Safety of Coastal Defense Systems
An Assessment of the Reliability of Coastal Systems in the Event of Rising Water Levels due to Climate Change

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Abstract

The traditional design approach to coastal defense systems on the German North Sea coast is essentially deterministic. The determination of the required dike height along the Lower Saxonian North Sea coast of Germany is based on the accumulation of maximum historically recorded deviations from the high water levels due to spring tides, wind effects and the expected wave-run-up taking into account the maximum wave-height in front of the dike. Using this deterministic design approach an assessment of the safety of coastal defense systems and the effects of changing natural conditions, e.g. caused by climate changes, is hardly possible.

Therefore a probabilistic design approach using level III analysis is applied for selected coastal areas with specific coastal defense systems, e. g. sea dikes, summer dikes, forelands, wadden sea areas, islands.

Using the probability of wave overtopping to estimate damage to the hinterland, the probability and duration of flooding is taken as the basis for calculating the safety of each regional coastal defense system and its components. The probability of wave-heights and wave-overtopping is obtained from the probability density functions of the water-levels at high tide and the wind-conditions in the model area. These input parameters, i.e. water levels and wind conditions, are related to wave-heights at each location of the model area using numerical wave models and are used to determine wave run-up and overtopping rates along the dike.

Taking into account a change in the probability distributions of the input parameters, the effects of climate changes on the probability of wave overtoppping can be determined.

The probability of wave overtopping will be quadrupled given a rise of the mean sea level of 0.5 m and increase ten-fold given a rise in 1.0 m. The absolute value of the probability of wave-overtopping largely depends on the structure of the coastal defense system. The recurrence interval varies from 400 to 80000 years.

1 Introduction

The design criteria for coastal defense systems, applied in Germany, are traditionally based on the maximum historically recorded deviations from the average high water level due to spring tides, wind effects and the expected wave-run-up taking into account the maximum wave-height in front of the dike. This deterministic design process is used by the German Commitee for Coastal Protection [1] and is shown in figure 1.

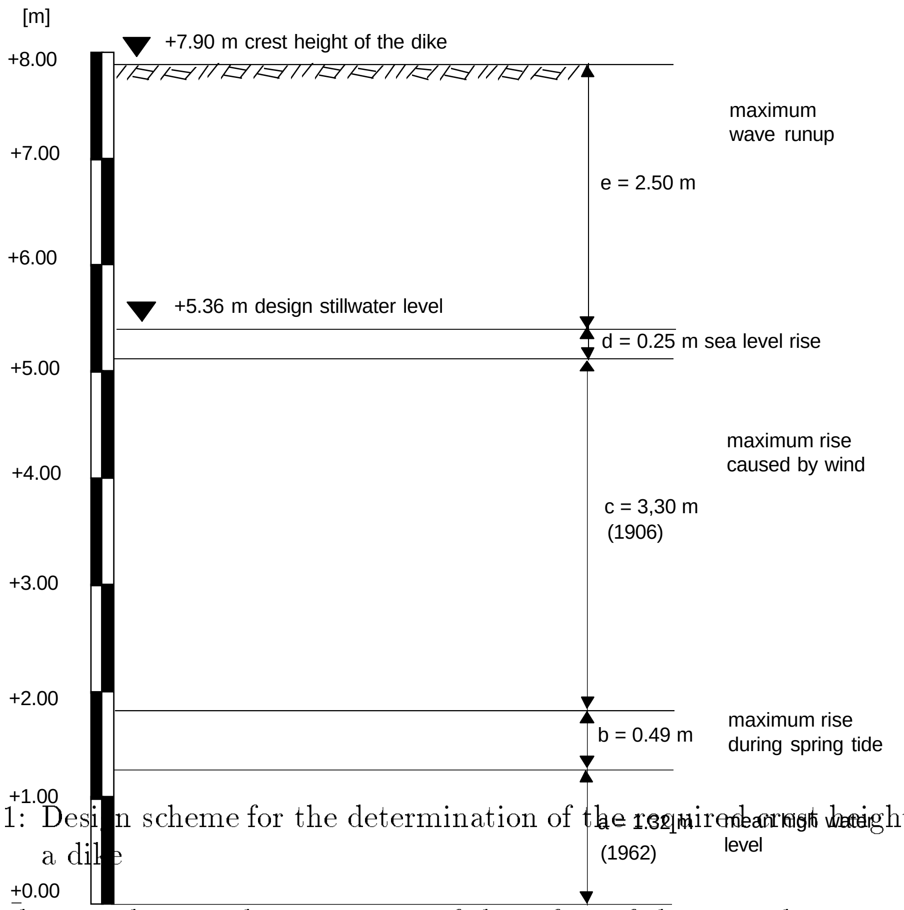

Figure 1: Design scheme for the determination of the required crest height of a dike

Using this design scheme a determination of the safety of the coastal protection, i.e. the recurrence interval of wave overtopping at the dike, is almost impossible, as is the estimation of changing safety of the protection system due to altering loads, e.g. rising sea level.

Probability-based design concepts enable these limitations to be overcome and have been presented by Plate and Duckstein [2]. An adaptation of this probabilistic design scheme for assessing the safety of flood defences has been worked out by the Technical Advisory Committee on Water Defences (TAW) [3].

This paper will show a practical application of the stated probabilistic design scheme using level III analysis. It is restricted to the failure mechanisms of overflowing and wave overtopping of the dike and neglects other minor and less important modes of failure, e.g. piping. The probability of failure of different coastal defense systems will be calculated for today's hydraulic loads - water levels and wave action - and taking into account increased hydraulic loads due to climatic changes.

2 Safety of Coastal Defense Systems

A coastal defense system is a combination of different coastal protection elements, e.g. dune islands, wadden areas, forelands, brush groynes and dikes. Figure 2 (left part) shows an example of a coastal defence system.

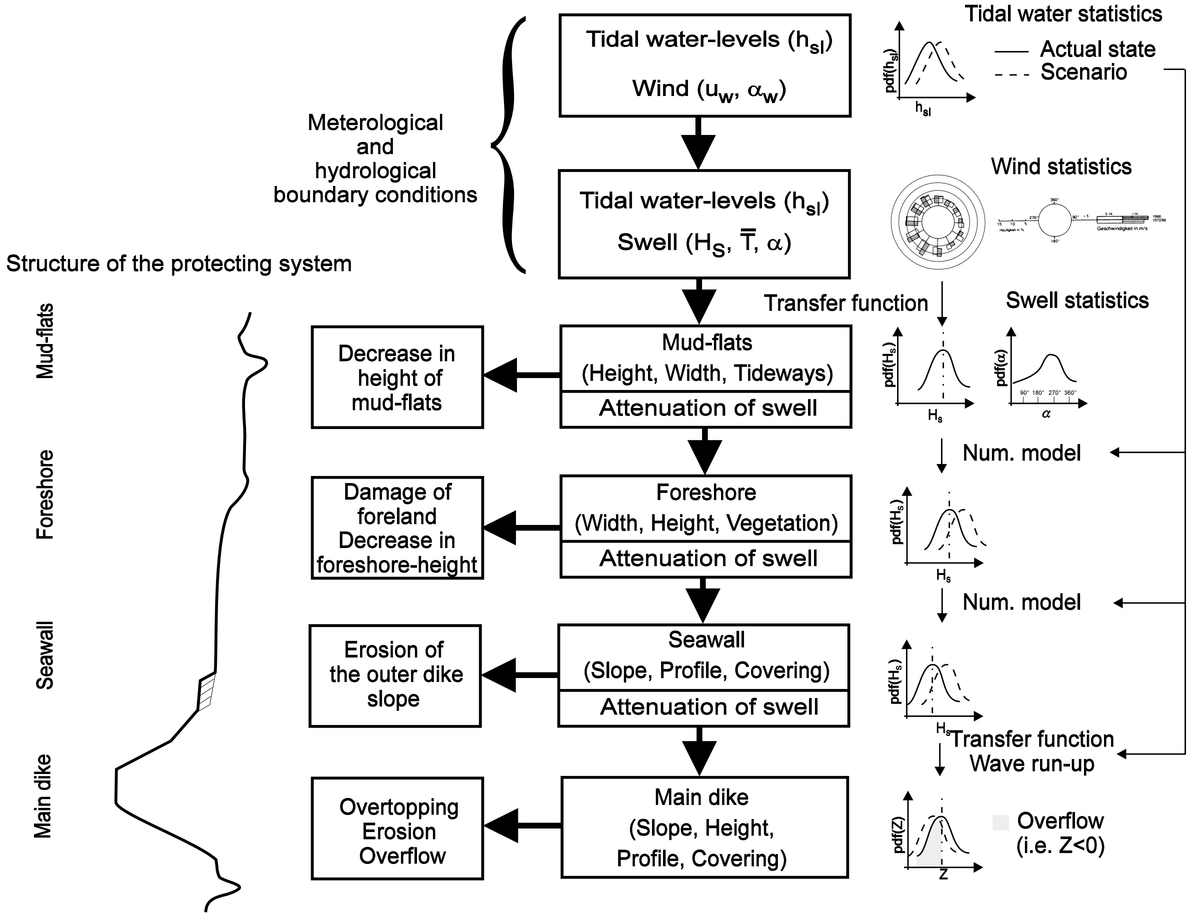

Figure 2: Probabilistic evaluation scheme for Coastal Defense Systems. An example of a coastal protection system is shown left, the applied model chain for predicting wave run-up is presented in the middle and the probabilistic approach is indicated on the right hand side.

As a standard of safety for the complete coastal protection system, the probability or the recurrence interval of wave overtopping at the most landward protection element, i. e. the dike, can be used. The failure mechanism of overtopping can be described mathematically by means of the following a reliability function

$$Z = h_d - h_{sl} - R_w \tag{1}$$

which depends on the dike height h_d, the water level in front of the dike h_{sl} and the wave run-up R_w. For $Z < 0$ the protection system fails, i.e. overtopping occurs. The wave run-up can be calculated using Battjes [4] formula

$$R_w = \frac{1}{n}\overline{T}_d\sqrt{gH_{s,d}} \tag{2}$$

in which $1/n$ is the dike slope, $\overline{T}_d$ is the mean wave period, g is the acceleration due to gravity and $H_{s,d}$ is the wave height in front of the dike. Besides the Battjes formula various others can be found in Tautenhain [5].

The wave height in front of the dike is a function of the water-level h_{sl}, the incoming wave field on the seaward side of the coastal protection system, which can be described by the significant wave height H_s, the mean period $\overline{T}$ and the angle of propagation α, the wind field with the parameters wind velocity u_w and wind direction α_w. This can be described mathematically by

$$\begin{aligned} H_{s,d} &= \tilde{f}(h_{sl}, H_s, \overline{T}, \alpha, u_w, \alpha_w) && (3)\\ T_d &= \tilde{g}(h_{sl}, H_s, \overline{T}, \alpha, u_w, \alpha_w) && (4)\\ R_w &= \tilde{h}(h_{sl}, H_s, \overline{T}, \alpha, u_w, \alpha_w) && (5) \end{aligned}$$

The transfer functions $\tilde{f}$, $\tilde{g}$ and $\tilde{h}$ depend on the structure of the coastal protection system and its elements and can be determined using a wave model, which is indicated in the middle of figure 2.

The parameters h_{sl}, H_s, $\overline{T}$, α, u_w, α_w on the seaward side are probability distributed. Therefore the parameters of $H_{s,d}$, $\overline{T}_d$, R_w and Z at the dike are also probability distributed (figure 2, right). The mathematical relationship between the probability functions of the seaward parameters and the parameters at the dike are given by

$$\begin{aligned} p_{(H_{s,d})} &= \int\cdots\int_{H_{s,d}=\tilde{f}(h_{sl},H_s,\overline{T},\alpha,u_w,\alpha_w)}\cdots \\ &\quad \cdots p_{(h_{sl},H_S,T,\alpha,u_w,\alpha_w)}dh_{sl}\,dH_S\,dT\,d\alpha\,du_w\,d\alpha_w && (6)\\ p_{(\overline{T}_d)} &= \int\cdots\int_{\overline{T}_d=\tilde{g}(h_{sl},H_s,\overline{T},\alpha,u_w,\alpha_w)}\cdots \\ &\quad \cdots p_{(h_{sl},H_S,T,\alpha,u_w,\alpha_w)}dh_{sl}\,dH_S\,dT\,d\alpha\,du_w\,d\alpha_w && (7)\\ p_{(R_w)} &= \int\cdots\int_{R_w=\tilde{h}(h_{sl},H_s,\overline{T},\alpha,u_w,\alpha_w)}\cdots \\ &\quad \cdots p_{(h_{sl},H_S,T,\alpha,u_w,\alpha_w)}dh_{sl}\,dH_S\,dT\,d\alpha\,du_w\,d\alpha_w && (8)\\ p_{(Z)} &= \int\cdots\int_{Z=h_d-h_{sl}-\tilde{h}(h_{sl},H_s,\overline{T},\alpha,u_w,\alpha_w)}\cdots \\ &\quad \cdots p_{(h_{sl},H_S,T,\alpha,u_w,\alpha_w)}dh_{sl}\,dH_S\,dT\,d\alpha\,du_w\,d\alpha_w && (9) \end{aligned}$$

with $p_{(h_{sl},H_s,T,\alpha,u_w,\alpha_w)}$ being the joint probability distribution of the parameters on the seaward side of the coastal defense system, $p_{(H_{s,d})}$ the probability distribution (pdf) of the significant wave height in front of the dike, $p_{(\overline{T}_d)}$ the pdf of mean wave period at the dike, $p_{(\overline{R}_w)}$ the pdf of the wave run-up, $p_{(Z)}$ the pdf of the reliability function.

By integrating the pdf of the reliability function over a negative range we can calculate the probability of wave overtopping $p_{Z<0}$, i.e. failure of the coastal protection system as a whole:

$$p_{Z<0} = \int_{-\infty}^{0} p_{(Z)} dZ \tag{10}$$

The recurrence interval T_r of wave overtopping equals the inverse of the probability of failure ($T_r = 1/p_{Z<0}$).

Changing hydraulic loads will result in a change in the joint pdf of the incident parameters and therefore alter the reccurence interval of failure. Changes in the form of the coastal protection system will alter the transfer functions $\tilde{f}$, $\tilde{g}$, $\tilde{h}$ and therefore alter the reccurence interval as well.

In practice a strong correlation exists between wind conditions and wave conditions. It is therefore possible to estimate the wave conditions at the seaward boundary using wind data, e.g. by using $\alpha = \alpha_w$, $H_s = 0.283 \cdot u_w^2/g \tanh\left(0.53 \cdot (gd/u_w^2)^{(3/4)}\right)$ and $T = 7.54 \cdot u_w/g \tanh\left(0.833 \cdot (gd/u_w^2)^{(3/8)}\right)$,in which d is the water depth depending on h_{sl} , described by CERC [6] or by using more locally valid equations derives from field measurements; for the study of the East-Frisian coast of Germany Niemeyer [7] gives the relationship $H_s = 0.35\,(u_w^2/g)^{0.66}$. The derivation of wave conditions from wind conditions is also preferable because in contrast to measurements of water-levels and wind conditions, long term measurements of wave conditions are very rare. Since H_s, T and α are functionally dependent on u_w, α_w and h_{sl} the joint probability function $p_{(h_{sl},H_S,T,\alpha,u_w,\alpha_w)}$ reduces to $p_{(h_{sl},u_w,\alpha_w)}$ and the equations 6 to 9 reduce to a triple integration.

3 Wave Propagation within Coastal Protection Systems

The transfer functions $\tilde{f}$, $\tilde{g}$ and $\tilde{h}$ largely depend on the coastal defence system and have been determined using the numerical wave model HISWA (Hindcast Shallow Water Waves) described by Booij et al. [8].

Figures 3 and 4 show the significant wave height and the location of the research area.
Because of the varying extent of coastal protection elements - the forelying islands, reefs and wadden areas cover a very large area in contrast to the elements located

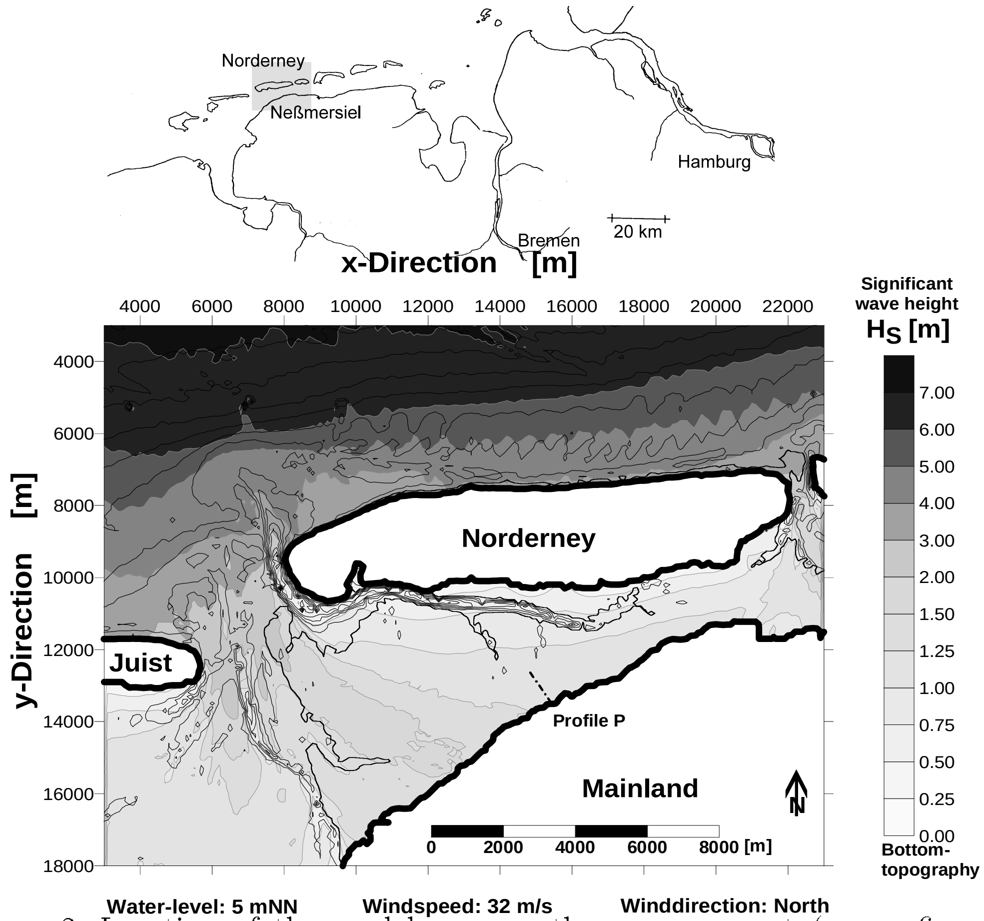

Figure 3: Location of the model area on the german coast (upper figure) Modification of the wave height due to islands and wadden area (lower figure)

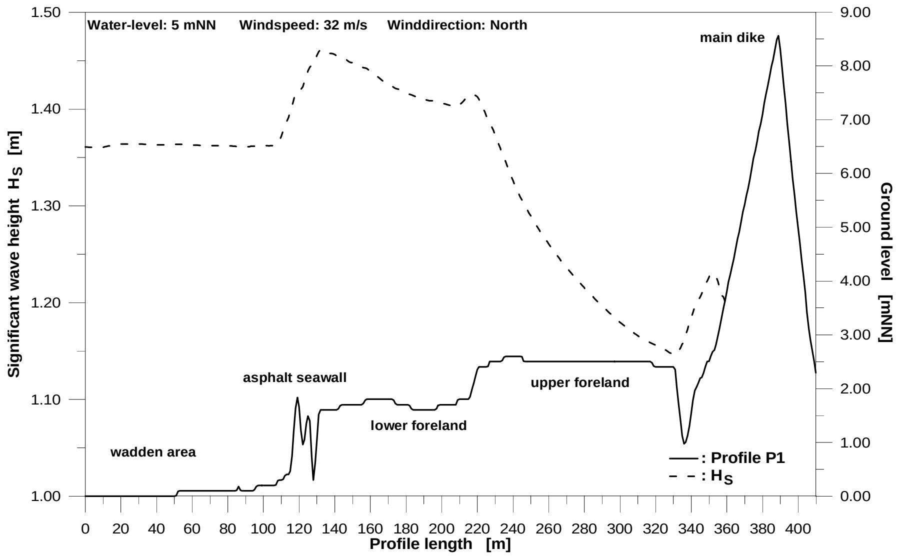

Figure 4: Modification of the wave height due to a seawall and foreland

next to the coast line, like brush groynes, forelands and summer dikes - wave propagation has been carried out using different grid spacings.

An example of the results is shown in figure 3 calculated using a grid spacing of 100 m for the numerical calculations at the seaward end of the coastal protection system and in figure 4 using a spacing of 1 m directly in front of the dike. Figure 3 shows the importance of islands in reducing the wave height. It also reveals the dependence of wave attack on the location along the coast. The damping effect of forelands on waves can be seen in figure 4.

4 Results

The coastal protection system being examined is part of the Lower-Saxonian Coast of Germany (Fig. 3) The joint probability function $p_{(h_{sl},u_w,\alpha_w)}$ describing the load on the coastal protection system has been determined using 50-years of measurements of tidal water-levels and wind speed. In order to visualise the joint probability function, it can be factorized to give the approximation $p_{(h_{sl},u_w,\alpha_w)} \approx p_{(h_sl)} \cdot p_{(u_w,\alpha_w)}$. The pdf of the high water level is shown in figure 5 and the pdf of wind-speed and direction is shown in figure 6.

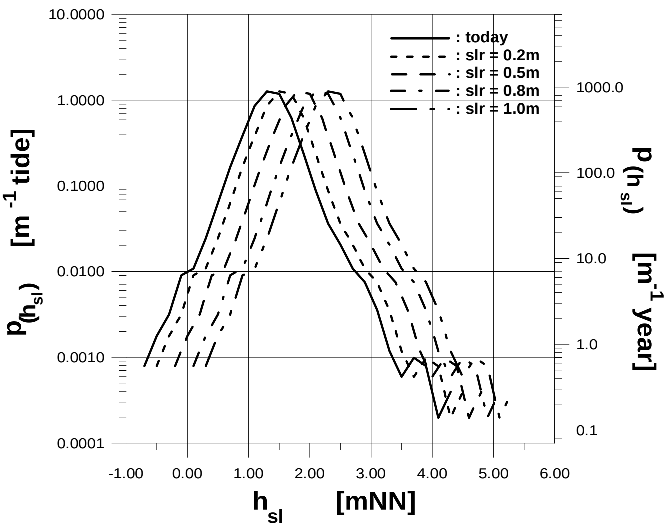

Figure 5: Probability density function of high water level. The solid line represents today's situation and the the dashed lines are scenarios for a sea-level rise (SLR) of 0.2 m to 1.0 m.

Besides today's pdf of high water level (solid line) figure 5 shows possible scenarios of pdfs after a sea-level rise of 0.2 m to 1.0 m, which have been determined by shifting the whole distribution to higher water-levels. The anticipated rise of 0.2 m to 1.0 m may be reached within one hundred years [9].

A change in wave parameters within the coastal protection system results in chang-

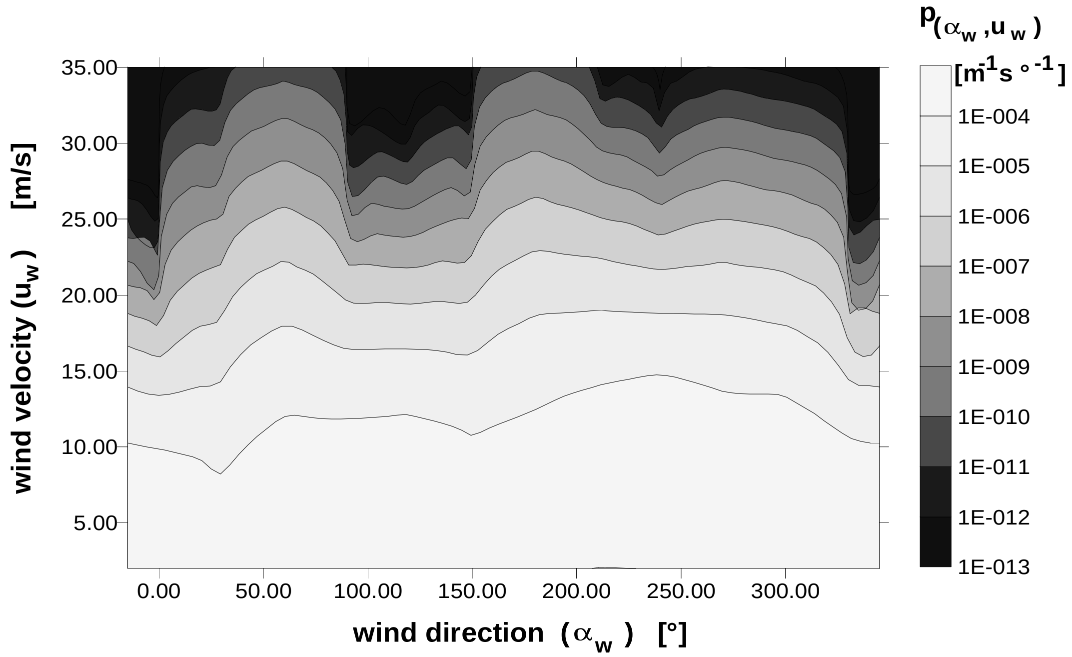

Figure 6: Joint probability density function of wind direction and wind speed at the German Bight

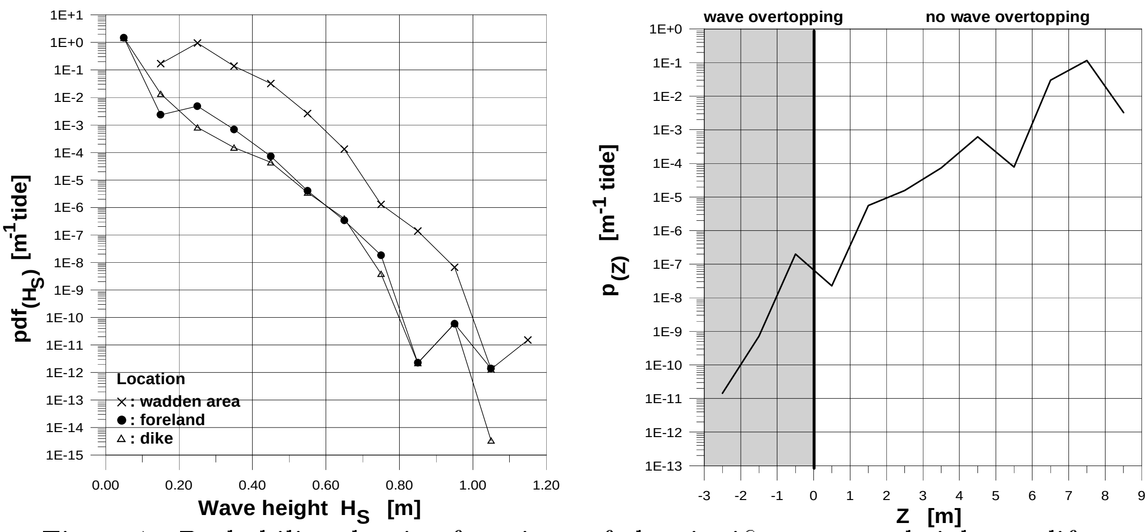

Figure 7: Probability density functions of the significant wave height at different locations within the Costal Defense System (left) and of the reliability function (right)

ing pdfs of the parameters and the reliability function (see eq. (6) and eq. (9)). This is shown in figure 7 for the significant wave height and the reliability function using today's pdfs of input parameters.

Figure 7 shows that the probability of higher waves is reduced coming from the seaward side (wadden area) of the coastal protection system towards the dike. The degree of reduction is a measure of the effectiveness of the protection system. The shaded area in figure 7 (right) relates to failure, i.e. $Z < 0$.

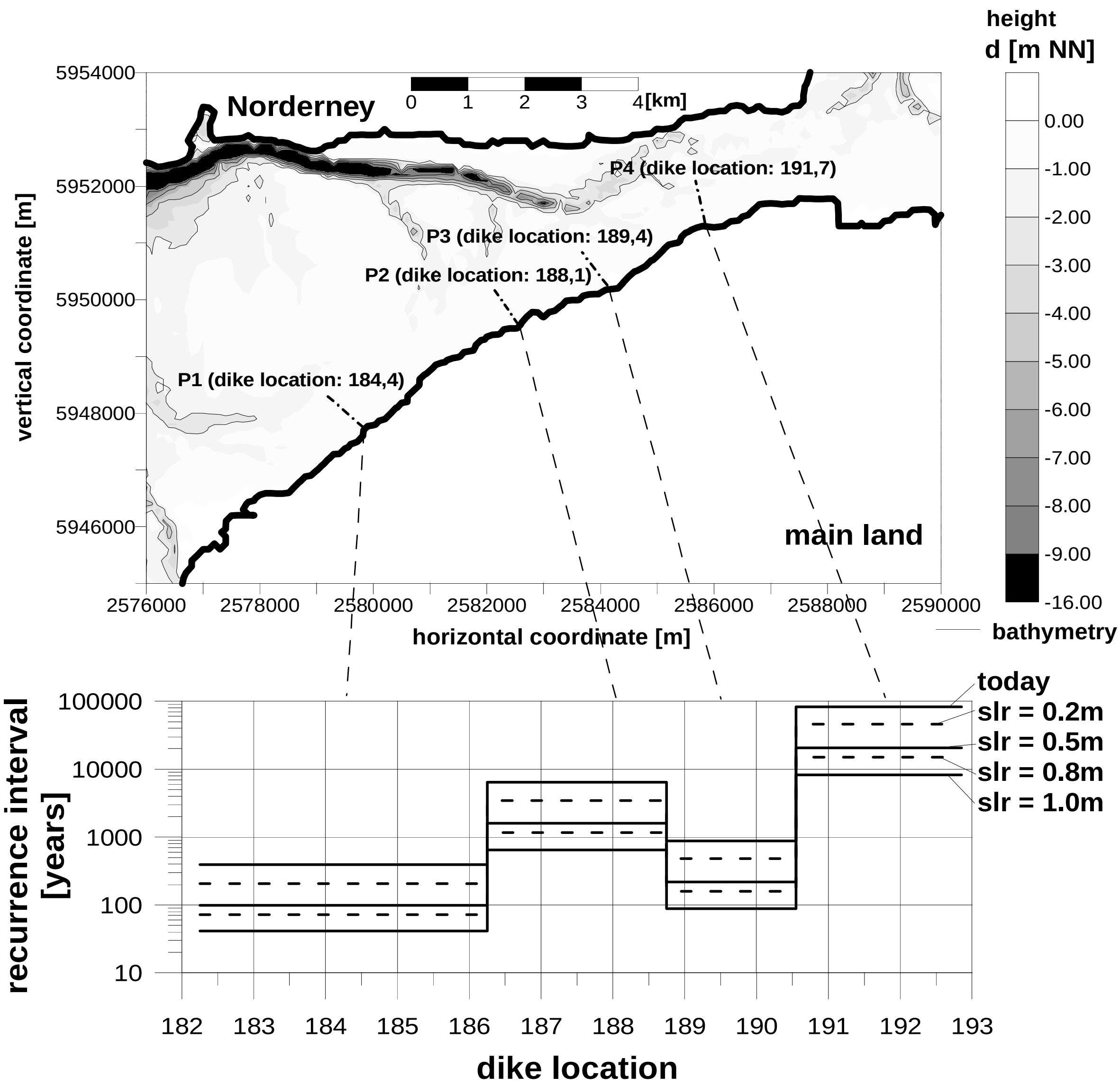

Figure 8: Recurrence interval of wave overtopping along the Lower-Saxonian coast for today and different scenarios of sea-level rise

Calculating the probability of failure for different coastal defense systems and locations along the German coast (see eq. (10)) gives a recurrence interval T_r that varies from 400 to 80000 years. This is despite the fact, that the coastal defense systems have been designed using the same standard scheme, described in the introduction. Figure 8 shows the influence of the location along the coast on the recurrence interval for today's pdf of water-levels and the assumed pdf after a sea-level rise.

A sea-level rise of 0.5 m will reduce the recurrence interval to a quarter of today's value and a rise of 1 m to a tenth, almost independently of the location along the coast.

5 Conclusion

The shortcomings of traditional design schemes which take into account only maximum deviations of water levels have been pointed out. These problems can be overcome by using probabilistic design schemes which lead to a more economic design of coastal defense systems and provide a means for determining the impact of climatic changes on coastal protection.

Acknowledgments
This research was supported in part by the Ministry of the Environment of Lower Saxony, Germany. We also thank T. Scorer for his help in editing the manuscript.

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