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Rehabilitation of Coastal Protections at Tidal Lowlands

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Abstract

Some lowlands at the German North Sea Coast are not protected by artificial but by natural coastal protection elements. Unfortunately the natural protections are not able to cope with rising water levels as a consequence of climate change.

Therefore a change in the management of coastal protections is going on, replacing natural coastal defenses by artificial defenses. The evaluation of the necessity of this change is worked out using a probabilistic design scheme. Within this scheme the return periods of flooding of the coastal hinterland in case of storm surges is calculated for today's and future conditions of water levels, waves and winds. Besides that the probabilistic design scheme also includes an identification of possible flood zones and of the values at risk. The information on return periods and flood zones is used to compare different coping strategies for rising water levels, like the reinforcement of natural coastal protections, e.g. by installation of additional artificial coastal protections.

Finally an optimized design scheme for the additional coastal protections is worked out minimizing the total costs, i.e. annual costs of construction and maintenance as well as the annually expected loss.

Introduction

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Most lowlands at the German North Sea Coast are protected by sea dikes from flooding. Nevertheless there are still some regions which are not protected by artificial coastal defenses, but by natural elements. A valuable region of this kind is the lowland of the district Sahlenburg 5 km south of the sea port of the city of Cuxhaven located at the estuaries Weser und Elbe (Figure 1).

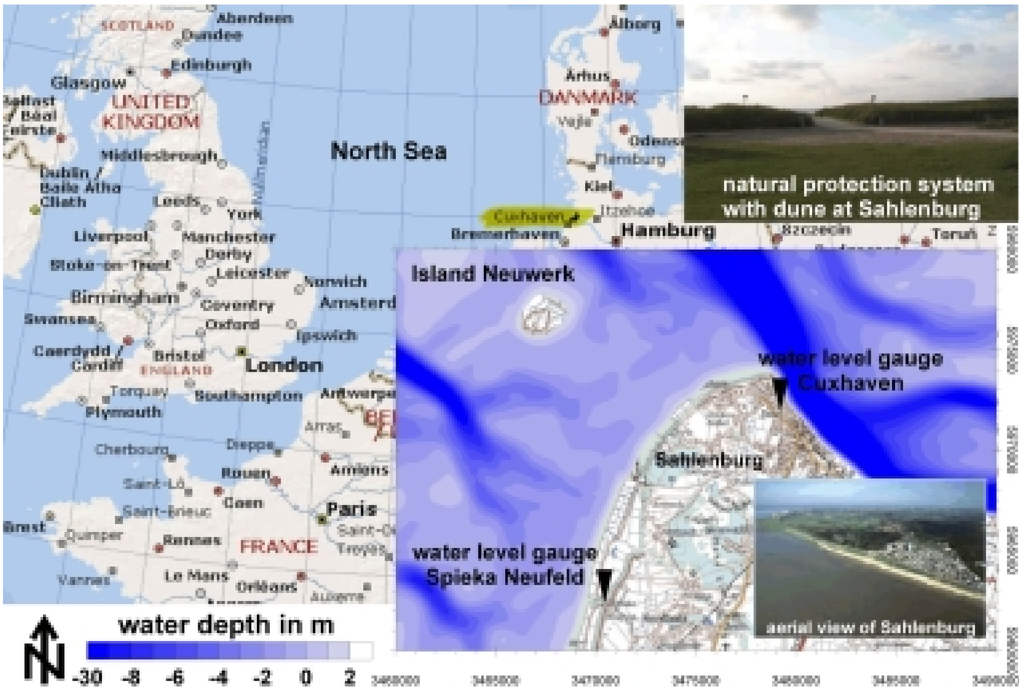


Figure 1. Location of the lowland of Sahlenburg at the estuary Weser south of Cuxhaven and photography of the natural protection system with dune

In the moment this lowland is protected by dunes (Figure 1) with a crest height of 4.0 m above mean sea level (MSL) from flooding. The terrain height of the lowland is approximately 2.0 m above MSL. It covers an area of 1.1 km² and is used for tourist and recreational purposes including many apartment houses and camping sites. The risk for the lowland will increase, respectively the safety standard provided by the dunes will be reduced significantly in the event of water level rise e.g. due to climate change. It is possible to quantify this effect employing the probabilistic design concept put forward by the CUR (1990) and employed by Mai and v. Lieberman (2000) at the German Coast. In order to compensate the change in the standard of safety it is planned to reinforce the natural coastal protection system by the construction of a sea dike. The optimal design parameter, especially the height of the dike, are determined using different steps of the probabilistic design concept. The first step of the design takes only into account the recurrence interval of flooding while the second step also focuses on the consequences of flooding. Within the third step the design also includes the construction costs of the sea dike. These are used in combination with the risk of flooding to optimize the design with respect to the total costs.

Definition of the Risk of Flooding

The risk of flooding of a coastal lowland is defined as the product of the probability of flooding and their consequences (Mai and v. Lieberman, 2000),

i.e. risk = probability of flooding x consequences of flooding. (1)

The probability of flooding equals the probability of failure of the dunes respectively the planned dike. Typical failure modes are put together by the CUR (1989) for dunes and by the CUR (1990) for dikes. The predominant failure mode of the dunes is the overflow while for the dike it is wave overtopping (Mai and Zimmermann, 2000).

The consequences of flooding are estimated by an identification of the flood prone areas and the values affected in case of inundation. The values affected by inundation are function of the total value (maximum possible loss) and the damage factor depending on the inundation characteristics (water level, speed, duration) (Mai and v. Lieberman, 2000),

i.e. consequences of flooding = damage factor x maximum possible loss (2)

Besides of the risk the annual construction and maintanace costs of the coastal protection, determine the total annual costs,

i.e. total annual costs = risk + annual construction costs (3)

The total annual costs provide a measure for the optimisation of the design. In the optimal design point the total costs are minimized (Headland et al., 1999).

Probability of Failure of Dune or Dike

Today’s failure probability, i.e. the probability of overflow at the dunes, is directly related to the statistics of tidal high water level derived from 100 year data-set of level gauging. Figure 2 (left) shows the statistics of the tidal high water level at neighbouring gauges in the south and in the north. In the moment the recurrence interval, i.e. the inverse of the probability of overflow of the dunes equals 12.5 years. In case of a rise in tidal high water level of 50 cm to be expected within the next 50 years (von Storch and Reichhard, 2000) the recurrence interval will be reduced to 4 years (Figure 2, right).

Reinforcing the coastal protection system by construction of a dike the failure probability of the coastal defense system is reduced. The probability of wave overtopping at the sea dike exceeding an overtopping rate of 2 $m^3/m/h$ is related on the one hand side to the statistics of tidal high water level and on the other side on the statistics of wave run-up respectively on the wave statistics as the mathematical formulation of the failure mode of wave overtopping indicates:

$$\text{limit state of overtopping} = \text{crest height} - \text{high water level} - \text{wave run-up} \quad (4)$$

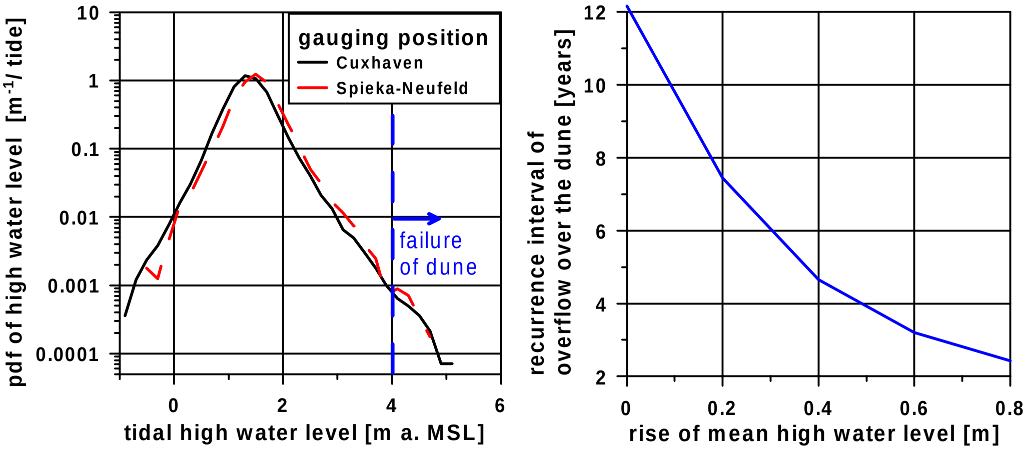


Figure 2. Statistics of tidal high water level at gauges in the south and north of Sahlenburg (left), Probability of overflow at the dunes in case of a rising mean tidal high water level (right).

In contrast to the statistics of tidal high water levels the statistics on waves cannot be derived directly from on-site measurements. Therefore the wave statistics is derived from the statistics of water level and wind (Mai and Zimmermann, 2000) employing the numerical wave model SWAN (Ris, 1997, Mai and Ohle, 1999). An example of the wave conditions at the coast of Sahlenburg is given in Figure 3.

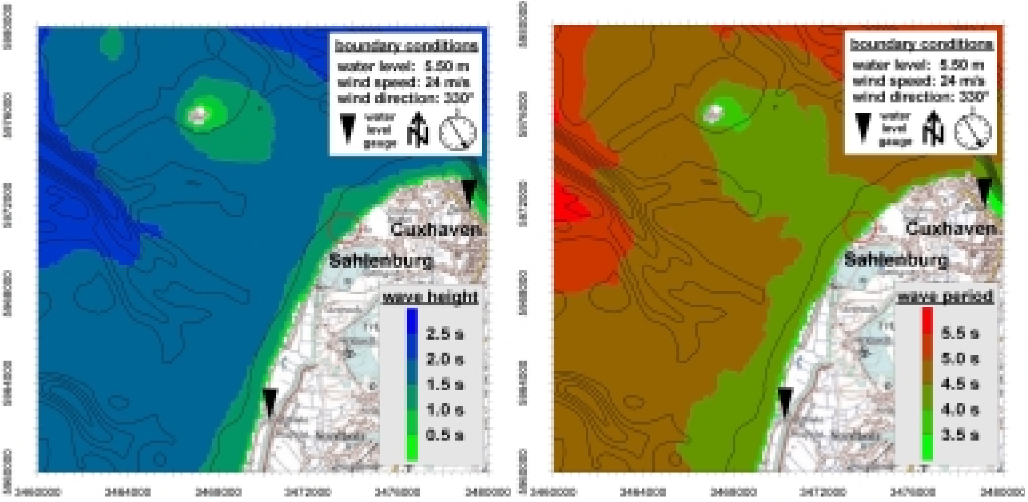


Figure 3. Wave conditions in the estuary Weser at the coast of Sahlenburg (left: significant wave height, right: mean wave period)

Assuming a standard cross section of the dike with grassed slopes of 1 to 6 on the seaward side the probability of wave overtopping becomes a function of the crest height. Figure 4 displays the dependence of the recurrence interval of wave overtopping on the crest height for different scenarios of the statistics of water level. The recurrence interval of wave overtopping at a dike with a height of 6.6 m a. MSL amounts to 50 years today and is reduced to 12.5 years in case of a rise in water level of 50 cm.

Therefore it is possible to cope with the reduction of the safety of Sahlenburg against overflow over the dunes by construction of a dike of a height of 6.6 m.

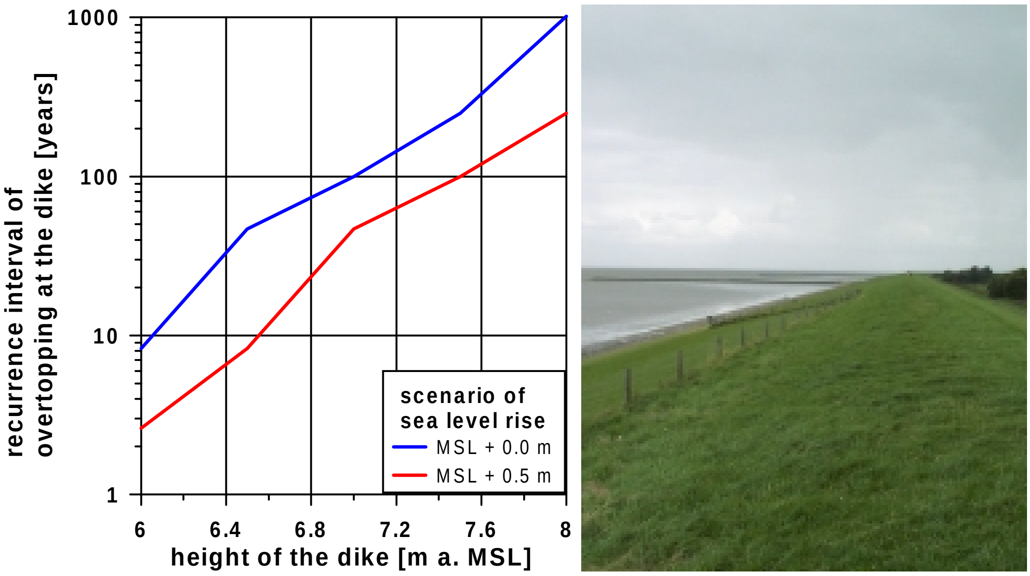


Figure 4. Recurrence interval of wave overtopping over a sea dike at Sahlenburg as a function of its height for today's and future conditions of water levels

Mapping of flood zones

In case of a failure of the dunes respecitvely of the dike the low lying hinterland is flooded. The inundation process was modeled using the two-dimensional hydrodynamic model MIKE21 (Abott, M.B. and Warren, I.R., 1981) for the most severe storm surge at the German North Sea coast happened in 1976 (Figure 5, D). Characteristic results of the simulations are shown in Figure 5.

The maximum water depth in case of flooding is 0.7 m, the duration of flooding varies from 8 h directly at the sea to 5 h at the landward boundary of the flood zone and the maximum flow velocities are up to 1.4 m/s at the location of failure of the coastal protections.

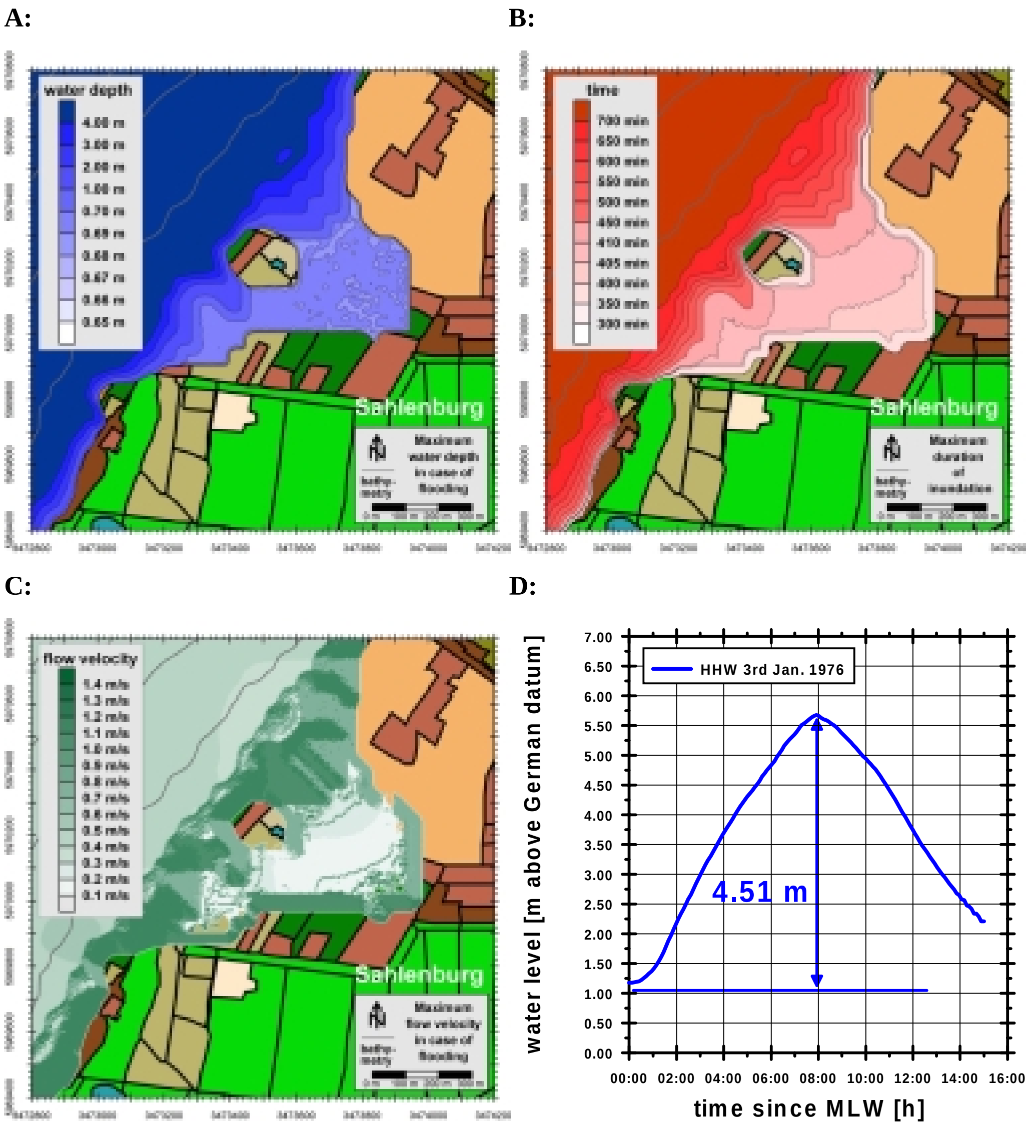


Figure 5. Characteristics of the inundation process (A: water depth, B: duration of flooding, C: max. flow velocity, D: storm surge in 1976).

Values at risk

Having mapped the flood zone the maximum possible loss is estimated analysing and valueing the different land uses. The land uses are derived from the digital landscape model (DLM) of the federal agency for land surveying (LGN) of Lower Saxony, Germany, shown in Figure 6. The value of the different uses is estimated on the one hand side by disaggregation of county statistics (Kiese and Leineweber, 2000) and on the other hand side by direct valueing of single items, e.g. apartment houses. An overview over the assets is listed in Figure 7.

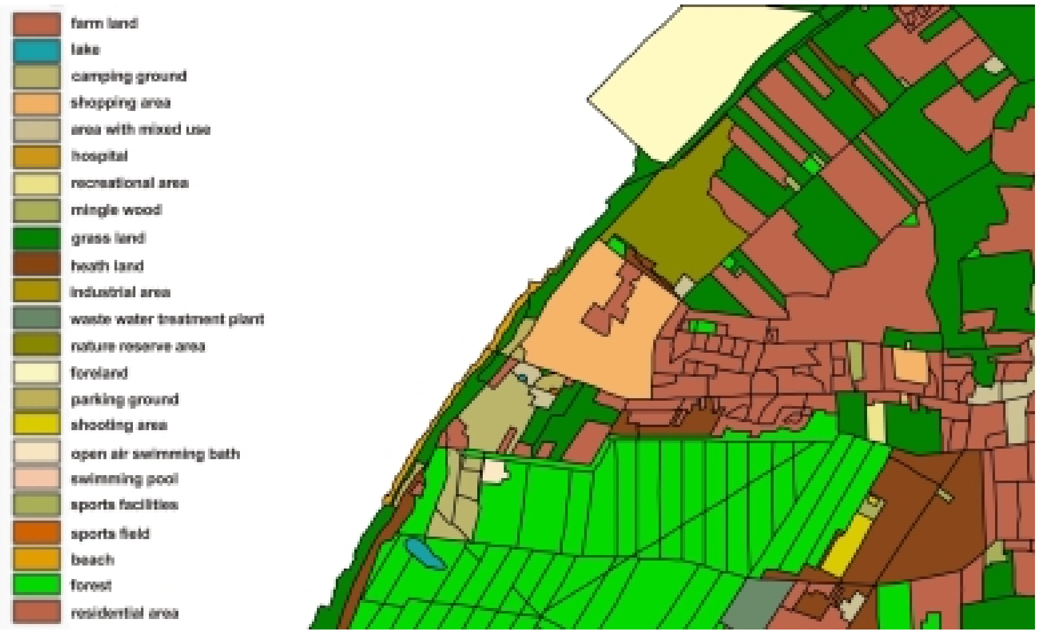
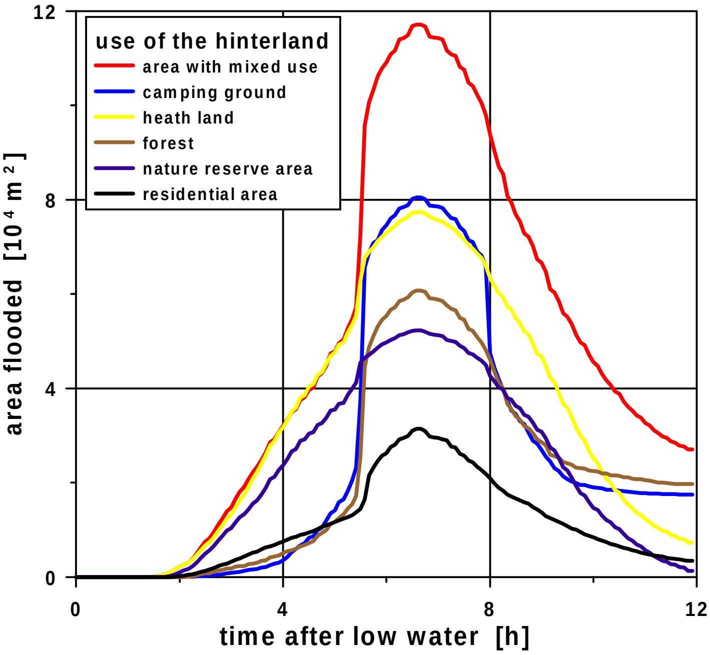


Figure 6. Land uses within the flood zone.



use of hinterland	
area flooded [10^4 m²]	total value [mio. US $]
farm land	
67.2	3.1
area with mixed use	
11.8	293.1
camping ground	
8.0	21.9
heath land	
7.8	2.1
forest	
6.0	1.7
nature reserve area	
5.2	1.4
residential area	
3.2	31.0

Figure 7. Time dependent flooding of the hinterland distinguishing different land uses.

In case of a failure of the coastal protection system the different uses of the hinterland are affected by time dependent flooding. A time series of the extension of areas inundated is given in Figure 7, e.g. revealing a maximum extension of the camping sites flooded of 80,000 m^2 and of the residential areas flooded of 35,000 m^2. Analyzing these time series a classification of the land uses at risk with respect to the maximum inundation depth and the duration of flooding is worked out and exemplary visualized in Figure 8.

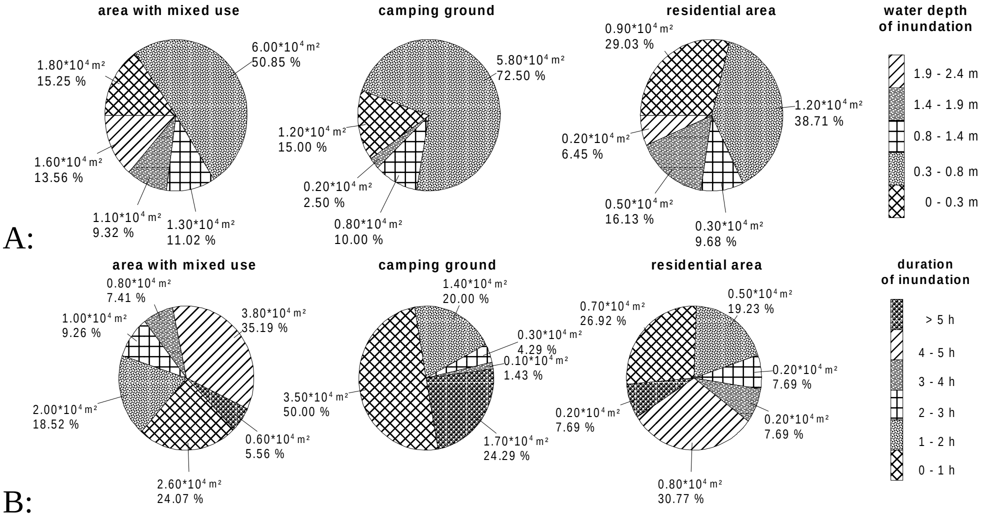
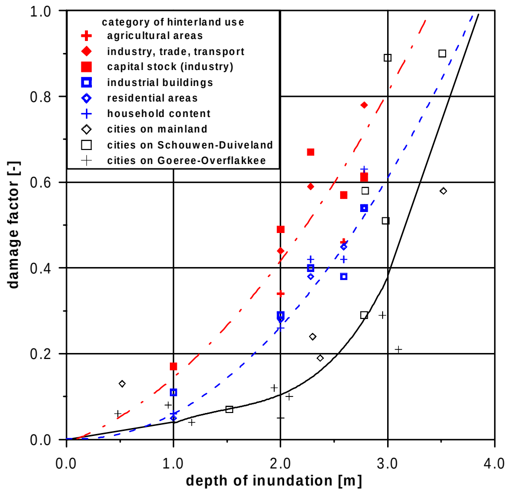


Figure 8. Classification of the utilization with respect to water depth (A) and duration of flooding (B)



use of hinterland	loss [mio. US $]
farm land	1.43
area with mixed use	14.66
camping ground	0.22
heath land	0.28
forest	0.07
nature reserve area	0.19
residential area	1.27
total	**18.11**

Figure 9. Parameterization of the degree of damage as a function of the inundation depth (CUR, 1990) (left) and classification of damage with respect to the utilization (right)

In case of flooding the values within the flood zone are not completely destroyed but only damaged to a certain degree. The degree of damage is usually parameterized by the inundation depth. An example of a parameterization of the degree of damage is given in Figure 9. The total damage amounts to 18.11 mio. US $. Therefore the risk of the lowland protected by dunes is 1.45 mio. US $/year and increases to 5.80 mio. US $/year in the event of a water level rise of 0.5 m.

Risk optimized mitigation strategy

The construction of a dike mitigates the risk by reducing the probability of flooding respectively the probability of failure of the coastal protection system (see Figure 4). However this benefit of a construction of a dike is partly revoked by its costs. Figure 10 (left) graphs the annual construction costs, i.e. the construction costs per year of lifetime, as a function of crest height. The cost estimation is based on costs incurred by recent projects of dike construction works in Germany and assumes a life time of 75 years and a length of 1400 m. The optimal crest height of the dike in case of a sea level rise of 0.5 m is calculated to 9 m a. MSL minimizing the total costs, as shown in Figure 10 (right).

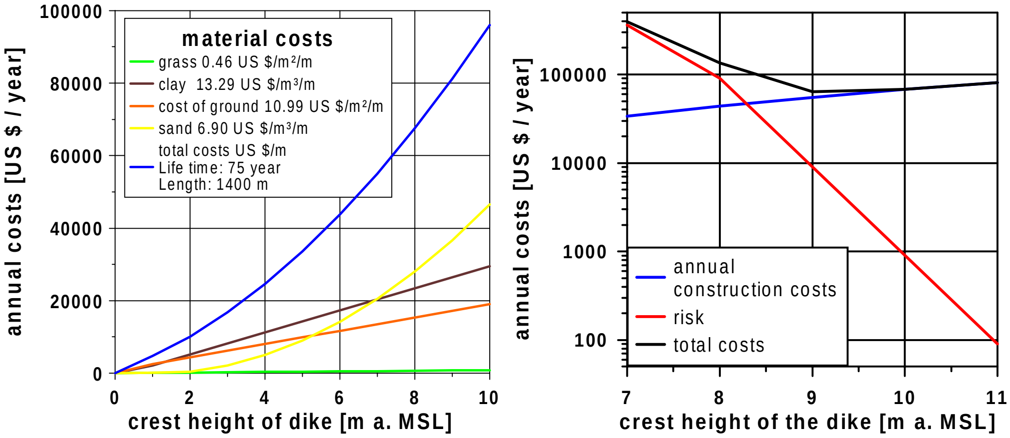


Figure 10. Annual construction costs of a dike (Ohle, N. and Dunker, S., 2001) (left) and optimization of the crest height of a dike by minimization of the total costs (right)

Conclusion

With the proposed risk optimized design concept the basis of an economically balanced dike construction is worked out and exemplified. This concept provides a possibility to estimate the effect of sea level rise on coastal safety. The future general planning of coastal protections will use it as a means for cost reduction.

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