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Importance of Forelands and Summer Dikes for Coastal Safety

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Abstract

The safety of coastal hinterlands is strongly influenced by the structure of the coastal defense system. It is widely accepted that additional coastal defence elements, like forelands and summer dikes, increase coastal safety. This increase in safety is quantified using the method of a probabilistic analysis calculating the flood risk of the hinterland with and without foreland and summer dike. Both components of risk analysis, i.e. failure probability of the coastal defense system and consequences in case of flooding after failure of the defense system, are analyzed. While studies stated the reduction of failure probability of coastal defense systems by additional elements so far this study also exemplifies the reduction of consequence of flooding by additional coastal defense elements. At the German coast the flood risk of coastal hinterlands is reduced by 76 % at coastal defense systems with foreland and by 91 % with foreland and summer dike.

Introduction

Besides of main dikes coastal defense systems at German North Sea comprise additional elements, e. g. forelands and summer dikes, in front of the sea dike [1]. These additional elements have significant importance for coastal safety. On the one hand side they reduce the wave loads on the sea dike [2, 3] and on the other hand side they provide an additional protection in case of a breach of the sea dike minimizing the consequences in case of inundation. Despite of these positive impacts especially the deconstruction of existing summer dikes is discussed as a compensation for the extensions of the harbours of Bremerhaven [4] and Wilhelmshaven [5] in the moment in order to reclaim salt marshes along the coast. Figure 1 provides an overview over the German coastline at the estuaries Jade and Weser with possible locations of a removal of summer dikes. The deconstruction of summer dikes is brought to discussion from the ecological point of view because a consideration of forelands and summer dikes is missing in the design schemes of coastal defense management.

Risk analysis provides a possible way of introducing additional defense elements in coastal management and quantifying their positive effect on coastal safety. The method of risk analysis [6] is based on the equation

risk = probability of failure of the coastal defense system x consequences of failure (1)

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A worked out example focussing on both aspects of risk analysis, the probability of failure and the consequences of failure, is presented for the coast north of the city of Bremerhaven. A detailed view and profile of the terrain height is given in Figure 2.

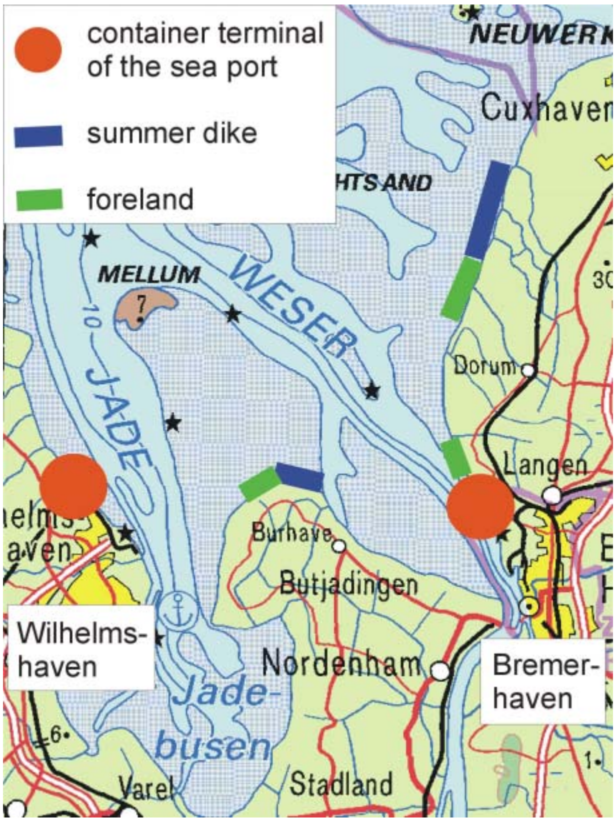

Figure 1: Forelands, summer dikes and sea ports at the estuaries of Jade and Weser

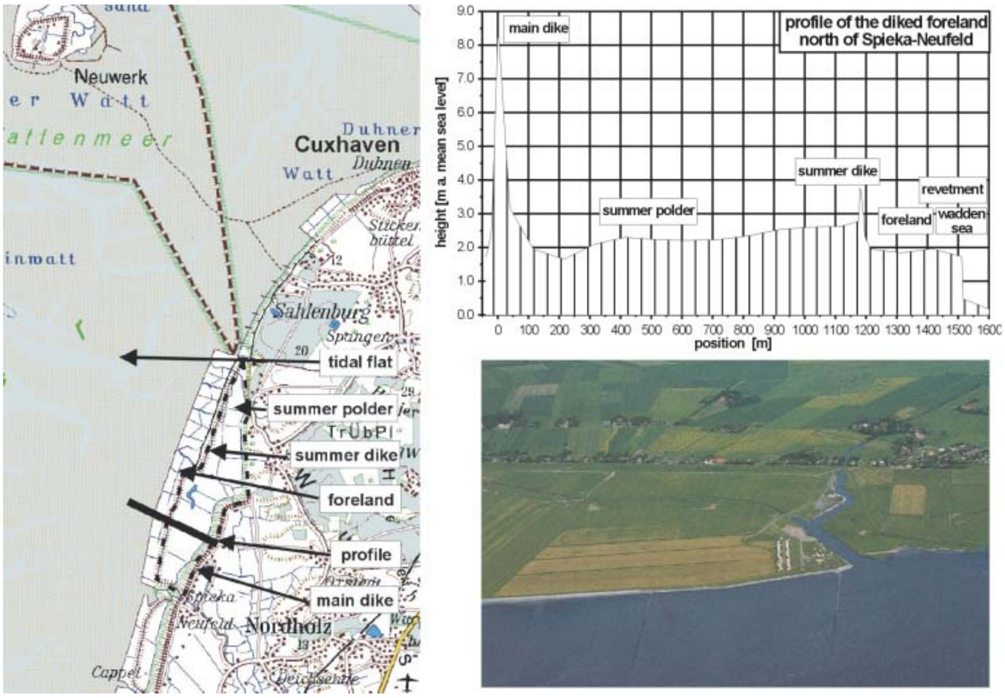

Figure 2: Focus area: Foreland and summer dike north of Bremerhaven [6]
left: map, right: terrain profile, photography

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Failure probability of coastal defense systems with and without foreland and summer dike

The basis for the calculation of the failure probability of a coastal defense system is the identification of the predominant failure mode(s). For coastal defense systems along the North Sea coast with sea dikes being the main defense element breaching after wave overtopping at the dike is the predominant failure mode [7]. The mathematical description of this failure mode is given by the following limit-state function depending on water levels and wave load [8]

$$Z = h_d - wl - R(H_s, T_m, \theta) = h_d - wl - 1.95 \cdot \gamma_f \gamma_b \gamma_\theta \cdot \sqrt{\frac{g}{2 \cdot \pi}} \cdot H_s T_m \tan(\alpha_d) \qquad (2)$$

Alternative formulations of the limit state function are given in [10]. While water levels are not changed significantly by forelands and summer dikes during storm surges the wave load is altered. Figure 3 clarifies the reduction of wave load giving an example of a one-dimensional numerical simulation with the model SWAN [11]. Both significant wave height and mean wave period are reduced by foreland and summer dike. While the reduction of wave load by a foreland amounts to 20 % even for maximum water levels the additional effect of summer dikes is only 5 % because the foreland is comparably wide. The incoming wave field at the seaward drop of the foreland (position: 1600 m) is calculated as a function of wind conditions by two-dimensional numerical simulations [5] as given in figure 4. Using these simulations the joint probabilities of water level and waves are calculated from the joint probabilities of water level and wind.

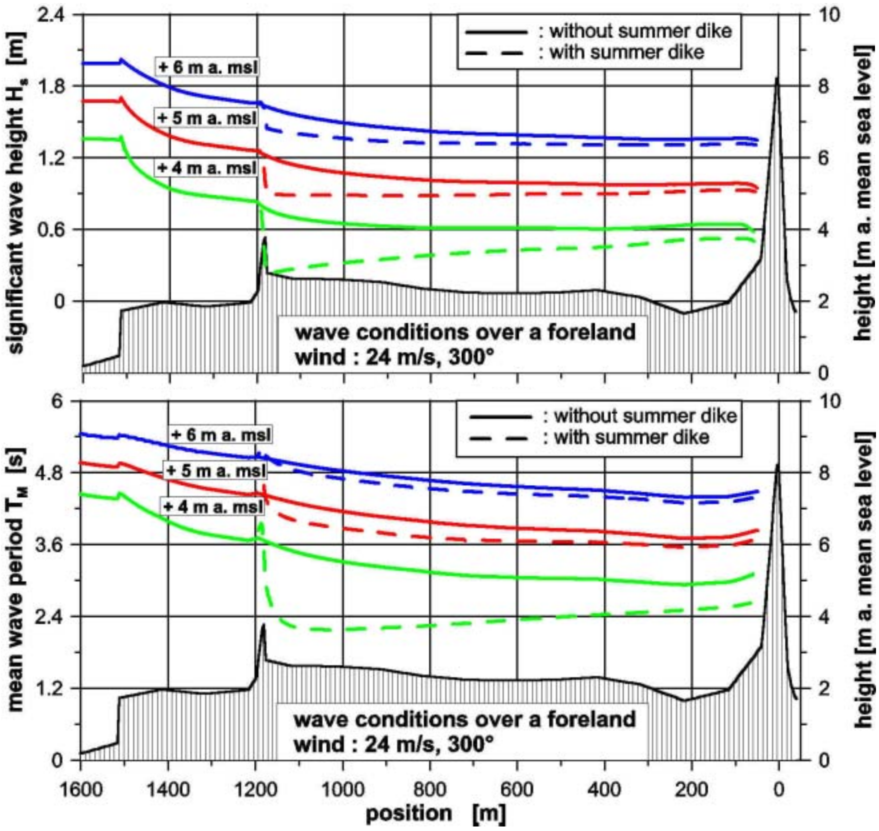

Figure 3: Reduction of wave load by foreland and summer dike [6]

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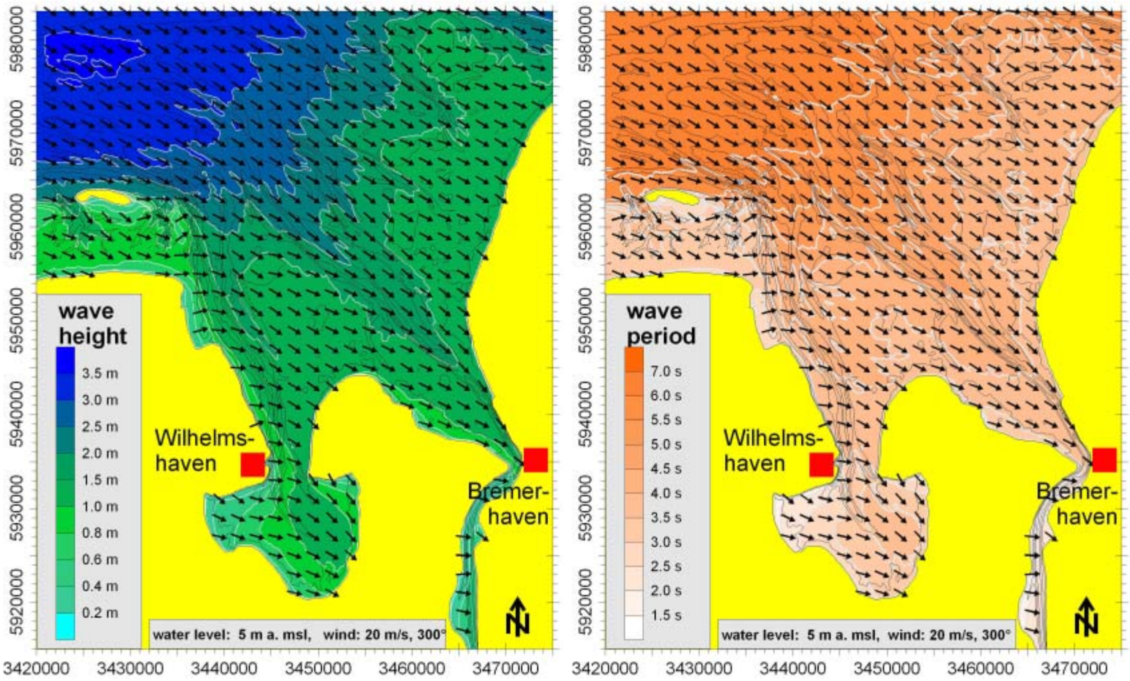

Figure 4: Numerical simulation of wave propagation within the Jade-Weser estuary

This joint probability is used to calculate the probability of wave overtopping and dike breaching [9]

$$P_{Z<0} = \int\limits_{Z=h_d - wl - R_{98}(wl, H_s(wl,u_w,\theta_w), T_m(wl,u_w,\theta_w))<0} p_{wl,u_w,\theta_w}(wl, u_w, \theta_w)\, dwl\, du_w\, d\theta_w \qquad (3)$$

The joint probability of water level and wind is derived from long-term measurements of water-levels and wind introducing the conditional probability of wind

$$p_{wl,u_w,\gamma_w}(wl, u_w, \theta_w) = p_{wl}(wl) \cdot p_{u_w,\theta_w}(u_w, \theta_w \mid wl) \qquad (4)$$

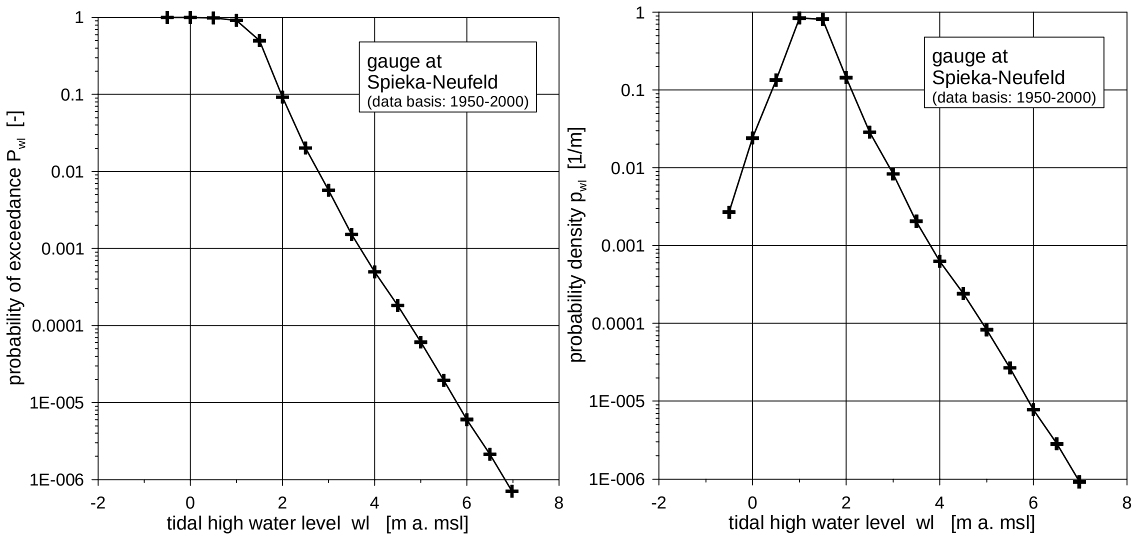

Figure 5: Probability of exceedance (left) and probability density function (right) of water levels at the gauge Spieka-Neufeld north of Bremerhaven

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Wind speed and direction are assumed to be uncorrelated

$$p_{u_w,\theta_w}(u_w,\theta_w \mid wl) = p_{u_w}(u_w \mid wl) \cdot p_{\theta_w}(\theta_w \mid wl) \quad (5)$$

Figure 5 shows the probability of water levels at the focus area given in figure 2. The probability of extreme water levels is calculated by extrapolation using the log-Pearson 3 distribution. Alternative types of extrapolation are tested in [12].

The conditional probability of wind speed and direction is given for different tidal high water levels in figure 6. With the equations (1) to (5) the failure probability of the coastal defense system without any foreland and summer dike is calculated to 0.0132 (recurrence interval: approx. 75 years) while the recurrence interval of the coastal defense system with foreland equals approx. 300 years and with foreland and summer dike approx. 760 years.

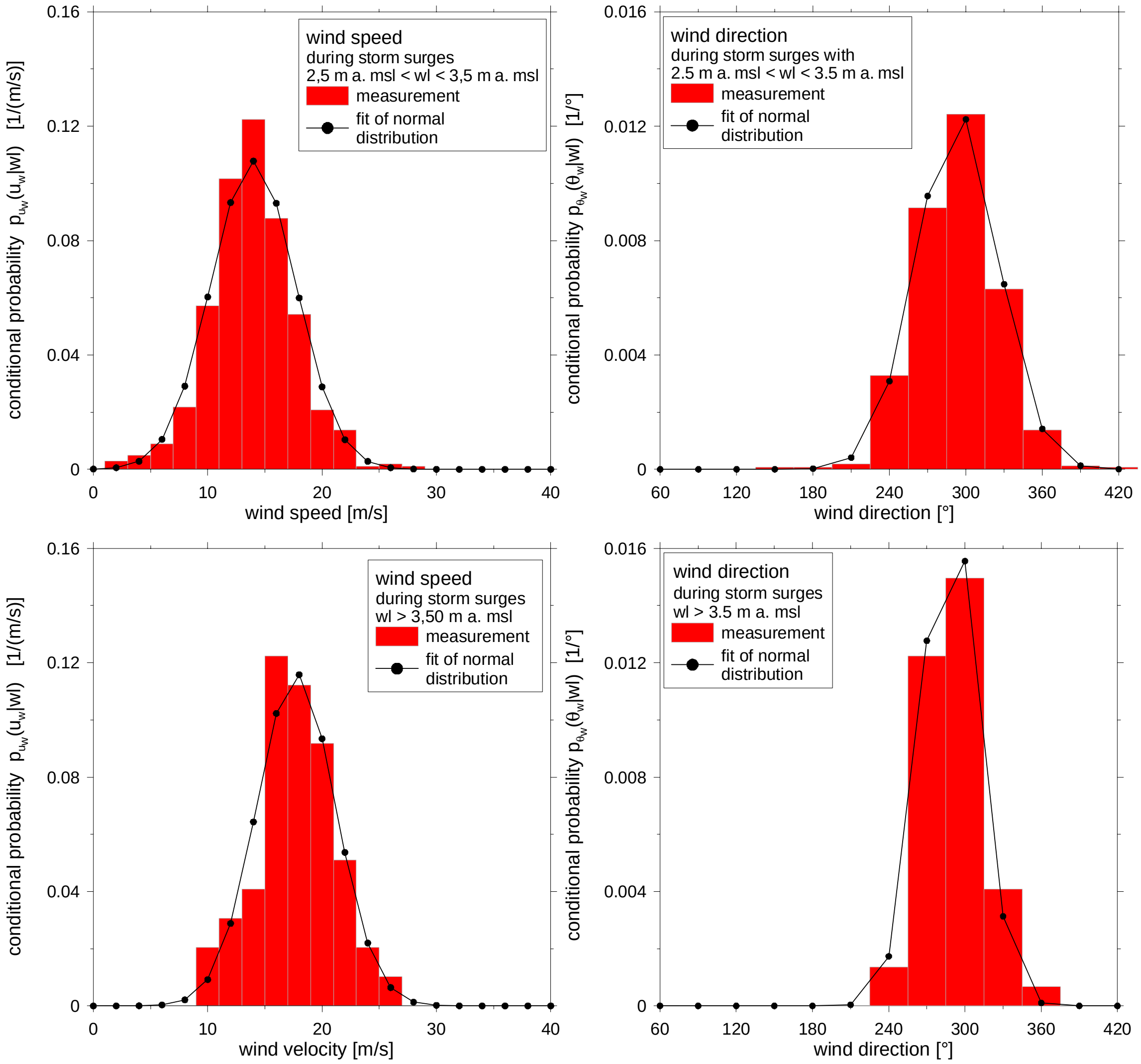

Figure 6: Conditional probability of wind speed (left) and direction (right) for a water level from 2.5 m above mean sea level (msl) to 3.5 m a. msl (top) and above 3.5 m a. msl (bottom)

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Inundation consequences in case of failure of coastal defense systems with and without foreland and summer dike

As a consequences of the failure of a sea dike the coastal hinterland is flooded. Numerical simulations are the best way to map the flood zone [13]. An example of a numerical simulation using the model MIKE 21 HD is given in figure 7. It is shown that the finally flooded area is not influenced by the structure of the coastal defense system. However the water volume inundating through the dike breach is significantly reduced by additional defense elements. The reduction of the inundating water volume is up to 7 % for systems with foreland and 9 % for systems with foreland and summer dike. The reduction of the inundating water volume leads to a comparable reduction of the average water depth in the flooded area. The land uses affected by flooding are analyzed using a digital terrain model [14]. Figure 8 gives an example of the analysis of the land uses. The degree of damage to the various land uses is a function of water depth. A histogram of the water depth in zones of different land uses as well as typical damage functions are given in figure 9.

For the predominant land uses the average depth of flooding and the mean degree of damage are listed in table 1. Forelands reduce the degree of damage by 36.2 % to 35.2 %. In case of additional summer dikes a further reduction of the degree of damage by 2.7 % to 32.5 % is found.

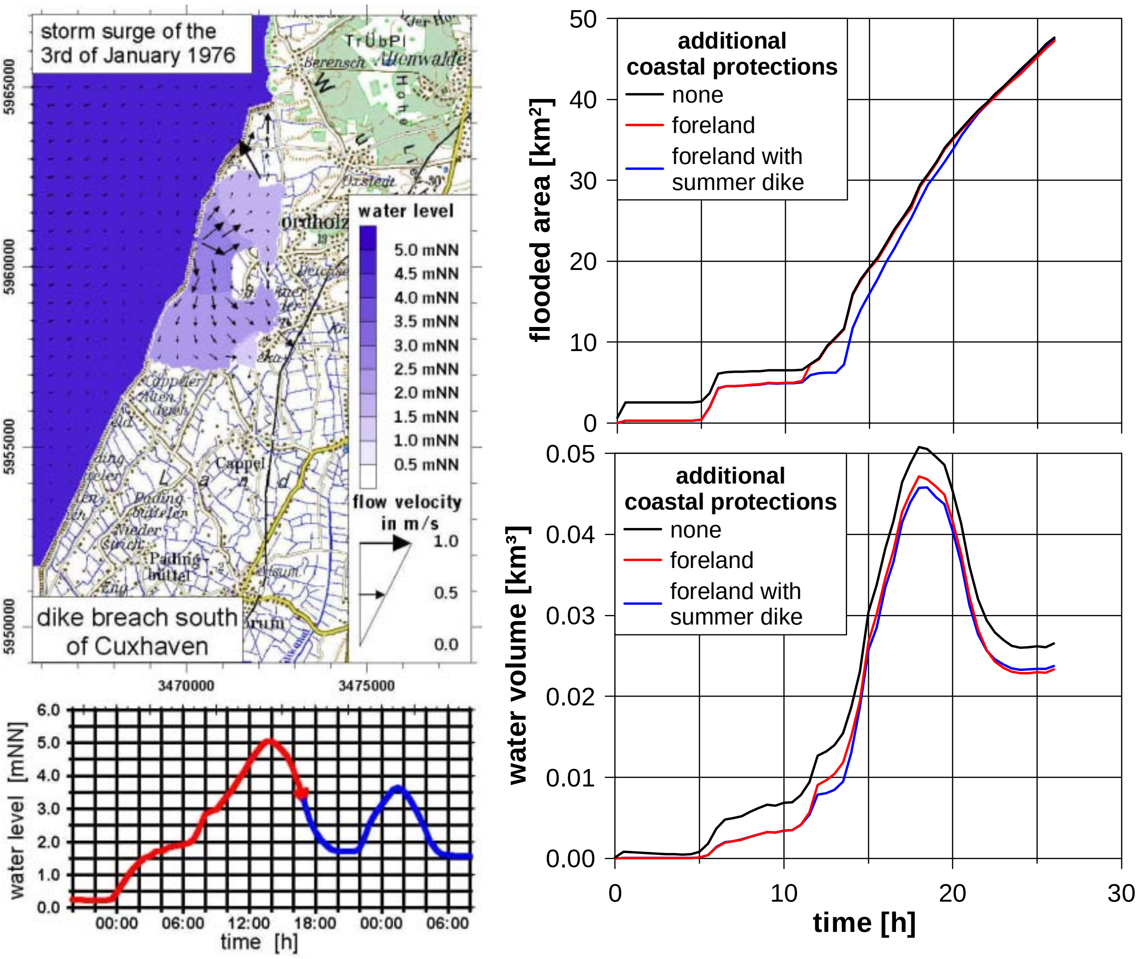

Figure 7: Influence of foreland and summer dike on coastal flooding

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	sea dike		sea dike with foreland		sea dike with foreland and summer dike	
land use	mean depth	damage	mean depth	damage	mean depth	damage
arable land	0.87 m	0.420	0.85 m	0.414	0.80 m	0.396
mixed use	0.56 m	0.210	0.56 m	0.209	0.52 m	0.204
residential	0.51 m	0.154	0.51 m	0.154	0.48 m	0.150
industrial	0.90 m	0.197	0.90 m	0.197	0.90 m	0.197
grass land	0.89 m	0.353	0.86 m	0.341	0.75 m	0.308

Table 1: Average degree of damage for different types of coastal defense systems

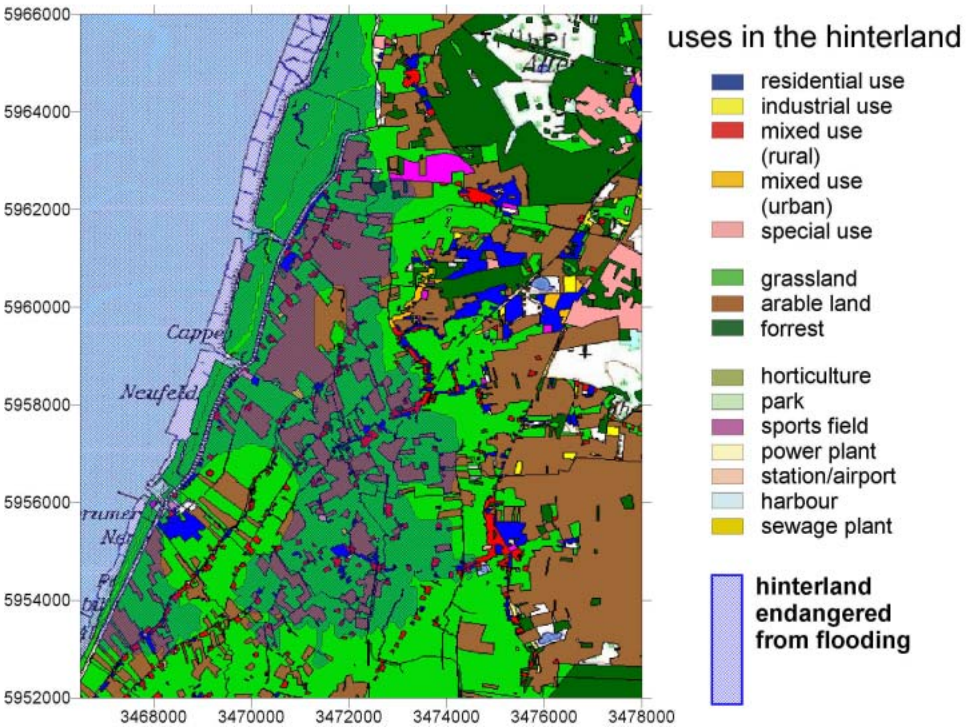

Figure 8: Analysis of land uses in the flood zone

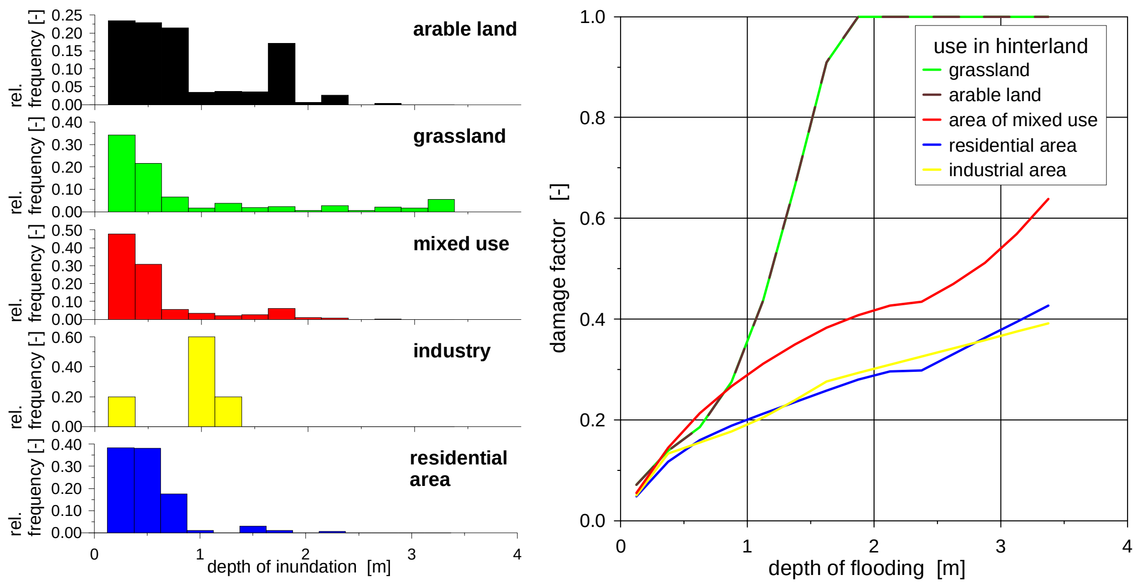

Figure 9: Histogram of the water depth in the flood zone (left) and typical damage functions for various land uses (right)

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A monetary appraisal of the damage in case of flooding is possible introducing the average value of different land uses per unit area

$$C = \sum_u v_u \cdot \varphi_u \cdot A_u \tag{6}$$

The damage amounts to 68 Mio € for hinterlands defended by sea dikes. The damage is reduced to 65.8 Mio € in case of additional forelands and to 63.0 Mio € in case of additional forelands and summer dikes.

land use	value per unit area	sea dike		sea dike with foreland		sea dike with foreland and summer dike	
		area flooded	damage	area flooded	damage	area flooded	damage
arable land	1 €/m²	11.1 km²	4.7 Mio €	11.0 km²	4.6 Mio €	10.9 km²	4.3 Mio €
mixed use	123 €/m²	1.19 km²	30.7 Mio €	1.15 km²	29.6 Mio €	1.14 km²	28.6 Mio €
residential	158 €/m²	0.91 km³	22.1 Mio €	0.88 km²	21.4 Mio €	0.88 km²	20.9 Mio €
industrial	86 €/m²	0.01 km²	0.2 Mio €	0.01 km²	0.2 Mio €	0.01 km²	0.2 Mio €
grass land	1 €/m²	29.2 km²	10.3 Mio €	29.2 km²	10.0 Mio €	29.1 km²	9.0 Mio €
total	-	42.4 km²	68.0 Mio €	42.2 km²	65.8 Mio €	42.0 km²	63.0 Mio €

Table 2: Damage due to flooding for different types of coastal defense systems

Flood risk

The reduction of the probability of failure by additional coastal defense elements and the reduced consequences lead to a considerable reduction in flood risk. Using (1) the risk is calculated to 0.91 Mio €/a for coastal defense systems with a sea dike without foreland and summer dike. Additional defense elements, like foreland and summer dike, reduce the risk to 0.22 €/a respectively 0.082 €/a.

This information on the risk of hinterlands protected by different types of coastal defense systems is an essential part for the development of optimal strategies in coastal defense. It is included into the GIS-based decision support system RISC "risk information system coast" developed at the Franzius-Institute.

Conclusion

The method of risk analysis proved the importance of forelands and summer dikes in coastal protection. The reduction of risk by forelands amounts to 75.8 % while summer dikes only to an additional reduction of 62.7 %. Within the future design of measures compensating ecological impacts of harbour works these results will help to estimate the feedback of ecologically motivated changes of the coastal defense system on the coastal safety. It will help to balance ecological and engineering needs in the coastal zone.

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Nomenclature

A_u	flooded area of certain use in the hinterland
h_d	height of the sea dike
H_s	significant wave height
p_{u_w,θ_w}	conditional probability of wind speed and direction
p_{u_w}	conditional probability of wind speed
p_{wl}	probability density function of water level
p_{wl,u_w,θ_w}	combined probability density function of water level, wind speed and direction
$P_{Z<0}$	probability of failure
p_{θ_w}	conditional probability of wind direction
R	wave run-up
T_m	mean wave period
u_w	wind velocity
v_u	value of an area of certain use in the hinterland per unit area
wl	water level
α_d	slope of the sea dike
γ_b	reduction factor at sea dikes with berms
γ_f	reduction factor for rough surfaces
γ_θ	reduction factor for oblique wave attack
θ	angle of wave attack
θ_w	wind direction
φ_u	damage function
Z	limit-state function

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