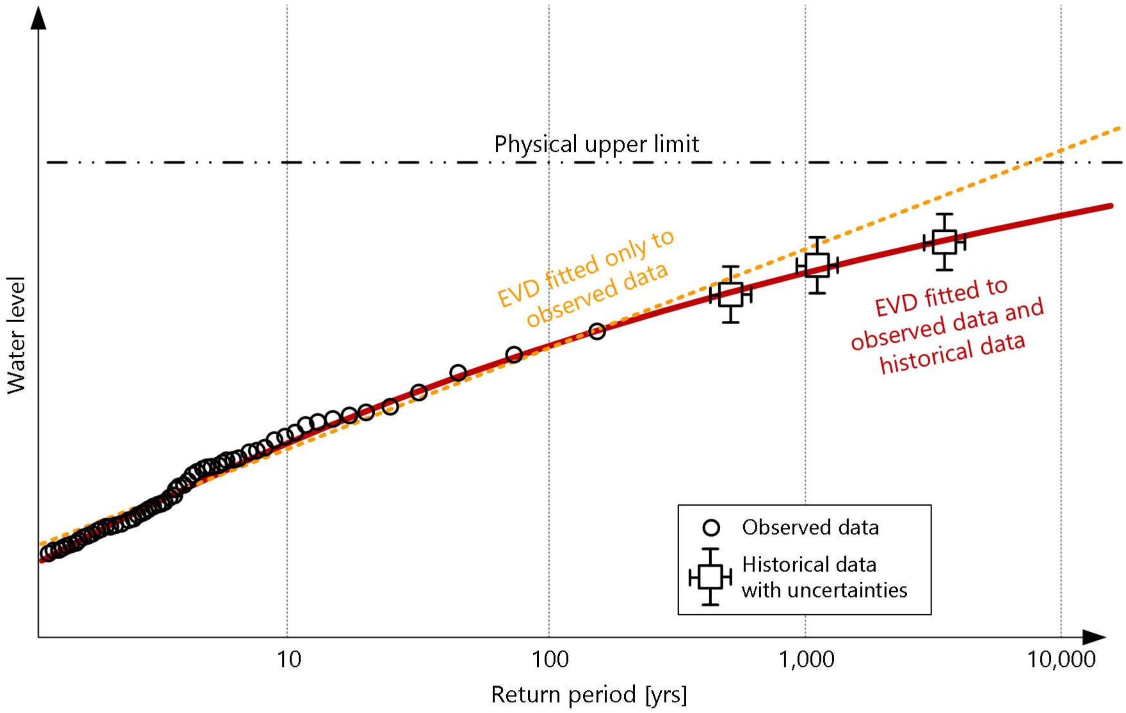

Fig. 1. Exemplary EVA: The fit of an extreme value distribution (EVD) to observed data (orange) yields good results for extrapolations within a short range (c.f. Coles, 2001). Extremely rare events (e.g. the 10,000-year-event) tend to be overestimated and estimated water levels possibly exceed physical upper limits. Historical data can help to improve the estimation by adding more support points to the EVD fit (red).

Studies with a similar aim use model chains to reconstruct historic storm surge heights. For example, Baart et al. (2011) use historic paintings to derive unmeasured water levels and numerical simulations to describe morphologic changes in order to improve the EVA estimates of extreme storm surges for the Netherlands. The chosen approach allows an improvement but also introduces uncertainties, i.a. due to inevitable model assumptions while our approach focuses on the transfer of observed trends in water level time series. Other studies try to estimate storm surge probabilities and risks for large areas (e.g. Haigh et al., 2013) or even the global coastline (e.g. Muis et al., 2016) while we work on the detailed description of locally severe historic storm surges.

In detail, we briefly highlight how extreme storm surges shaped coastal areas in the past using the German North Sea coast as an example. We show and discuss how historical extreme storm surge water levels can be projected on today’s conditions in order to provide improved knowledge for future extreme value statistics. Finally, we compare the results with model estimates from recent coastal engineering research projects, which try to explore possible physical upper limits in extreme water levels.

2 Coastline Changes and Extreme Water Levels in the North Sea

Sea level rise, storm surges, human activities, and anthropogenic effects have mainly driven the formation of today’s German North Sea coastline including its islands and islets called “Halligen”. The appearance has been altered over time due to diking, land reclamation, waterway dredging, and peat degradation, as well as following soil erosion resulting from salt production by burning peat (Jensen, 2019). However, besides from human activities, sea level rise and storm surges may have caused the most dramatic changes along the coastline over the past centuries. Examples for coastline changes due to storms or sea level rise can be found around the globe. Today alterations are often changed back to a previous state, e.g. by beach nourishments, or initially prevented by using technical coastal protection. In order to design measures, either fixed in place like a dike or flexible and temporary like a beach nourishment, design values of hydrodynamics are mandatory to provide efficient protection based on a defined level of safety.

The past gives examples for coastline changes as a consequence of insufficient coastal protection, simply because of a lack of knowledge concerning extreme storm surges at that time. One of the most catastrophic storm surges in medieval times was the “Grote Mandrenke” which dramatically changed large parts of the North Frisian and East Frisian coastline. In January 1362, the storm surge destroyed the small dikes and flooded the hinterland. Large areas of the flooded land were no longer suitable for farming and turned into tidal flats, since the dikes had not been rebuilt. Subsequently, the North Sea took these areas in the following centuries (Hadler et al., 2017). Furthermore, the storm surge of 1362 caused the sinking and loss of Rungholt, which was a major settlement with the same or probably more importance than ancient Hamburg or Kiel. With the "Second Grote Mandrenke" in 1634, the coastline was altered again towards a shape, which is similar to today's coastline, as shown in Fig. 2 (Gade et al., 2017).

These events, which are two of many more severe storm surges, highlight the importance of the knowledge about extreme storm surges and emphasize the need for robust extreme value estimations in order to provide sufficient coastal protection measures. Since statistical methods always rely on a data basis as large as possible, the incorporation of historic events, which are not on tide gauge records, is an important step towards improved design values. Although we only highlight the North Sea region in this paper, the need for precise long-term databases exists globally, as shown e.g. by Needham and Keim (2011) for the Gulf of Mexico.

Fig. 2. Development of the North Frisian coastline (red box) due to severe storm surges 1362 and 1634, after Gade et al. (2017) and Behre (2008).

3 Projection of Historical Storm Surge Events

The first storm surge heights along the German North Sea coast where reported from a storm surge in 1164 with about 20,000 fatalities (Kramer and Rohde, 1992). More historical storm surge disasters where reported in 1362, 1634, 1717, 1825, and 1906 for the entire southern North Sea coastline (Jensen and Schwarzer, 2013). Brahms (1754) conducted first studies on the historical storm surge events and their heights, followed by Woebcken (1924) and others. With regard to engineering purposes, storm surge heights, are only documented well enough since the second half of the 20th century, beginning with the disastrous flooding of the Netherlands in 1953. The earlier events often lack detailed information and precise measurement. Projections to present day conditions of the historical events over the last 1000 years would be very helpful for the extreme value analysis. The projection has to account for different geological and morphodynamic processes, which altered the coastal regime over the last centuries.

For the classification of historical storm surge water levels and especially for the comparison with today's storm surges, the consideration of changes in the overall coastal system is essential. In order to estimate how high a storm surge observed in the past would rise today under the same meteorological and astronomical conditions, three factors must be taken into account:

1. Anthropogenic changes in bathymetry and coastline,
2. subsidence and uplift with resulting bathymetric changes, and
3. changes in mean sea level.

Anthropogenically induced changes in bathymetry and coastline have a major effect on coastal hydrodynamics. In the course of the last century, significant changes in tidal dynamics have been observed due to land reclamation measures in the form of littoral fields, beach nourishments and the diking of originally unprotected lowlands, as well as the successive deepening of shipping fairways.

Subsidence or uplift of the land, measured relative to mean sea level, lead to an increase or reduction of the run-up heights with regard to the storm surge water levels measurable at the gauge. The bathymetric effects of subsidence and uplift also superimpose with anthropogenic morphology changes described above. First descriptions of the impact of land subsidence date back to the 19th and early 20th century (e.g. Brahms, 1754; Schütte, 1908). Following the retreat of the ice sheets in northern Europe after the last ice age and the associated relief of the earth's crust, strong land uplifts occurred, which can still be measured today in Scandinavia. In return, isostatic crustal adjustment causes land subsidence with rates of up to 1.5 mm/year in northern Germany (Sirocko et al., 2008). Additionally, the extraction of natural gas leads to regionally amplified subsidence rates.

The described effects show the complexity of the coastal system and its processes, which result in water level changes at the coastline. For coastal engineering and dimensioning of coastal protection, it is important to estimate how these changes gradually intensify storm surge water levels. Using projections of historical events on today's conditions, considering trends measured by tide gauges, can help to improve the design standards.

Fig. 3 shows the projection of different historical storm surge water levels at the tide gauge Emden. The historic storm surge events (red ●) occurred before the start of permanent tide gauge records in 1946 and were compiled by Rhode (1977) using storm surge markers at local buildings. While the mean sea level (MSL) trend in the Ems estuary ranges from 1.3 to 1.7 mm/year, a stronger increase of 3.4 mm/year has been observed at mean tidal high waters (MHW) (see e.g. Jensen et al., 2014). Therefore, the projection has been conducted for trends of 1.5, 2.5, and 3.5 mm/year in order to cover the entire range of different trends and to visualize the uncertainties (indicated as red ▲, ■ and ▼, respectively). Applying the trends to selected past events shows, that these events would have exceeded the high storm surges in the second half of the 20th century if they had occurred under present day conditions. Further increases, which are not covered by the linear projection, may include storm surge height amplifications due to changes in bathymetry and coastline as well as the damping effect of dike failures and overflow which occurred during the historic events (sketched as red △).

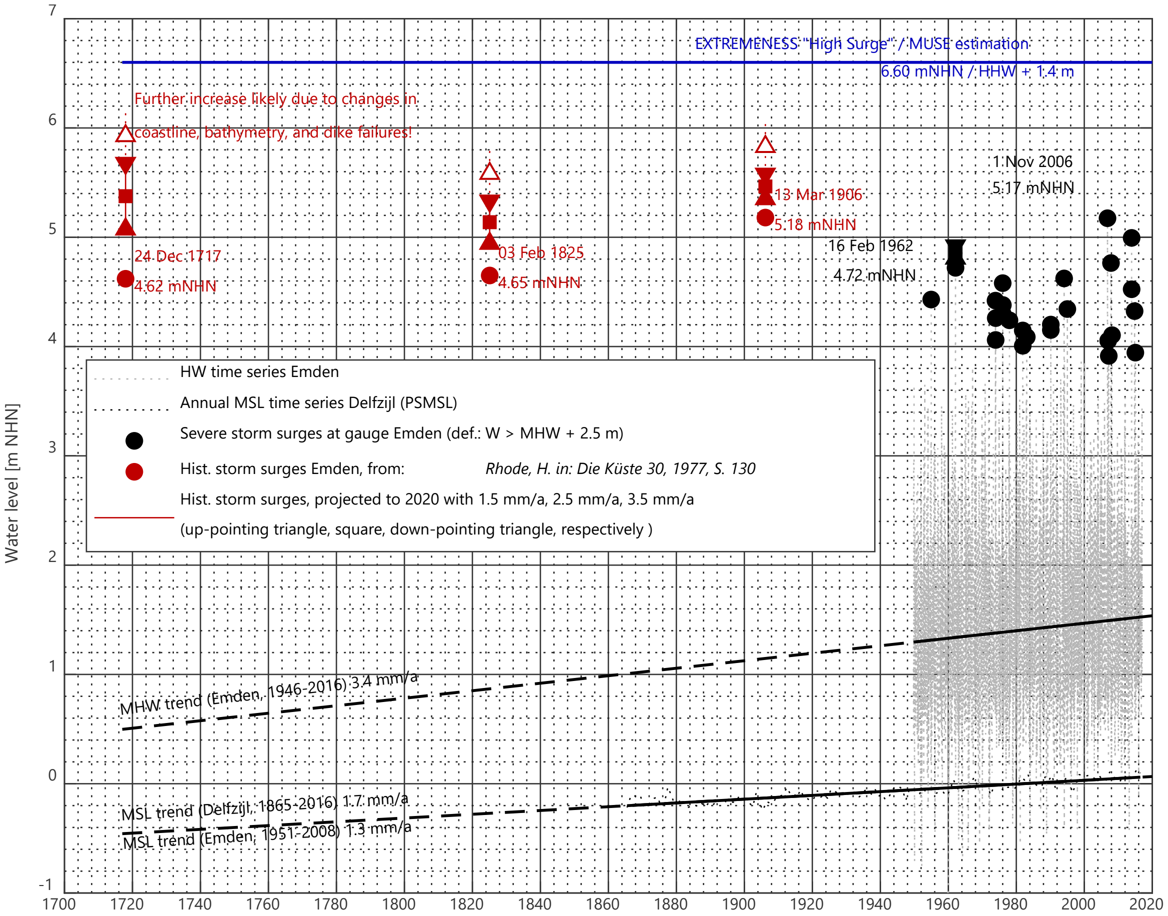

Fig. 3. Projection of historic storm surge heights on today's conditions for the tide gauge at Emden harbor, in comparison to results of the research projects MUSE and EXTREMNESS. Historical events (red ●) are projected using different trends of MSL and MHW (red ▲, ■ and ▼, respectively). Further uncertainties are indicated as red △).

Overall, the simple linear projection of the extreme events shows the potential of past storms. As an example, during the storm surge December 24, 1717 water levels rose up to 4.62 m in Emden. Considering observed trends in mean high water levels, this storm surge can be projected in the range between 5.10 m and 5.70 m, without consideration of other increasing effects like bathymetry changes or dike failures that occurred back in 1717. The resulting height is around or above observed events of the second half of the 20th century, when continuous tide gauge measurements became available. The storm surge could be the highest event under present day conditions, and is therefore relevant for design water level estimations.

4 Modeling Extreme Storm Surge Scenarios

Knowledge of the probability of the occurrence of certain storm surge levels is essential for coastal flood risk management. Recent coastal engineering research projects took a step towards estimating a physical upper limit of extreme storm surge water levels. Two project results are indicated with a blue threshold in Fig. 3 and allow a plausibility check of the projected extreme events and vice versa.

The project MUSE ("Model-backed investigations of storm surges with very low probabilities of occurrence"), funded by the German Federal Ministry of Education and Research, estimated possible extreme storm surge water levels in the entire German Bight based on model simulations and statistical analyses (Jensen et al., 2006). The model simulations were performed by using modeling chains of the German Weather Service (DWD) and Federal Maritime and Hydrographic Agency of Germany (BSH). The results were statistically evaluated at the Research Institute for Water and Environment at the University of Siegen. Using numerical prediction models, DWD computed physically possible weather and wind situations that may cause extreme storm surges in the German Bight. Besides the wind speed, the wind direction as well as the storm track are key factors for the formation of extreme water levels at the coast. Combinations leading to the most severe impacts were tested. All computations were physically consistent, i.e. only realistic weather scenarios were analyzed. The weather and wind situations computed by DWD were transferred to the BSH, which computed the resulting water levels and wind setup heights for a number of coastal locations. BSH used physically consistent numerical 2D and 3D operational storm surge forecasting models. The contribution of BSH focused especially on the selection and development of a suitable wind stress modeling approach for very high wind speeds, which may exceed 30 m/s. As Donelan et al. (2004) show using physical model experiments, a limiting state in sea surface roughness is reached at wind speeds of about 33 m/s. A further increase of wind speed does not yield a larger surge and therefore no increase in total water levels at the coast. Jensen et al. (2006) finally show that weather conditions can possibly occur in the German North Sea region, which may lead to storm surge levels exceeding the maximum levels observed so far by up to 1.40 m without stating this level as an absolute physical maximum. Changes in meteorological and hydrodynamic boundaries, e.g. driven by climate change, may shift possible storm surge heights above the estimation for today's conditions.

The ongoing project EXTREMENESS, also funded by the German Federal Ministry of Education and Research, continues the work of MUSE and examines extreme meteorological drivers and possible amplifications for the Ems estuary (Lower Saxony, Germany). Existing datasets of climate reanalysis and reconstruction simulations were searched for extreme conditions, which were then amplified, e.g. by a superposition with spring tide water levels (Ganske et al., 2018). The found hydrological and meteorological boundary conditions were then simulated using a two-dimensional numerical model to estimate storm surge water levels along the coast of the Ems estuary. Preliminary results show, that extreme storm surges may lead to water levels of 6.60 m above mean sea level, which is, for the harbor of Emden, circa 1.60 m above the highest event on record and can be statistically rated as a 1,400-year event (Ulm et al., 2019). A further step within the project EXTREMENESS is the application of different models to reconstruct events from historic meteorological data (i.e. wind and pressure fields). The German Weather Service digitized maps, e.g. from the 1906 storm surge, and provides the data for simulation runs.

With the project MUSTOK ("Modelling of extreme storm surges on the German Baltic Sea Coastline"), funded by the German Coastal Engineering Research Council (KFKI) with funds of the German Federal Ministry for Education and Research from 2005 to 2008, an approach similar to MUSE was used to reconstruct extreme water levels in the Baltic Sea (Jensen, 2009). On November 13, 1872, the most devastating storm surge on record occurred in the western Baltic Sea. In the project

MUSTOK, this event has successfully been reconstructed with a model chain of spatiotemporal high-resolution data of wind speeds and air pressure. The reconstruction of this storm surge event shows a very good agreement of water levels from observations and simulations forced by these reconstructed data (Rosenhagen and Bork, 2009). The project shows that modern modeling techniques allow the simulation of past events, which can then be used for extreme value estimations.

5 Conclusions and Outlook

The projects EXTREMENESS, MUSE, and MUSTOK show that observed storm surges of the past decades could have been more severe under unfavorable conditions and that the reconstruction of historical storm surge events is possible with remarkable results. All projects used a model chain to describe extreme meteorological conditions and the resulting storm surge water levels. While MUSE worked on the physically correct storm surge generation under extreme conditions, MUSTOK and EXTREMENESS focus on the reconstruction of historic events to estimate physically upper limits. The found heights of physically plausible extreme storm surge levels match the projection presented in this paper, which uses a simple but robust method to estimate how high extreme water levels would rise under present day conditions. Since the used projection needs careful consideration of local long-term effects in time series data, the described approach might not be suitable for global applications. It rather provides a robust tool for model verification, as shown for the three projects. Based on the results, it will be possible to improve the evaluation of extreme storm surge peak water levels with respect to their probability of occurrence, e.g. by using approaches shown by van Gelder (1996). Both methods, the projection as well as the simulation, allow an improvement of design water level estimations, since previously disregarded events can now be incorporated in statistical analyses. With a reconstruction of historical storm surges, e.g. 1362, 1634, 1717, or 1825 the basis for a statistical/probabilistical EVA is improved, yielding more robust design water levels and smaller uncertainties.

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