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YET ANOTHER 100YR STORM SURGE EVENT: THE ROLE OF INDIVIDUAL STORM SURGES ON DESIGN WATER LEVELS

Jürgen Jensen[1], Arne Arns[1], and Thomas Wahl[2]

Key words: return water levels, return periods, storm surges, design levels, Xaver.

ABSTRACT

On December 6th 2013 the German coastline was hit by the extra tropical cyclone "Xaver", which caused the highest water levels on record in some places. In the media, the resulting storm surge was quickly referred to as a "once in one hundred years" event or a "century storm surge". Based on 12 tide gauges in the German Bight, we estimate return periods of the observed water levels during Xaver and find that they were much lower than 100 years. However, in some places Xaver caused increases in the 200-year return water level estimates, which are often used for the design of coastal defences in the region. This highlights the need to re-assess design levels periodically and especially after such extreme events.

I. INTRODUCTION

On December 6th 2013 the German coastline was hit by the storm "Xaver", which caused the highest water levels on record at some coastline stretches. The associated damages were, however, relatively small which is undoubtedly a result of continuous maintenance and upgrading of the coastal defence system after the large 1953 and 1962 storm surges in the UK/Netherlands and Germany, respectively. In the media, Xaver's storm surge was quickly referred to as a "once in one hundred years" event, a term which is often used to emphasize the severity of natural hazards. With respect to its statistical meaning, this terminology is misleading and its excessive and casual usage draws a picture implying that such an event occurs more than once in a century. From the statistical point of view, this is of course possible but in most cases the term is not based on reliable analyses but is simply a dramatic first guess. For non-experts, this indicates a more frequent occurrence of extremes which in turn is believed to be a consequence of climate change. Here we analyse the storm surge water levels caused by Xaver to compare the public perception with the objective estimation. Furthermore, we investigate the impact of Xaver on return water levels in the German Bight and associated implications for coastal defenses.

II. STUDY AREA AND DATA SETS

Our study focuses on the German Bight located in the south-eastern part of the North Sea (highlighted by the blue square in Fig. 1(a)). The areas off the German coastline are part of the Wadden Sea which is one of the world's largest intertidal wetlands and has been included in the UNESCO World Heritage List since 2009. Details of the area and locations of 12 tide gauges which were considered for the present study are shown in Fig. 1(b). All tide gauges provide records of observed still water levels, consisting of mean sea level, tides, and surges (or non-tidal residuals), at least from the mid-20th century (the longest record of Cuxhaven goes back to 1843). Both the tidal and surge components are affected by shallow water effects, which lead to significant differences in the observed water levels across stations (Jensen and Müller-Navarra, 2008). These make it difficult to transfer information about the likelihood of extreme water levels from one station to another. Therefore, the assessment of the role of individual storm surges on design water levels needs to be conducted based on a collection of different stations.

III. DESIGN LEVEL ESTIMATION

Extreme value analysis can be used to estimate both the heights and occurrence probabilities of extreme events such as floods or storm surge water levels. Design levels of coastal defences are also often based on some form of statistical analysis (Dixon and Tawn, 1994). Over the last five decades, several different extreme value analysis methods for estimating probabilities of extreme still water levels have been developed (see Haigh et al., 2010 for an overview). However, none of these methods is generally applicable to all regions and stations.

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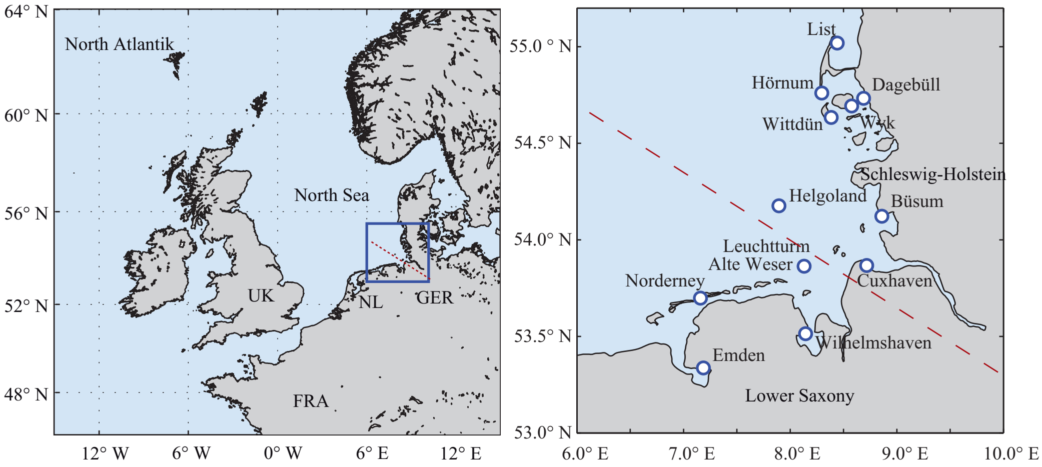

Fig. 1. (a) Location of the study area (blue rectangle) and (b) location of the tide gauges that are considered in this study.

In general, direct extreme value analysis methods can be divided into two distinct classes as follows: the block maxima (BM) method and the peak over threshold (POT) method, with each of them linked to a specific statistical model. Both approaches are referred to as "direct", because they consider the extremes of the observed total still water levels instead of modelling the astronomical tidal and non-tidal components separately. Direct methods have been widely applied in the past but there is currently no universally accepted procedure available that can be adapted to derive design levels. Instead, different procedures and methods have been applied not only on transnational, but also on national scales, resulting in a heterogeneous level of protection.

For instance, the German North Sea coastline has a length of ~1,500 km and comprised of the federal states of Lower Saxony and Schleswig-Holstein that directly border the North Sea. In Schleswig-Holstein, the design heights of coastal protection measures are calculated using extreme value analyses; defences such as sea dikes are constructed towards water levels with a exceedance probability of PE = 0.005 [1/a], i.e. an average recurrence interval of T = 200 years. As input, tidal high water records are needed. In addition to the statistically derived return water levels, the increase in mean sea level due to climate change (by 2100) is considered by adding 0.50 m on top of the design levels. In Lower Saxony by contrast, design levels are calculated using a deterministic procedure: the mean tidal high water level is combined with the largest observed storm surge, the difference between the largest spring tide and mean tidal high water, and a projected mean sea-level rise (NLWKN, 2007). As a result of these different procedures, it is difficult to assess the level of protection offered by defences across the different federal states and equally difficult to compare these with defences in neighbouring countries (e.g. the Netherlands and Denmark), which also use different design approaches and statistical techniques. The impact of individual storm surge events on design levels in the different federal states can also be hardly compared directly if different methodologies are used.

To objectively assess the effect of an individual storm surge event on design levels in the German Bight, we adapt the methodology proposed in Arns et al. (2013). They tested the main direct methods (BM and POT) to assess probabilities of extreme still water levels considering a wide range of strategies to create the extreme value datasets and a range of different model setups. They highlighted that the POT method yields more reliable and more stable estimates of probabilities of extreme still water levels than the BM method. Arns et al. (2013) also provided guidance for coastal engineers and operators for objectively setting up the POT model. For the German Bight, these recommendations involve using the POT approach which is based on the idea to consider all values exceeding a certain threshold; hence, it makes better use of the available data by including all events which are considered "extreme" (Lang et al., 1999).

As shown in Balkema and de Haan (1974) and Pickands (1975) the generalized Pareto distribution (GPD) is the limiting distribution for such excesses (i.e. the POT sample), encompassing a number of common extreme functions (Hawkes et al., 2008). The GPD is defined as

$$\mathrm{GPD} = 1 - \left[1 + \frac{\xi\, y}{\tilde{\sigma}}\right]^{1/\xi} \tag{1}$$

where $\tilde{\sigma} = \sigma + \xi(u - \mu)$
with the location parameter μ, the scale parameter σ, the shape parameter ξ and threshold value u (Coles, 2001).

In addition Arns et al. (2013) further recommended to

- create a stationary dataset using a 1-year moving average trend correction of the high water level peaks,
- create a POT sample using the 99.7th percentile threshold exceedances,
- use the extremal index (see Coles, 2001) for declustering to assure independency between successive events, and
- fit the GPD to the POT sample.

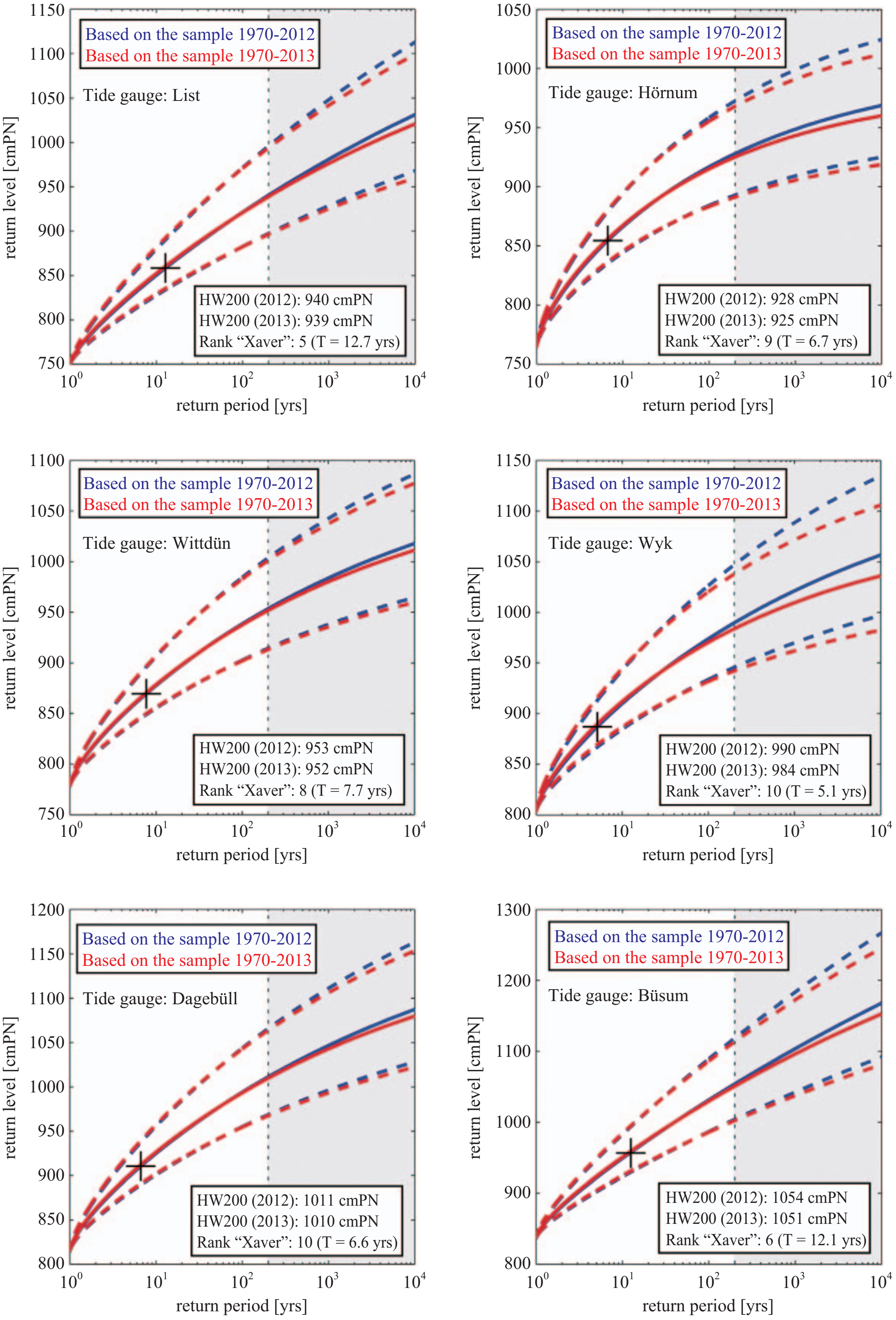

Fig. 2. Estimated return water levels at six stations which are located in the federal state of Schleswig-Holstein. The blue curve shows return levels derived from the 1970 to 2012 data; the red curve shows the same results but derived from the 1970 to 2013 data sample; the solid lines show the best fit of the distributions, the dashed lines indicated the 95% confidence bounds.

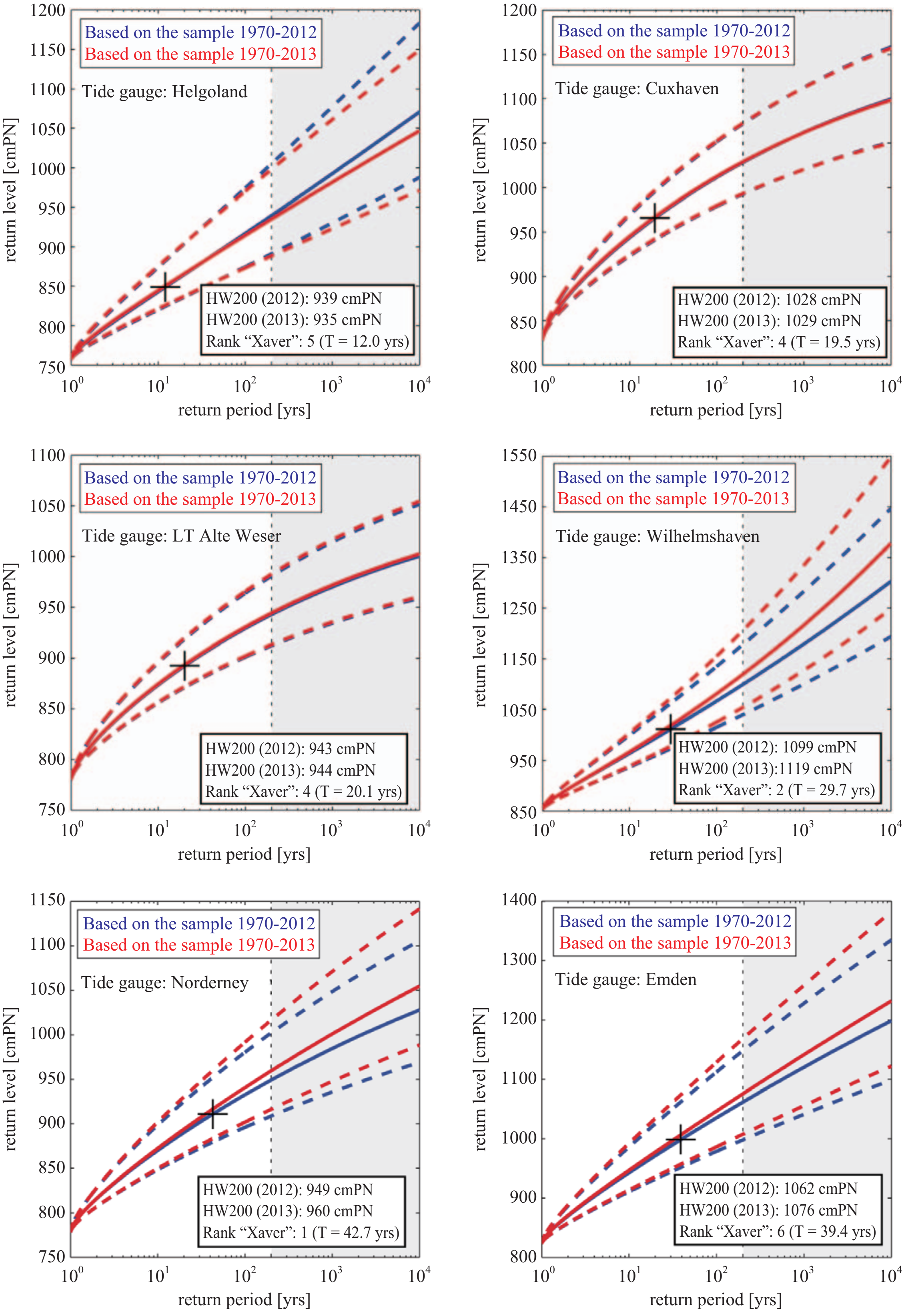

Fig. 3. Estimated return water levels at one station which is located in the federal state of Schleswig-Holstein (Helgoland) and five stations in Lower Saxony (all remaining gauges). The blue curve shows return levels derived from the 1970 to 2012 data; the red curve shows the same results but derived from the 1970 to 2013 data sample; the solid lines show the best fit of the distributions, the dashed lines indicated the 95% confidence bounds.

Table 1. Return water level changes in consequence of considering Xaver.

Station	HW200 cmPN (2012)	HW200 cmPN (2013)	Δh cm (2013-2012)	Federal state	Return period of Xaver (yrs.)
List	940	939	-1	SH	12.7
Hörnum	928	925	-3	SH	6.7
Wittdün	953	952	-1	SH	7.7
Wyk	990	984	-6	SH	5.1
Dagebüll	1011	1010	-1	SH	6.6
Büsum	1054	1051	-3	SH	12.1
Helgoland	939	935	-4	SH	12.0
Cuxhaven	1028	1029	+1	LS	19.5
LT Alte Weser	943	944	+1	LS	20.1
Wilhelmshaven	1099	1119	+20	LS	29.7
Norderney	949	960	+11	LS	42.7
Emden	1062	1076	+14	LS	39.4

To estimate the effect of one (major) individual storm surge event, the design levels are estimated for all 12 stations in the German Bight using either a sample that has been constructed from the 1970 to 2012 data (Xaver is not included; blue curves in Figs. 2 and 3) or from the 1970 to 2013 data (Xaver is included, red curves in Figs. 2 and 3). The results from both analyses are compared to highlight the impact of storm surge Xaver on estimates of design relevant return water levels.

IV. RESULTS

Fig. 2 shows the results for six stations, which are all located in the northern part of the German Bight (i.e. the federal state of Schleswig-Holstein). At all stations, it is estimated that storm surge Xaver had a return period between T ≈ 5 (Wyk) and T ≈ 13 (Norderney) years (based on the sample derived from 1970 to 2012 data). Changes in the return water levels for return periods between 1 and 200 years, after Xaver is included in the analysis (1970 to 2013 sample), are negligible (return periods above T = 200 years are grey shaded to highlight the large uncertainties in those estimates).

Fig. 3 shows estimated return water levels at one station located in Schleswig-Holstein (Helgoland) and five stations in Lower Saxony (all remaining gauges). At Helgoland (Island), Cuxhaven and Leuchtturm (LT) Alte Weser, return periods of the Xaver storm surge water levels range from T ≈ 12 to T ≈ 20 years and changes in the return water levels for return periods between 1 and 200 years are again small.

At Wilhelmshaven, storm surge Xaver had a return period of T ≈ 30, at Emden of T ≈ 40 years and at Norderney of T ≈ 43 years. At all three stations, the return water levels increase when the 1970 to 2013 sample is used. With respect to the design of coastal defences, this yields an increase in design levels of $11 \leq \Delta h \leq 20$ cm.

Table 1 summarizes the estimated return water levels for the return period of T = 200 years (used to derive design levels in Schleswig-Holstein) at all 12 stations as given in Fig. 2 and Fig. 3. The table also indicates in which federal state a particular tide gauge station is located. All stations located in Lower Saxony (LS) show small to moderate increases in return water levels due to Xaver whereas the return water levels in Schleswig-Holstein (SH) show small decreases.

V. CONCLUSIONS

We calculated return water levels for 12 tide gauges in the German Bight using records that cover either 43 (1970 to 2012; excluding Xaver) or 44 (1970 to 2013; including Xaver) years of total water level observations. Our analyses highlight that Xaver caused water levels with return periods ranging from T ≈ 5 years (Wyk) to T ≈ 43 years (Norderney), much less than is implied when referring to it as a “once in one hundred years event”. With respect to the public risk perception, this term is misleading and may result in a misinterpretation of hazards that may occur in the future.

The water levels in the German Bight are strongly influenced by shallow water effects and a complex topography of the coastline. This is why storm surge water levels can differ significantly between stations (see e.g. Jensen and Müller-Navarra 2008). In extreme value analyses, where models are likely to be extrapolated beyond the period of observations, this may cause even larger differences in the estimated return water levels at different locations – even if they are close to each other (Arns, 2014). The design level assessment therefore needs to be conducted using local tide gauge data.

The analyses furthermore showed that one individual event has the potential to impact statistically derived return (and design) water levels. The observed increases are, however, much smaller than the uncertainties (shown as dashed lines in Figs. 2 and 3) associated with the estimates, but coastal defences are usually constructed towards the distributions best fit and not the upper/lower confidence bounds. Our analyses point to negligible increases in return water levels along the coastline of Schleswig-Holstein and increases of up to 20 cm along the Lower Saxony coast. These findings highlight the need to periodically re-asses design water levels (and upgrade when necessary) to offer an appropriate level of protection over the projected lifetime of the structure.

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