RISK ANALYSIS – TOOL FOR INTEGRATED COASTAL PLANNING

by

S. Mai[1] and C. Zimmermann[2]

ABSTRACT

In Germany the coastal planning so far focuses on the design of coastal defences. The method of risk analysis helps to widen the scope of coastal planning considering not only the engineering but also socio-economic aspects, like the land use within the costal zone. Therefore a calculation scheme treating the risk due to storm surges is worked out and exemplary applied at the German North Sea Coast. The application of this probabilistic method revealed that today's deterministic design of coastal defences is not well balanced with respect to risk.

1. INTRODUCTION

The German coast on the North Sea is a typical tidally influenced coast. In case of storm surge the hinterland is endangered from flooding to a great extent. Fig. 1 exemplifies this for the coastline of the state of Lower-Saxony. The extent of the hinterland lying under the highest storm surge level of 5 m to 6 m above mean sea level (a. msl) amounts to 12000 km² with approx. 60 % lying under mean tidal high water level .

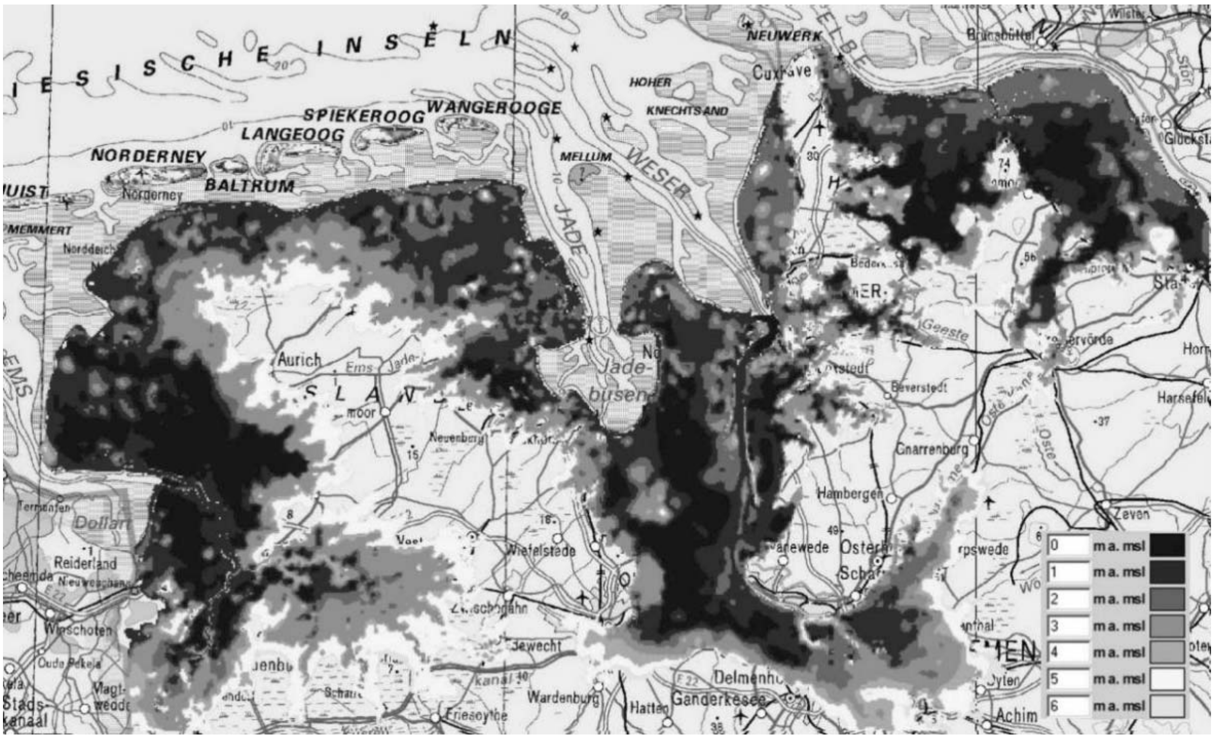


Figure 1: Hinterland On The Lower Saxonian Coast Lying Below The Highest Storm Surge Level

To protect the hinterland from flooding during storm surges a system of coastal defence elements is set-up. The main coastal defence elements along the coast are sea dikes. The design of these sea dikes is so far based on a deterministic scheme, outlined by FLÜGGE, G., FRANZIUS, O. and KUNZ, H. (2002) and e.g. applied by NIEMEYER, H-D. and KAISER, R. (2000). However the application of probabilistic design schemes, presented e.g. by VERGEER, G.J.H. (1990), becomes more common

[1] Dipl.-Phys. Dipl.-Ing., University of Hannover, Franzius-Institut, Nienburger Str. 4, 30167 Hannover, Germany, smai@mbox.fi.uni-hannover.de

[2] Prof. Dr.-Ing., University of Hannover, Franzius-Institut, Nienburger Str. 4, 30167 Hannover, Germany, zi@fi.uni-hannover.de

also in Germany (MAI, S., SCHWARZE, H. and ZIMMERMANN, C., 1997a) because they are essential for an integrated coastal planning.

The basis of the probabilistic risk analysis is given by *(1)*

$$risk = p_f \cdot c_f \qquad (1)$$

with the probability of failure p_f and the consequences of failure c_f. While the probability of failure relates especially to the field of coastal engineering other aspects of coastal planning, like the land use within the hinterland, and the values at risk, are introduced via the consequences of failure. The following paragraphs present a worked out example of probabilistic risk analysis for the coastal zone protected by sea dikes suggesting also some necessary approximations.

2. SAFETY OF COASTAL DEFENCES

2.1 Calculation Scheme

The first step in calculating the failure probability of sea dikes is the analysis of the possible failure modes. Fig. 2 combines these modes within a fault tree (VRIJLING, J.K., 1987). An extended fault tree is given by KORTENHAUS, A., OUMERACI, H., WEISSMANN, R., RICHWIEN, W. (2002). The predominant failure mode relates to wave overtopping as dike breaches during the storm surges of 1962 and 1976 indicate. Different stages of this failure mechanism are given in Fig. 3.

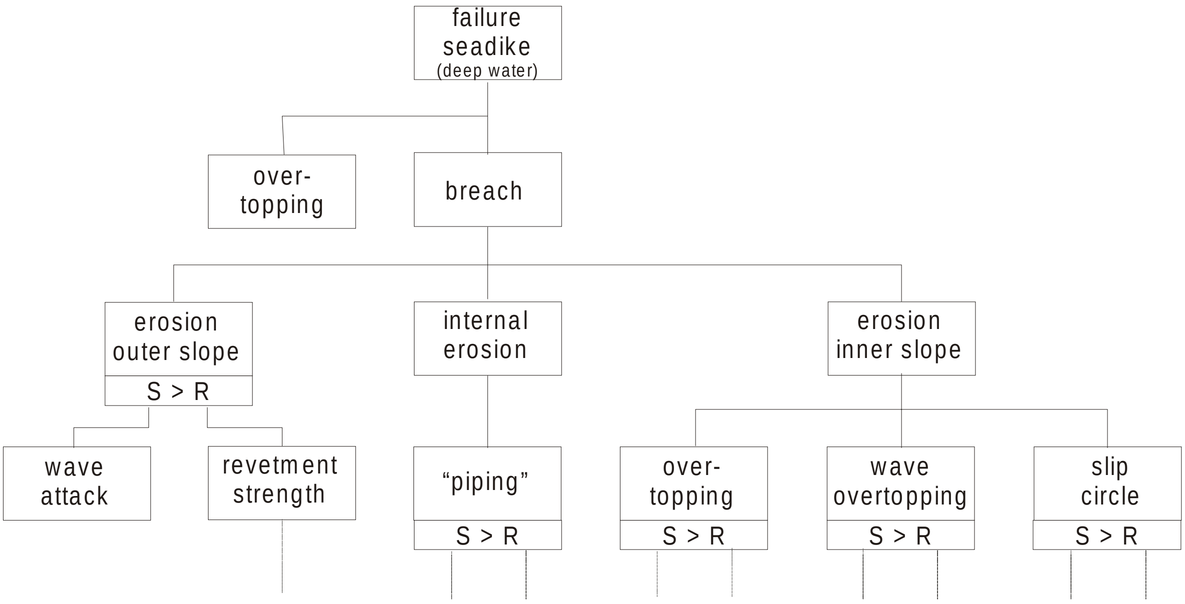


Figure 2: Fault Tree of a Sea Dike (VRIJLING, J.K., 1987)

Figure 3: Different Stages of the Failure Mechanism "Wave Overtopping"

The limit state function of wave overtopping is given by (2)

$$Z = h_D - wl - R_{98\%} \qquad (2)$$

with the height of the dike h_D, the water level wl, and the run-up $R_{98\%}$. A failure of the dike has to be assumed when the limit state function becomes negative. The failure probability is therefore calculated by (3)

$$p_f = \int_{Z<0} p_{wl,R_{98\%}}(wl, R_{98\%})\, dwl\, dR_{98\%} \tag{3}$$

with the joint probability distribution of water levels and wave run-up $p_{wl,R98\%}(wl,R_{98\%})$.

The run-up is a function of the wave load in front of the dike (OHLE, N., MÖLLER, J., SCHÜTTRUMPF, H., DAEMRICH, K.-F., OUMERACI, H., ZIMMERMANN, C., 2002)

$$R_{98\%} = 1.95 \cdot \gamma_f \gamma_b \gamma_\theta \cdot \sqrt{\frac{g}{2\cdot\pi} \cdot H_s} T_m \tan(\alpha_d) \tag{4}$$

with the significant wave height H_s, the mean wave period T_m, the slope of the dike α_d and the coefficients γ_θ, γ_b and γ_f introducing the influence of oblique wave approach, of a berm and of the roughness of the dike. If wave parameter in front of the dike are missing wind data may be used for parameterisation (MAI, S., SCHWARZE, H., ZIMMERMANN, C., 1997b)

$$H_s = f_{H_s}(wl, u_w, \theta_w) \tag{5}$$

$$T_m = f_{T_m}(wl, u_w, \theta_w) \tag{6}$$

$$\theta_s = f_{\theta_s}(wl, u_w, \theta_w) \tag{7}$$

with the wind speed resp. direction u_w *resp.* θ_w, the wave direction θ_s and the empirical functions f_{Hs}, f_{Tm} and $f_{\theta s}$.

The failure probability given in (3) then becomes a function of the joint probability distribution of water levels and wind $p_{wl,uw,\theta w}(wl,u_w,\theta_w)$

$$p_f = \int_{Z<0} p_{wl,u_w,\theta_w}(wl, u_w, \theta_w)\, dwl\, du_w d\theta_w \tag{8}$$

The joint probability distribution of water levels and wind can be split up into the probability distribution of water levels $p_{wl}(wl)$ and the conditional probability of wind $p_{uw,\theta w|wl}(u_w,\theta_w|wl)$

$$p_{wl,u_w,\theta_w}(wl, u_w, \theta_w) = p_{wl}(wl) \cdot p_{u_w,\theta_w|wl}(u_w, \theta_w \mid wl) \tag{9}$$

2.2 Probability of Water Levels during Storm Surges

The failure of sea dikes is related to extreme storm surges. Therefore the statistics of water level measurements carried out at some gauges on the German coast since approx. 1850 has to be extrapolated to very rare events. This extrapolation can be carried out employing different statistical models, like Gumbel, log-Pearson-3 and log-normal distribution. The different models result in a large scatter of extreme water levels with given probability. Fig. 4 exemplifies this for the extreme statistics of water levels measured near Bremerhaven located on the river Weser.

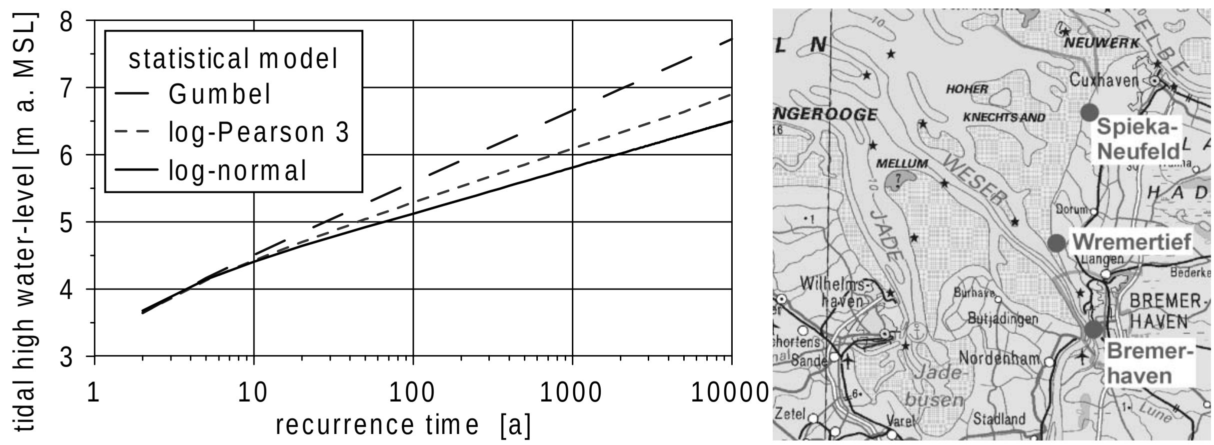


Figure 4: Extreme Statistics of Water Levels near Bremerhaven

At most locations on the German coast the log-Pearson-3 distribution agrees best to the measured statistics. The accuracy of the extrapolation strongly depends on the duration of the basic data. Therefore the extreme water levels at gauges registering only for a short time should not directly be calculated by extrapolation but by transfer from the gauge registering for a long time. Fig. 5 exemplifies this transfer of water levels from Bremerhaven to the neighbouring gauges at Wremertief resp. Spieka-Neufeld.

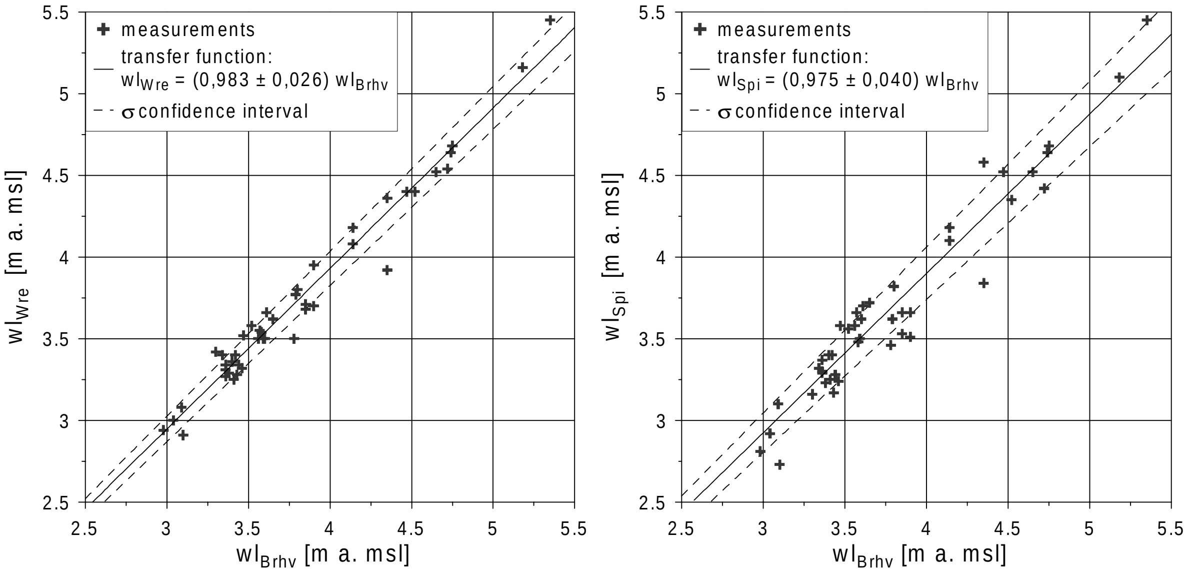


Figure 5: Transfer of Water Levels from Bremerhaven to Wremertief (left) resp. Spieka-Neufeld (right)

2.3 Probability of Winds during Storm Surges

At the German coast extreme water level relate to north-westerly winds with mean speeds of approx. 18 m/s. Because of the very small number of extreme storm surges the joint probability distribution of wind speed and direction cannot be determined accurately. The split up of the joint probability distribution into two separated probability distributions of wind speed $p_{uw|wl}(u_w|wl)$ and wind direction $p_{\theta w|wl}(\theta_w|wl)$ is an alternative (MAI, S., ZIMMERMANN, C., 2003)

$$p_{u_w,\theta_w|wl}(u_w,\theta_w \mid wl) = p_{u_w|wl}(u_w \mid wl) \cdot p_{\theta_w|wl}(\theta_w \mid wl) \tag{10}$$

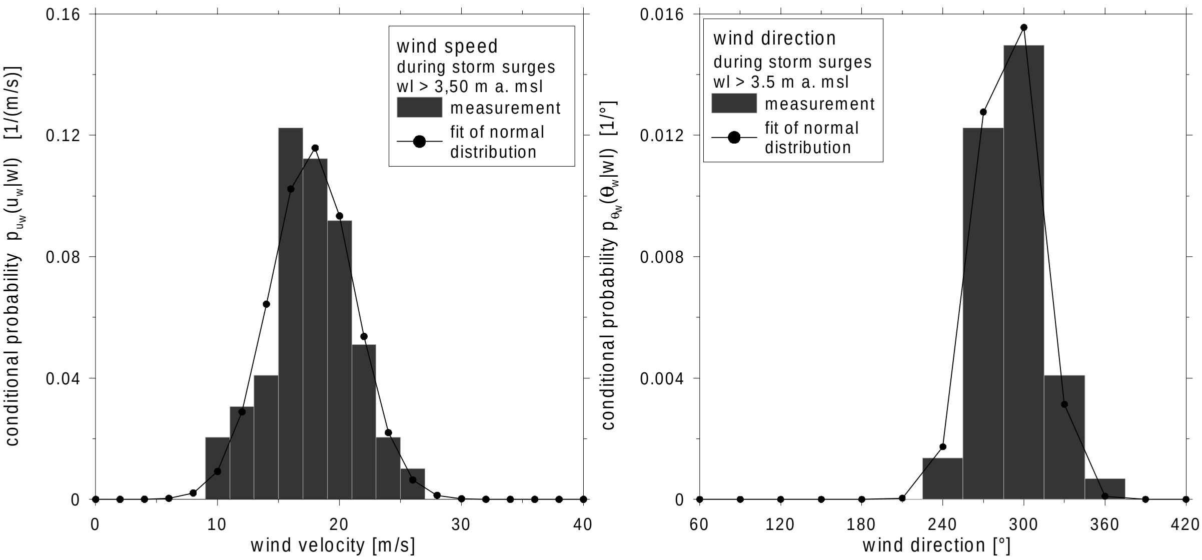


Figure 4: Statistics of Wind Speed (left) and Direction (right) during Storm Surges (MAI, S., ZIMMERMANN, C., 2003)

The separated probability distributions are well approximated by normal distributions.

2.4 Wave Statistics

The water level and wind conditions are transferred to wave parameters within the whole coastal zone using the numerical model SWAN (BOOIJ, N., RIS, R.C., HOLTHUIJSEN, L.H., 1999). Fig. 5 gives an example of the results of the numerical simulations of wave propagation within the estuary of Jade and Weser. Analysing a set of numerical simulations for different boundary conditions results in the transfer functions f_{Hs}, f_{Tm} and $f_{\theta s}$. Fig. 6 shows a set of transfer functions over the tidal flats near Bremerhaven.

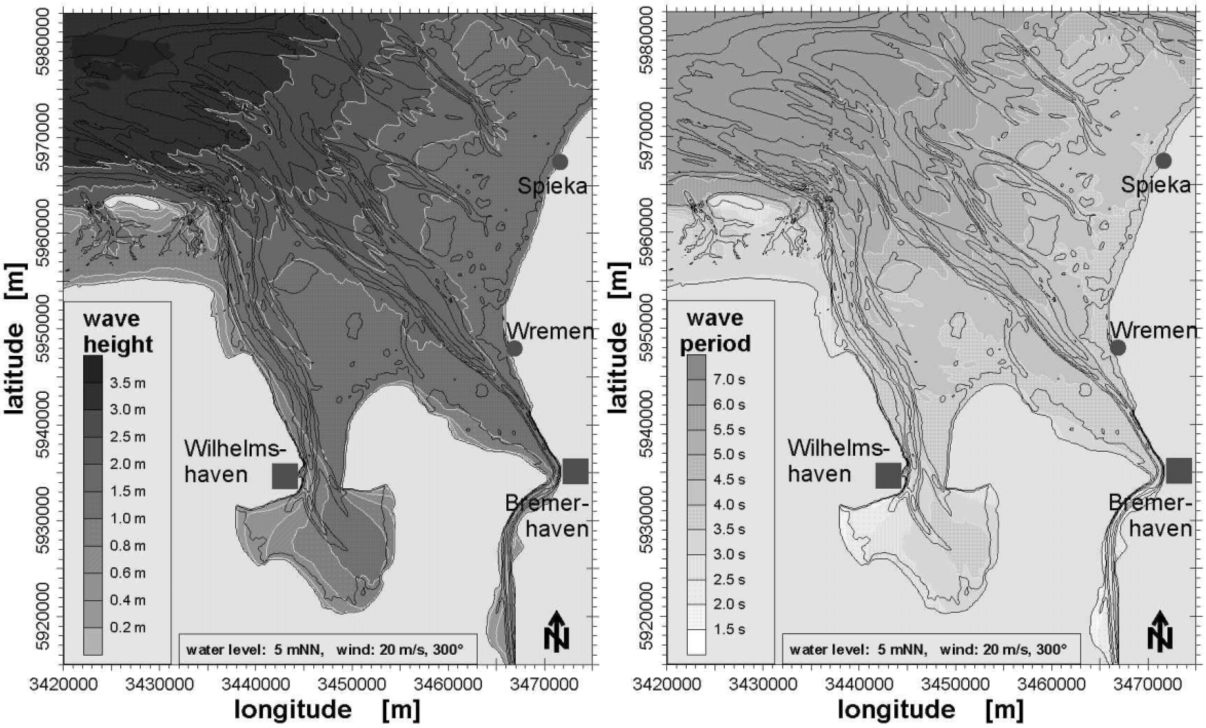


Figure 5: Wave Propagation in the Estuary of Jade and Weser – Significant Wave Height (left) and Mean Wave Period (right)

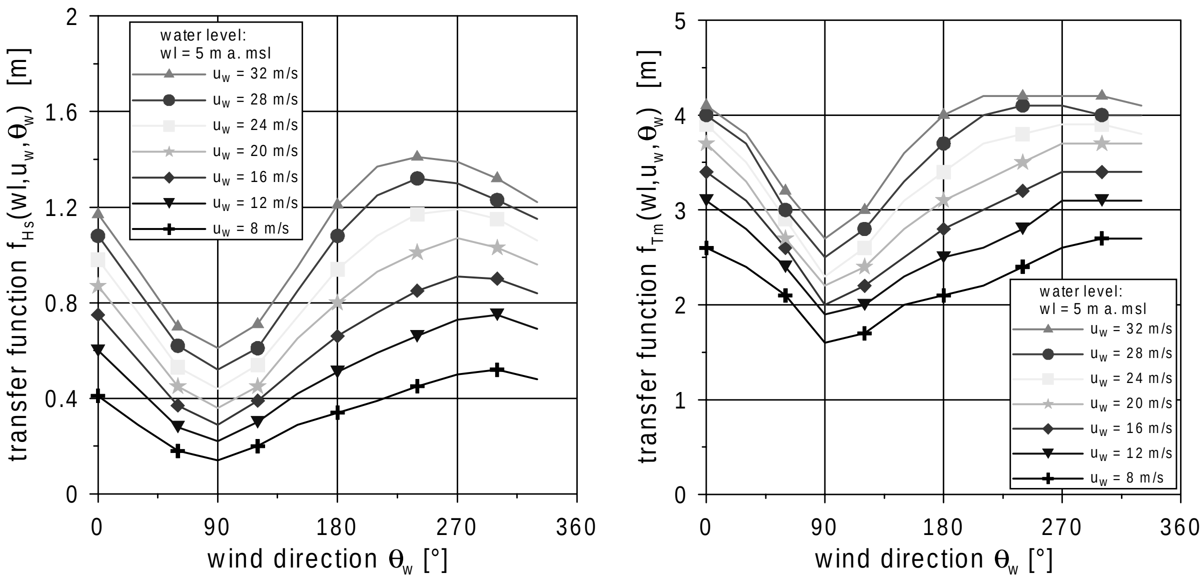


Figure 6: Transfer of Water Levels and Wind to Wave Conditions f_{Hs} (right) *and* f_{Tm} (left)

Both transfer functions and the statistics of water level and wind give the statistics of wave conditions:

$$p_{H_s}(H_s) = \int p_{wl,u_w,\theta_w}(wl,u_w,\theta_w)\,\delta(H_s - f_{H_s}(wl,u_w,\theta_w))\,dwl\,du_w\,d\theta_w \tag{11}$$

$$p_{T_m}(T_m) = \int p_{wl,u_w,\theta_w}(wl,u_w,\theta_w)\,\delta(T_m - f_{T_m}(wl,u_w,\theta_w))\,dwl\,du_w\,d\theta_w \tag{12}$$

$$p_{\theta_s}(\theta_s) = \int p_{wl,u_w,\theta_w}(wl,u_w,\theta_w)\,\delta(\theta_s - f_{\theta_s}(wl,u_w,\theta_w))\,dwl\,du_w\,d\theta_w \tag{13}$$

with the Dirac function δ. Fig. 7 shows the statistics of wave height and period over the tidal flat near Bremerhaven.

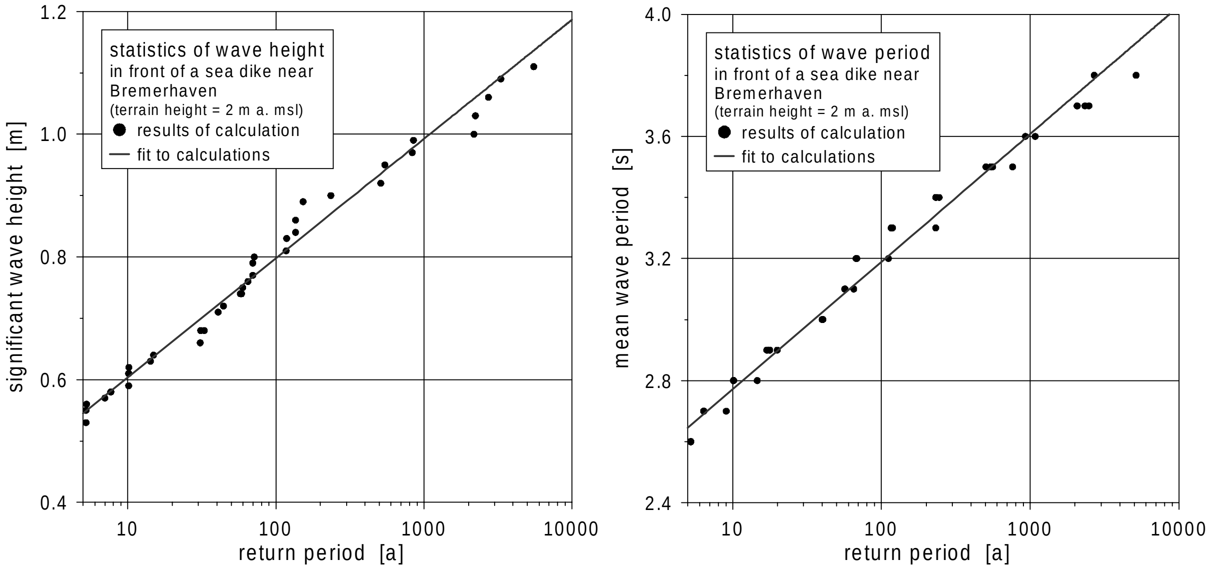
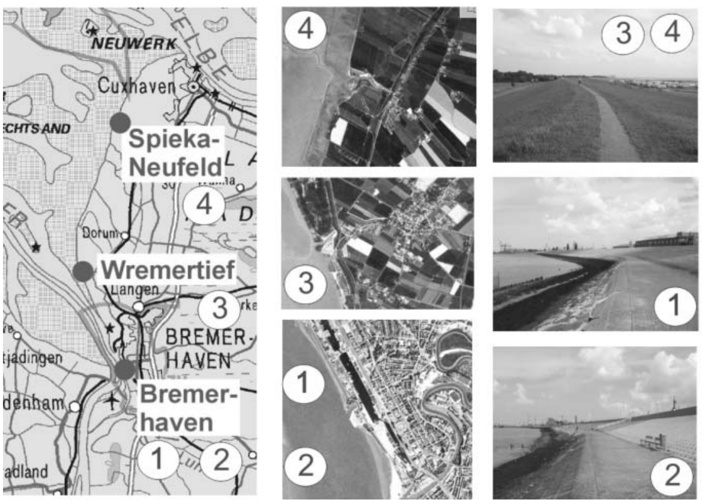


Figure 7: Wave Statistics over the Tidal Flats near Wremertief
Significant Wave Height (left), Wave Period (right)

2.5 Probability of Failure of Sea Dikes

Introducing the transfer functions f_{Hs}, f_{Tm} and $f_{\theta s}$ into (4) resp. (2) and (4) results in a function $f_{R98\%}$ resp. f_Z transferring water levels and wind into wave run-up resp. into the reliability function Z. For three locations on the coast at Bremerhaven, Wremertief and Spieka-Neufeld the probability of dike failure, calculated with (8), is given in Fig. 8.



Recurrence Interval of Wave Overtopping [years]	
Spieka-Neufeld	600
Wremen	> 1000
Bremerhaven (location 1)	500
Bremerhaven (location 2)	> 1000

Figure 8: Probability of Wave Overtopping at Seadikes

Within coastal planning the given procedure of calculating the probability of wave overtopping is applied to analyse the effect of extra coastal defence elements, like forelands or summer dikes, on coastal safety (MAI, S., VON LIEBERMAN, N., 2002).

Besides that the probability analysis gives the chance of estimating the effect of changing statistics of water levels on the safety (MAI, S., VON LIEBERMAN, N., 2000). It is found that a sea level rise of 0.50 m will approximately increase the probability of failure by a factor of four.

3. COASTAL HINTERLAND

3.1 Land Use of Coastal Hinterland

The variation of the failure probability of the sea dikes shown in Fig. 8 cannot be attributed to the changes in land use within the coastal hinterland. Fig. 9 gives an example of the uses within the hinterland protected by the sea dikes given in Fig. 8. Combining Fig. 8 and 9 it becomes obvious that the safety standard near the city of Bremerhaven does not reflect its dense population, while a comparably high safety standard is attributed to the sparsely populated area near Spieka-Neufeld. Besides of the economically valuable residential and industrial areas with a large number of inhabitants ecologically valuable important reserve areas play an important role in the calculation of the required safety standard.

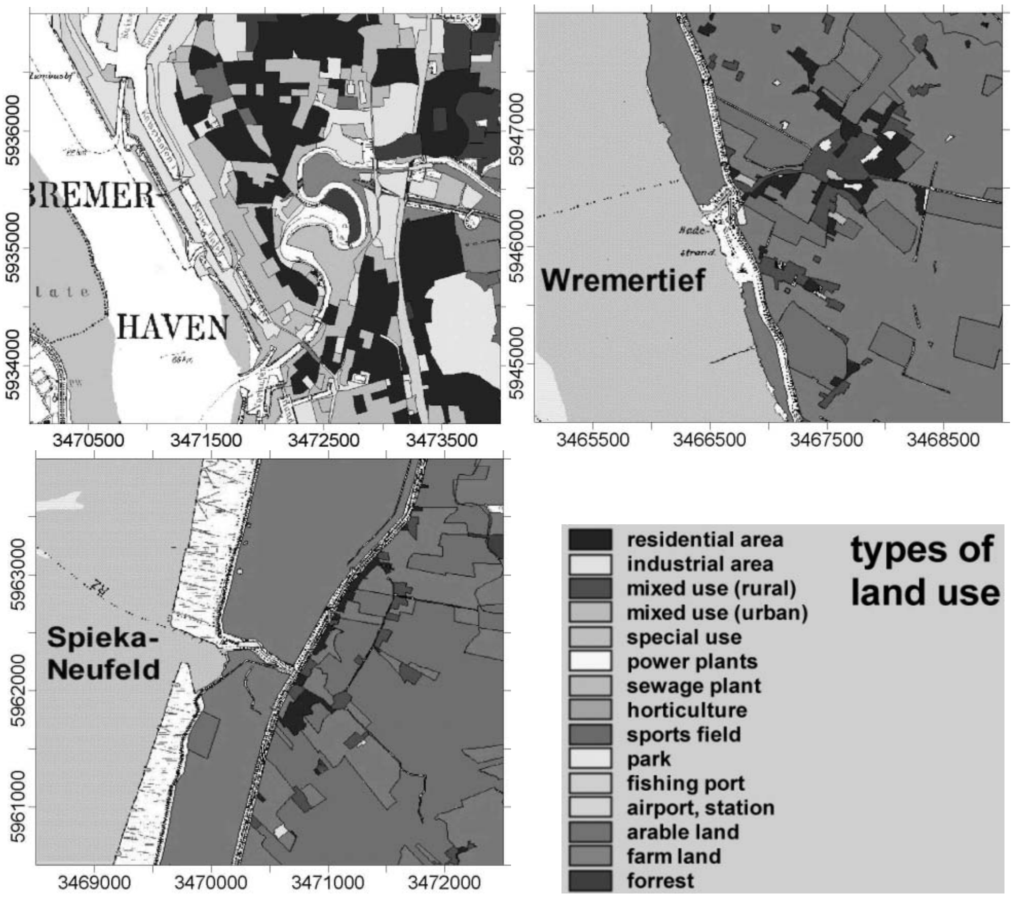


Figure 9: Land Use within the Coastal Hinterland near Bremerhaven (a), Wremertief (b) and Spieka-Neufeld (c)

3.2 Assets In Coastal Hinterlands

The assignment of an economic value to the different types of land use requires a disaggregation of state statistics onto a community level. The key variables within this disaggregation are the number of inhabitants resp. employees within each community (MEYER, V.,MAI, S., 2003) used to distribute residential and capital asset as well as stock value. Tab. 1 gives an overview over the total property and the inhabitants resp. employees in different coastal communities. Attributing the asset categories to the types of land use and distributing the assets homogenously within each community leads to a map of the economic value of the hinterland (Fig. 10).

Key Variable	Bremerhaven	Wremertief (community of Land Wursten)	Spieka-Neufeld (community of Nordholz)
Inhabitants	122000	8967	7482
Employees	45244	1196	1094
Area	70 km²	120 km²	65 km²
Residential Asset	6000 mill. €	476 mill. €	375 mill. €
Capital Asset	4800 mill. €	142 mill. €	145 mill. €
Stock Value	494 mill. €	21 mill. €	13 mill. €

Table 1: Key Variables of the coastal communities north of Bremerhaven (Inhabitants, Employees, Residential and Capital Asset as well as Stock Value)

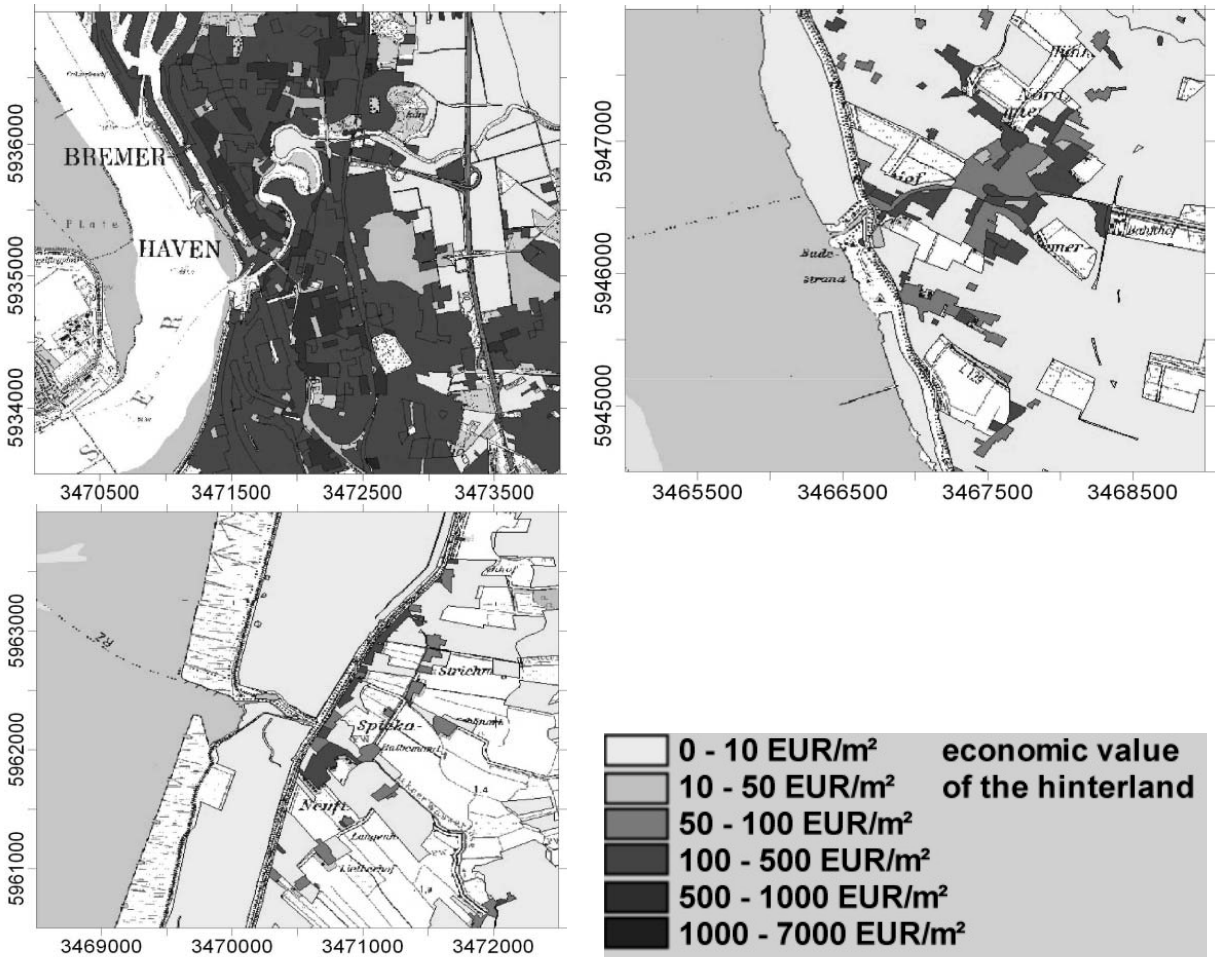


Figure 10: Map of the Economic Value of the Hinterland near Bremerhaven (a), Wremertief (b) and Spieka-Neufeld (c)

4. CONSEQUENCES OF DIKE FAILURE

4.1 Flooding of the Hinterland

The economic values within the hinterland are subject to flooding in case of failure of the coastal defence system. The historic severe storm surges in 1962 and 1976 revealed that in case of a significant wave overtopping at a sea dike a breach of up to 200 m develops.

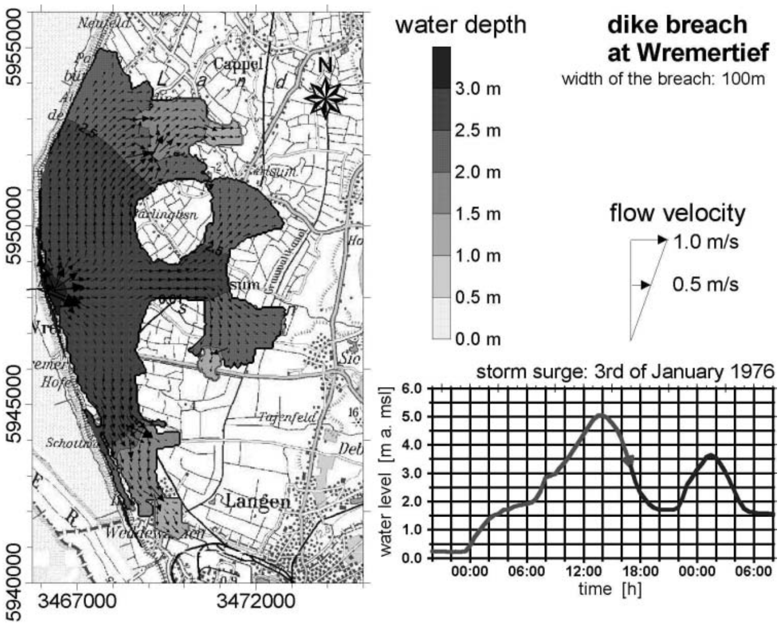


Figure 11: Numerical Simulation of the Flooding Process after a Dike Breach near Wremertief (storm surge of January 3rd 1976)

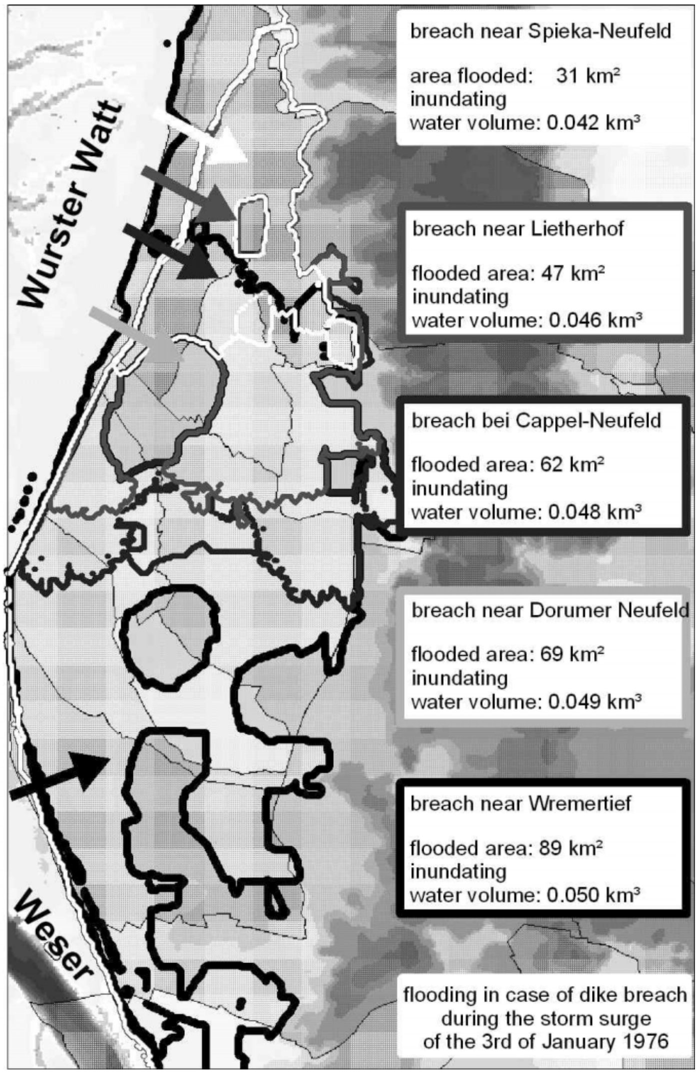


Figure 12: Dependence of the Characteristics of the Inundation on the Location of a Dike Breach

Due to consolidation the ground level of the breaches often correspond to the height of the surrounding. An estimate of the possible flood zone is calculated using numerical simulations under the assumption of a dike breach at the beginning of a storm surge. Fig. 11 gives an example of the numerical simulation of the flooding process after dike breach near Wremertief assuming a storm surge scenario comparable to the severe surge of the 3rd of January 1976.

Besides of the characteristics of the dike breach the structure of the hinterland, e.g. the width of the low-lying marsh land, has strong impact on the inundation. Fig. 12 reveals this dependence of the inundation characteristics on the location of the dike breach, e.g. a breach near Spieka-Neufeld results in a flooded area of 31 km² and a mean water depth of 1.3 m, while a breach near Wremertief leads to flooding of 89 km² and a water depth of 0.6 m. Furthermore the coastal defence elements in front of the sea dike effect the inundation process, as discussed by MAI, S. and ZIMMERMANN, C. (2003). Especially forelands significantly reduce the flood zone in case of a dike breach, while other elements, like summer dikes, are of minor importance. The integration of all coastal defence elements as well as the structure of the hinterland within coastal defence planning is a new, very favourable aspect of the method of risk analysis.

4.2 Damage Due To Flooding

The damage to the land uses respectively the economic values caused by flooding especially relates to the water depth of inundation. Other parameter, like the duration of flooding and the speed of the water inundating, are only important for certain types of land use. E.g. the duration of flooding determines the degree of damage to agricultural and natural reserve areas. The mathematical approach to the consequences of failure C_f is given by

$$C_f = \iint \left(\sum_i \varphi_i(x,y,d(x,y)) \cdot V_i(x,y) \right) dx\, dy \tag{14}$$

with the value per unit area of a certain asset class $V_i(x,y)$, its degree of damage $\varphi_i(x,y,d(x,y))$ and the water depth $d(x,y)$ at a certain position (x,y). Typical damage functions $\varphi_i(d)$ are given in Fig. 13. The combination of the results of the numerical mapping of the flood zone given in Fig. 12 and the mapped values within the hinterland given in Fig. 10 by using the damage functions given in Fig. 13 maps the damage in case of flooding (MAI, S., OHLE, N., ZIMMERMANN, C., 2002). Fig. 14 exemplifies the damage per unit area caused by flooding assuming a dike breach near Wremertief.

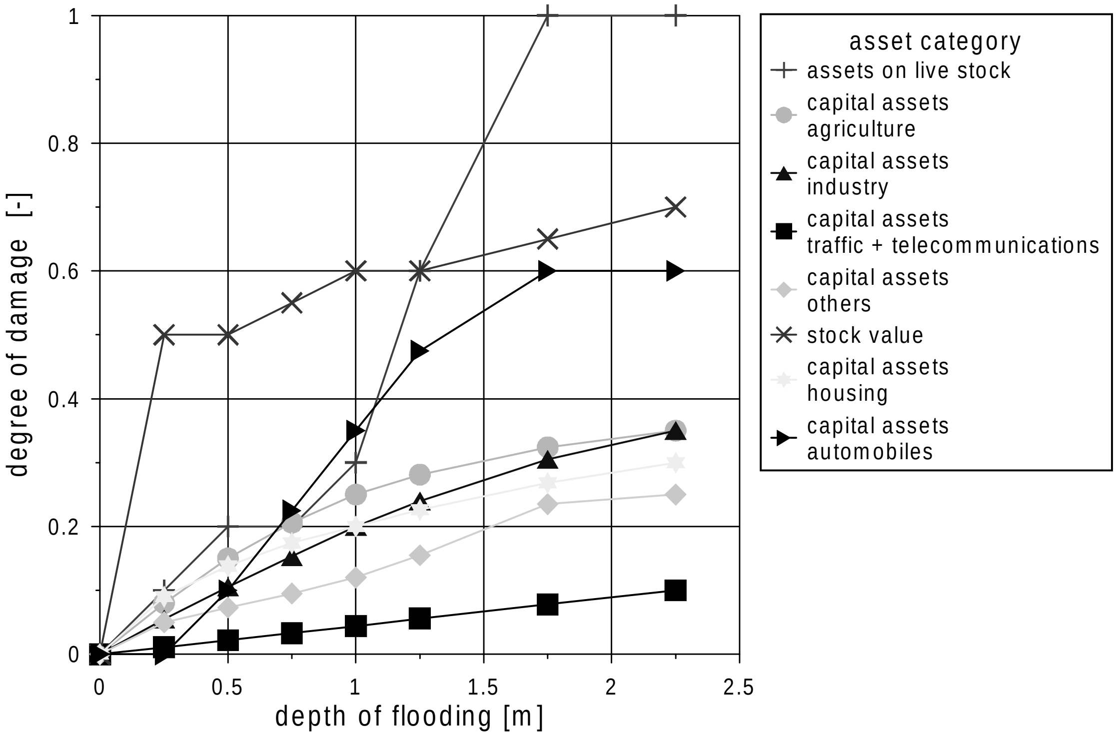


Figure 13: Damage Functions for Various Asset Classes (ELSNER, A., MAI, S., MEYER, V., ZIMMERMANN, C., 2003)

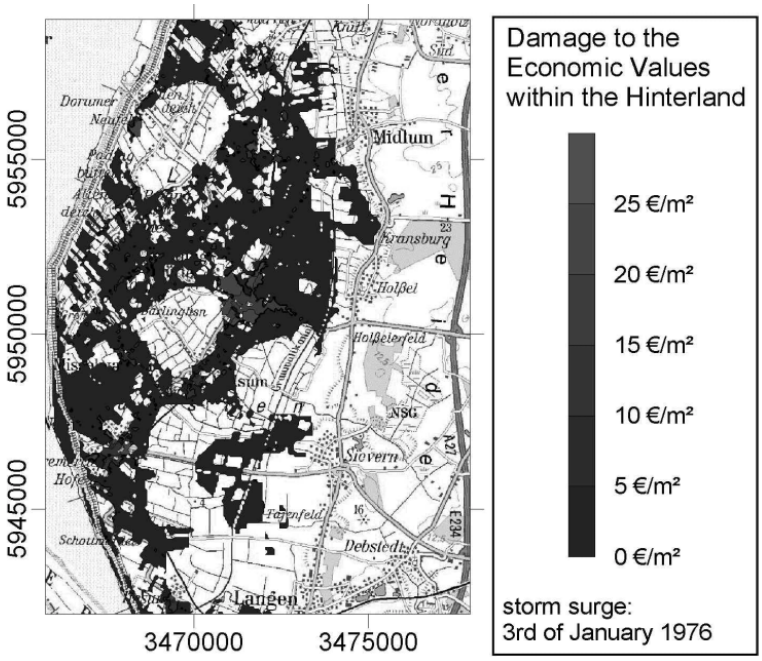


Figure 14: Damage to the Economic Values within the Hinterland Caused by Flooding in Case of Dike Breach near Wremertief

Integrating the damage per unit area over the flood zone leads to the total consequences of failure. E.g. the dike breach near Wremertief given in Figure 11 causes a total damage of 47 mill. €. In urban hinterlands, like Bremerhaven, the damage caused by flooding is much higher. In Bremerhaven a comparable storm surge scenario will cause a damage in the order of 500 mill. €.

5. RISK

The higher loss to be expected in case of a failure of coastal defences near Bremerhaven (paragraph 4.2) is not reflected in the safety of the coastal defence system of Bremerhaven. On the contrary the return period of failure of the coastal defence system is rather small, as given in paragraph 2.5. Therefore the risk calculated by (1) is for Bremerhaven with 1 mill. €/a much higher than for the rural neighbouring areas where the risk amounts to less than 0.047 mill. €/a.

6. CONCLUSIONS

The method of risk analysis revealed that today's coastal planning needs improvement because great differences in failure probability, expected loss in case of failure as well as in risk can be found. Risk provides a quantitative measure to integrate the land use in coastal planning. Besides of the economic properties, as given here, the introduction of ecological characteristics into risk analysis is now under way.

7. ACKNOWLEDGEMENT

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