

Risk Analysis – A Tool for Coastal Hazard Mitigation

S. Mai¹ and C. Zimmermann²

Abstract

Large parts of the coastal hinterlands at the German North Sea coast are endangered from flooding during storm surges. In order to improve hazard mitigation the method of risk analysis is introduced in the strategic planning of coastal defenses. Risk analysis comprises the calculation of the failure probability of different coastal defense structures, especially of sea dikes, and the determination of the consequences in case of flooding. The basic principles are outlined and exemplified in a climate impact assessment studying the effect of rising sea levels and intensifying winds on the risks related to storm surges. To cope with an increase of risk different strategies, like strengthening of existing coastal defense structures and introducing additional coastal defenses, are developed and evaluated with respect to their efficiency in reducing risk.

Introduction

German coastal hinterlands are protected from flooding by a system of coastal defense elements. Besides of sea dikes and storm surge barriers as the major elements additional defense structures, like forelands and overflow dikes can be found. Today's layout of the coastal defense system focuses very much on the major defense elements. The design of these defenses is based on deterministic methods in the moment. The land use of the protected hinterland as well as its economic value is not considered in the actual design. As a consequence the level of flood protection near cities with high economic value and a large population density is not higher than the level of safety near rural areas with low population density.

The probabilistic risk analysis is a possibility to overcome the mentioned deficits of deterministic design. A general description of this design concept is given by TAW/CUR (Vergeer, 1990).

¹Franzius Institute for Hydraulic, Waterways and Coastal Engineering, Department of Civil Engineering, University of Hannover, Nienburger Str. 4, 30167 Hannover, Germany (since 01/01/2005: Federal Institute of Hydrology, Mainzer Tor 1, 56068 Koblenz, Germany; PH (+49) 261-1306-5322; email: mai@bafg.de)

²Franzius Institute for Hydraulic, Waterways and Coastal Engineering, Department of Civil Engineering, University of Hannover, Nienburger Str. 4, 30167 Hannover, Germany; PH (+49) 511-762-5481; FAX (+49) 511-762-4002; email: zi@fi.uni-hannover.de

On the basis of the theory of TAW/CUR and the existing deterministic German design rules Mai and Zimmermann (2000) as well as Mai and Ohle (2002) proposed a probabilistic design concept for the German coast. This probabilistic methodology is applied in the presented study to analyze the influence of climate change, i.e. sea level rise and intensifying winds, on the coastal safety.

In order to mitigate the increasing hazards an adaptation of the coastal defense system is necessary. The strengthening of the existing main coastal defense elements, e.g. heightening of sea dikes, is the traditional strategy of adaptation. A possible alternative strategy is the set-up of additional coastal defense elements, like backward dikes. Both strategies will be exemplified in the following.

Concept of Probabilistic Risk Analysis

The basic idea of probabilistic risk analysis is the definition of the quantity risk (R) as the product of the probability (p_f) of failure, e.g. dike breach, and the consequences (C_f) in case of failure, e.g. economic losses due to flooding after dike breach:

$$R = p_f \cdot C_f$$

In order to calculate the failure probabilities the most important failure modes of the major coastal defense elements as well as the defense system respectively have to be identified and mathematically described by a limit state function (Z). For the sea dike as the predominant major coastal defense element the limit state function may be calculated from the height of the dike (h_D), the high water level (h_{wl}) in front of the dike and the wave run-up (R) at the dike:

$$Z = h_D - h_{wl} - R$$

Knowing the probability distribution (p) of the parameters h_D , h_{wl} , R the probability of failure, i.e. the probability of a negative Z , is calculated by

$$p_f = \int_{Z < 0} p_{R, h_{wl}}(R, h_{wl}) dR dh_{wl}$$

A more detailed description of the calculation of failure probabilities is given by Mai and Zimmermann (2003).

Flooding of low-lying coastal hinterland is the most important contribution to the consequences to be expected in case of a dike breach. The flooded area (A) as well as the depth of flooding (d) is generally determined using two-dimensional numerical simulations (Mai and Ohle, 2002). Due to the inundation the economic values (v) within the hinterland are partly damaged. The degree of damage ϕ is typically

parameterized with the depth of flooding. The consequences, i.e. the loss, may therefore be calculated by

$$C_f = \iint_A v(x,y) \cdot \varphi(d(x,y)) dA$$

A more detailed description of the estimation of the consequences in case of dike failure is given by Elsner et al. (2003). In the following the given concept is applied to a part of the German coastal zone between the seaports of Bremerhaven and Cuxhaven.

Failure Probabilities of Coastal Defenses

As presented in the previous paragraph the calculation of the failure probability of a sea dike requires the knowledge of the probability of tidal high water levels and wave run-up.

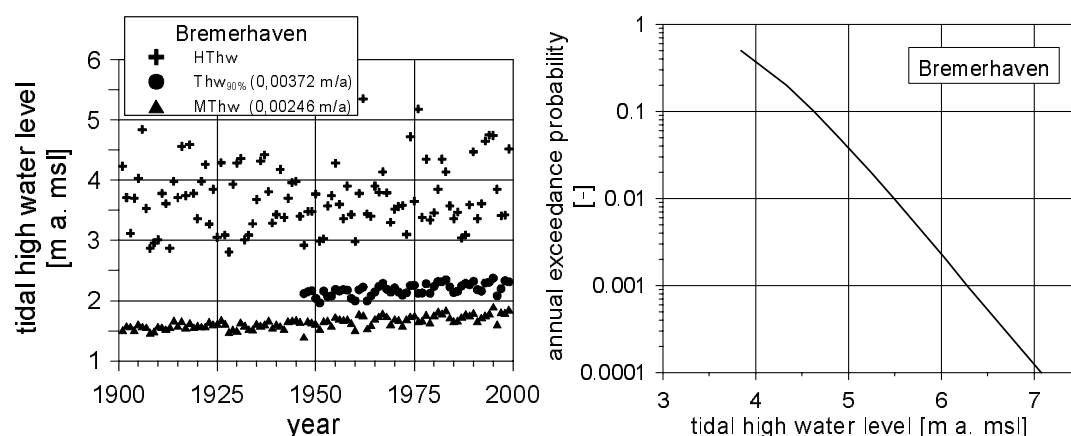


Figure 1. Data series of characteristic annual tidal high water levels (left) and statistics of extreme tidal high water levels (right)

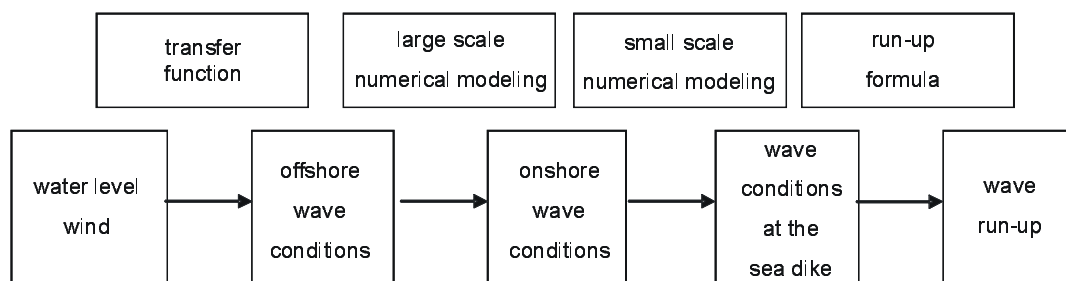


Figure 2. Modeling concept in order to relate wave run-up with water level and wind

The statistics of the tidal high water levels may be derived from long-term registrations of tide gauges. An example of the registered annual characteristic tidal high water levels is given in Figure 1 (left). After the homogenization of the data-set the statistics are derived by fitting a Log-Pearson 3 distribution to the data (see Figure 1, right). Uncertainties of different statistical models are discussed by Mai and Zimmermann (2000).

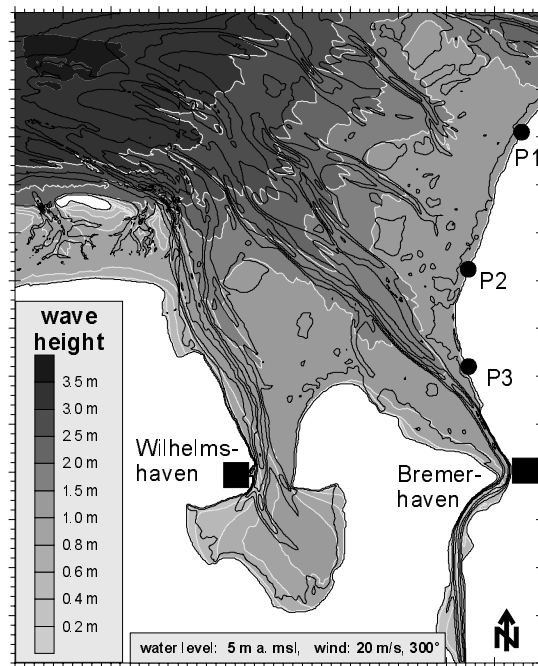


Figure 3. Large-scale modeling of wave propagation within the coastal zone

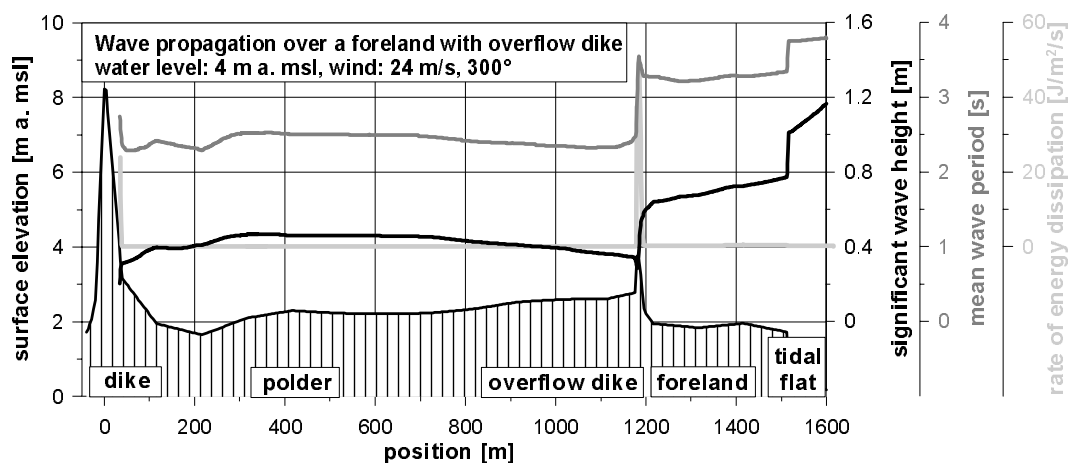


Figure 4. Small-scale modeling of wave propagation revealing the reduction of wave load due to additional coastal defense elements (here: foreland and overflow dikes)

In contrast to that the statistics of wave run-up cannot be derived from measurements because long-term recordings are missing. Therefore numerical simulations are used to relate the wave run-up with the water level and wind conditions because for these extreme statistics is available. The modeling concept is outlined in Figure 2. Examples of the major steps of this concept, i.e. large scale and small scale simulations of wave propagation, are given in Figure 3 and 4.

The numerical simulations reveal the reduction of wave load by additional minor coastal defense elements, like forelands and overflow dikes. Due to the reduction of wave load the safety of the coastal defense system is significantly increased as the following analysis shows (see Figure 5). Wave modeling is combined with the conditional probability of winds during storm surges (see Mai and Zimmermann, 2003) in order to calculate the statistics of waves and wave run-up. An example of the conditional probability of winds is given in Figure 6 showing that north-westerly winds with average speeds of 14 m/s to 18 m/s are typical during storm surges at the German coast.

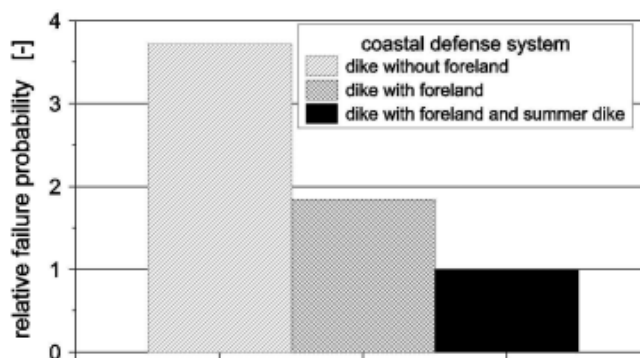


Figure 5. Effect of additional elements on the safety of the coastal defense system

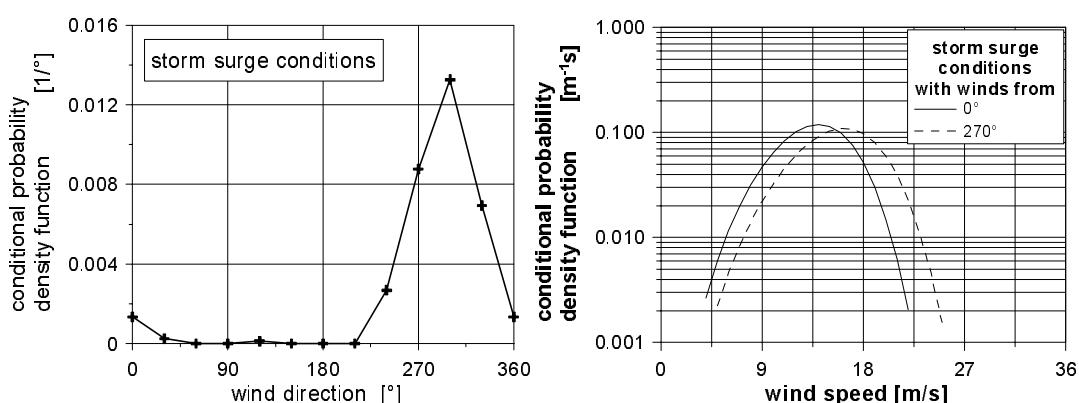


Figure 6. Conditional probability of wind direction (left) and wind speed (right) during storm surges

The joined extreme statistics of tidal high water levels and winds finally give the failure probability of sea dikes. With the actual dike height of 8.25 m at location P3 (see Figure 3) the annual failure probability amounts to 0.0003. An increase in the height of the dike of 1 m decreases the failure probability to 1/8 (see Figure 7).

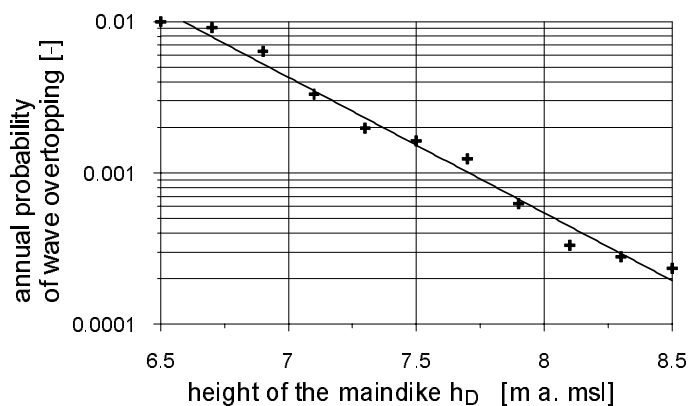


Figure 7. Influence of the height of a sea dike on its failure probability

Today's failure probability will increase in the event of an accelerating climate change leading to an increase in water level and wind speed. At the German coast a water level rise of 50 cm and an increase in wind speed of 7 % is anticipated within the next 50 years causing also a significant increase in wave load (Mai and Zimmermann, 2004). The effect of a sea level rise and of an intensification of wind speed on the failure probability is given in Figure 8. It can be seen that in case of the anticipated sea level rise the failure probability increases by a factor of approx. 5 while the anticipated intensification of the wind speed only leads to an increase of the failure probability by a factor of up to 1.25.

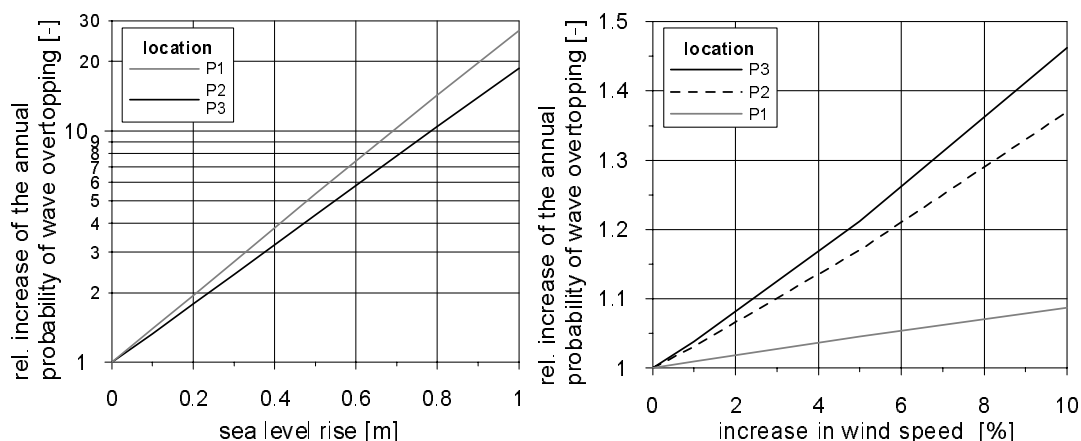


Figure 8. Increase of the failure probability (i.e. overflow) of coastal defense systems in case of water level rise and intensifying winds

Consequences of Failure of Coastal Defenses

The analyzed failure of sea dikes is on average related with dike breaches of 150 m as a review of historic breaching events shows. Assuming this width of breaching the flooding of the coastal hinterland is simulated with the hydrodynamic model MIKE 21 HD. The model is capable to calculate time-series of the spatial distribution of water levels and flow velocities within the hinterland. By further analysis of these time-series predictions of the available time for evacuation but also of the maximum water depth to be expected within the flood zone can be made. An example of the maximum water depth calculated for a dike breach near the location P3 is given in Figure 9.

A histogram of the maximum water depth within the flooded area is also given. In case of today's set-up of the coastal defense system with main dike and no additional secondary dike the mean depth of flooding is approximately 0.5 m.

Overlaying the land use with the maximum water depth allows an estimate of the assets effected from flooding by attributing the economic value per unit area to the different land uses. The damage to the effected economic values is calculated using damage functions given by Elsner et al. (2003). For the inundation given in Figure 10 the economic loss amounts to approx. to 100 Mio. €. The flood loss strongly depends on the location of a dike breach (see Figure 11).

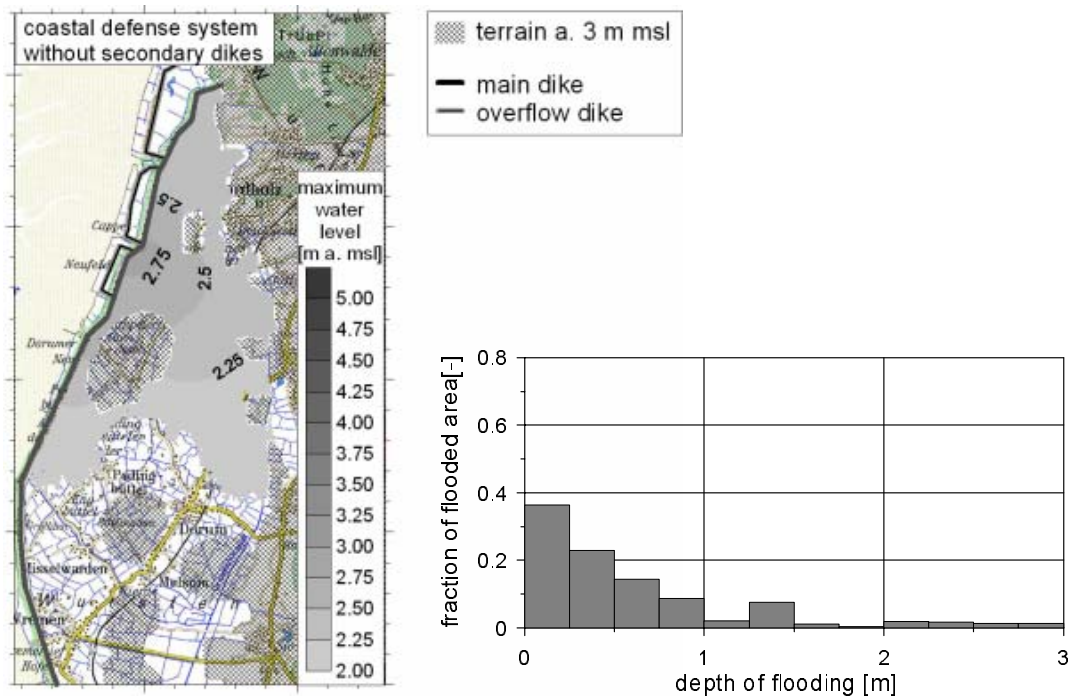


Figure 9. Inundation of the hinterland after dike breaching

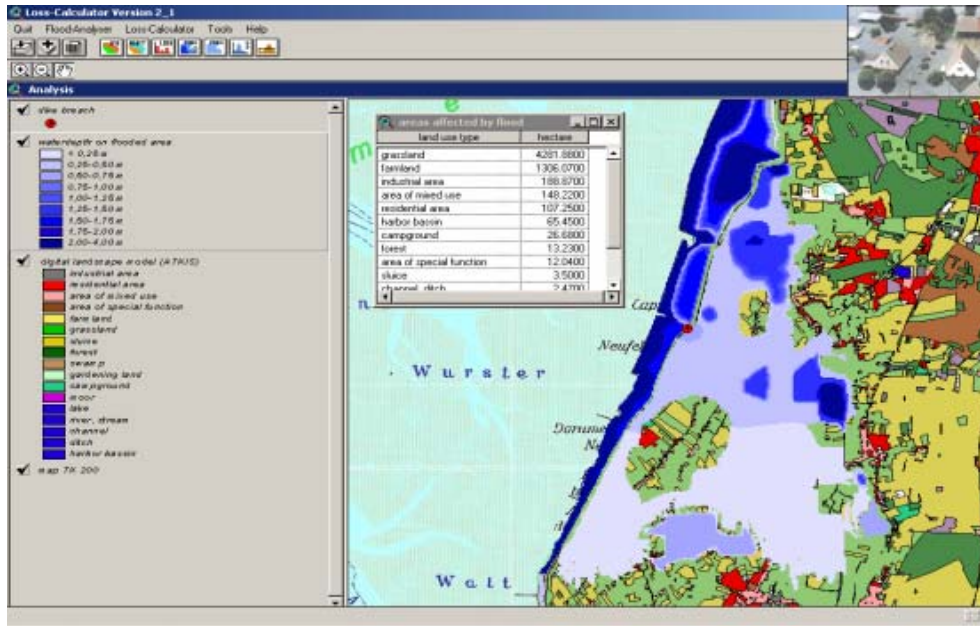


Figure 10. Overlay of maximum water depth and land use within the hinterland

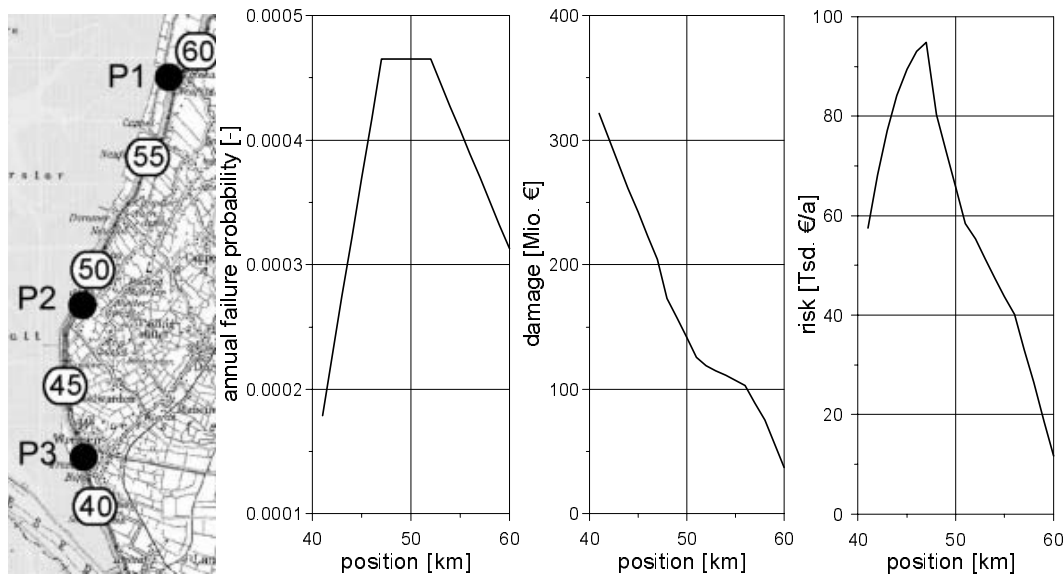


Figure 11. Variation of the storm surge risk (and its constituents - failure probability and consequences) along the German coast

Besides of the flood loss the failure probability of the coastal defense system also depends on the location at the coast. The variation of the annual probability of failure from approx. 0.0002 to 0.00045 relates to differences in the wave load on sea dike and its height. The multiplication of failure probability and loss of flooding gives a risk of approx. 15.000 to 95.000 €/a. This large variation of the risk along the coast reveals the shortcomings of deterministic design.

As the probability of failure the risk also increases in case of climate change. Because changes in loss related to climate change are rather small at the German coast the relative change in risk nearly equals the change in failure probability given in Figure 8.

Mitigation Strategies

In order to mitigate these increasing hazards strengthening of existing coastal defense systems by increasing the height of the main dike is possible.

In order to keep today's level of risk the additional height of the main dike amounts to 0.75 m in case of a sea level rise of 0.5 m and to approx. 0.25 m in case of an increase of wind speed by 7 % (see Figure 12). However, the height of the dike is limited by the bearing capacity of soils, especially in marsh land, and the space available for the foundations, especially in cities.

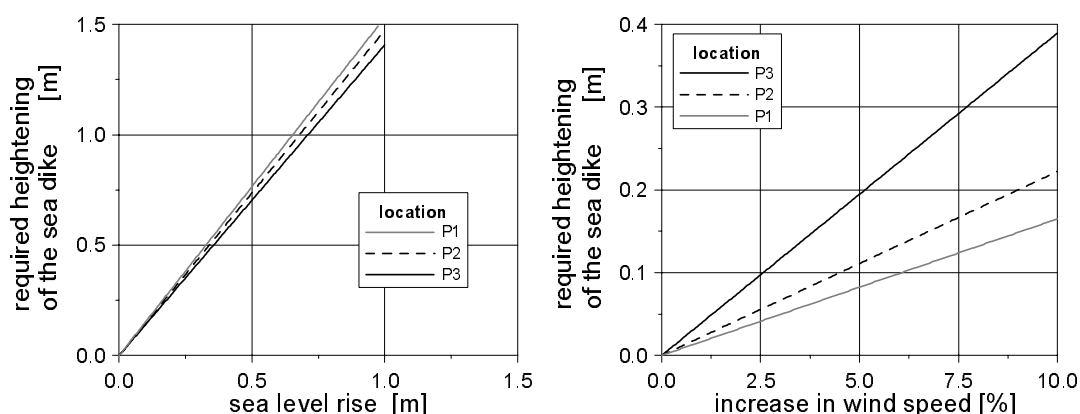


Figure 12. Required increase of sea dikes to keep safety standards in case of water level rise and increasing winds

In these cases the construction of additional coastal defense elements is a possible strategy. An example of an additional coastal element located in front of the main dike is the foreland or the overflow dike, both discussed in Figure 5. Additional defense elements may also be built behind the main dike. While elements in front of the main dike reduce the failure probability, elements behind the main dike result in a reduction of flood losses. An example of an additional secondary dike in the coastal hinterland is given in Figure 13. As shown, the flood zone is significantly reduced by the secondary dike. However, the histogram in Figure 13 reveals that the depth of flooding within the polder is about 1 m higher than without a secondary dike. In this situation the loss due to flooding is only reduced to 30 % although the flooded area is reduced to 25 %. With respect to climate change the proposed system with secondary dike compensates the adverse effect of a sea level rise of 0.35 m and is therefore equivalent to an increase in dike height of approx. 0.5 m.

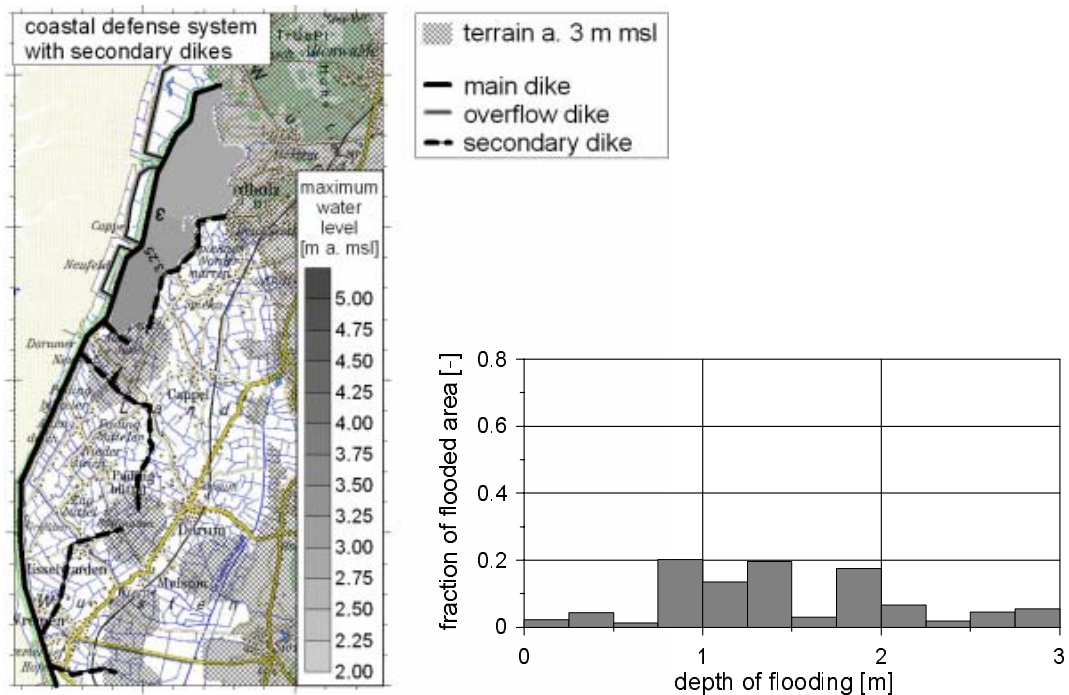


Figure 13. Effect of additional dikes on hinterland inundation

Conclusion

Applying the concept of probabilistic risk analysis shows that the safety of German coastal hinterlands from the presently applied deterministic design rules is rather unevenly distributed. Future reinforcement of the existing coastal defense system has to focus on high risk areas. Reinforcement will be necessary since the risk will increase within the next 50 years due to the anticipated climate change by a factor of five. This might be obtained with additional coastal defense elements like secondary dikes as fortification of present structures.

Acknowledgement

This work was funded by the German Federal Ministry for Education, Research and Science BMBF under 01 LD 0014 gratefully acknowledged by the authors.

References

Elsner, A., Mai, S., and Meyer, V., Zimmermann, C. (2003). "Integration of the Flood Risk in Coastal Hinterland Management." Proc. of the Int. Conf. CoastGis, CD-ROM, Genua, Italy.

- Mai, S., and Zimmermann, C. (2000). "Risk Analysis of Coastal Protections at Tidal Coasts." Proc. of the 2nd Int. Conf. Port Development & Coastal Environment, PDCE, 123-131, Varna, Bulgaria.
- Mai, S., and Ohle, N. (2002). "Rehabilitation of Coastal Protections at Tidal Lowlands." Proc. of the Int. Conf. Water Resources Planning and Management (EWRI), CD-ROM, Roanoke, Virginia, USA.
- Mai, S., Zimmermann, C. (2003). "Importance of Forelands and Summer Dikes for Coastal Safety." Proc. of the 3rd Int. Conf. Port Development & Coastal Environment, PDCE, 119-128, Varna, Bulgaria.
- Mai, S., Zimmermann, C. (2003) "Risk Analysis - Tool for Integrated Coastal Planning." Proc. of the 6th Int. Conf. on Coastal and Port Engineering in Developing Countries COPEDEC, CD-ROM, Colombo, Sri Lanka.
- Mai, S., Zimmermann, C. (2004). "Impact of Climate Change on the Wave Conditions in the Estuaries of Jade and Weser." Coastal Reports, 1, 93-10
- Vergeer, G J. H. (1990). *Probabilistic Design of Flood Defences*. Centre for Civil Engineering Research and Codes (CUR), report 141, Gouda, The Netherlands.