A Decision Support System for an Optimal Design of Sea Dikes with Respect to Risk

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Abstract Decision support systems (DSS) are under development in coastal zone management in Germany in the moment. An example for a DSS is the Risk Information System Coast (RISC) dealing with the flood risk of the German tidal low lands at the estuaries Weser and Jade. RISC provides information on the probability of failure of dikes derived from water levels and wave climate. The consequences of dike failure are also visualized in RISC including the mapping of flood zones and the calculation of loss and risk. The DSS supports the design of sea dikes optimising the height of the dike with respect to construction cost and risk taking into account additional coastal defence elements, e.g. foreland and summer dike.

Keywords Dike failure, flooding, loss in coastal zone, mitigation strategies.

Introduction

Decision support systems in coastal zone management

Decision support systems (DSS) become more and more common in integrated coastal zone management (ICZM). Existing DSSs applied in ICZM of the tidal coasts of the North Sea, like WaDBOS (de Kok et al., 2000), focus very much on the support in conflicts between ecology and economy while decision support in coastal defence management is at an initial state of development. For parts of the German North Sea Coast the Risk Information System Coast (RISC) gives advise in coastal defence management (von Lieberman and Mai, 2002).

The application of DSS in ICZM requires the integration of different modelling systems (IMS). Therefore (extendable) open modelling systems (OMS) are typically used in the development of DSS in order to guarantee its sustainability (Blind et al., 2001). The DSS for coastal defence management RISC uses ArcView as OMS environment. The methodology of risk analysis employed in RISC for decision making is outline in this paper focusing on the idea, its different steps and its realisation.

Basics of the analysis of flood risk and optimisation procedure

The analysis of flood risks is an important part of an integrated coastal zone management. It provides the basis for a decision support in flood defence (von Lieberman et al., 2001). The flood risk R_f is defined as the product of the probability of failure p_f of the flood defences, respectively the inverse of the recurrence interval T_f of failure, and the consequences of failure C_f (Mai and von Lieberman, 2000a):

$$R_f \ = \ p_f \ \text{x} \ C_f \ = \ T_f^{-1} \ \text{x} \ C_f \tag{1}$$

The probability of failure of sea dikes being the most important flood defence element in Germany is calculated considering wave overtopping as the most important failure mechanism (Mai and von Lieberman, 2000b). The failure probability is a function of the combined statistics of water-levels and waves and the geometry of the sea dike, e.g. the crest height of the dike h_d. Therefore the probability of failure of sea dikes becomes a function of the height of the dike $p_f(h_d)$.

The failure respectively breach of a sea dike after overtopping leads to flooding of the coastal hinterland. The inundation characteristics, e.g. water depth d, determine the degree of damage $\varphi(d)$, i.e. the fraction of loss L respectively consequences C_f in case of inundation and maximum possible loss MPL (Mai and von Lieberman, 2000b):

$$L \;=\; \varphi(d) \;\times\; MPL \tag{2}$$

The maximum possible loss is determined from the different land uses A_i within the area inundated and the average value v_i of the land uses per unit area :

$$MPL \;=\; \Sigma_i \; A_i \;\times\; v_i \tag{3}$$

The average value of the different land uses per unit area is calculated for each county in the coastal zone. For this reason the total area $A_{tot,i}$ and the total value $v_{tot,i}$ of the different land uses are determined within each county.

$$v_i \;=\; v_{tot,i} \;/\; A_{tot,i} \tag{4}$$

In order to optimise the design of the sea dike the total costs R_{tot} of flood hazards and the measures of their mitigation are determined considering on the one hand side the flood risk R_f and on the other hand side the annual costs of construction R_c:

$$R_{tot} \;=\; R_c \;+\; R_f \tag{5}$$

The annual costs of construction result R_c from the maintenance costs R_m and the cost of the initial construction C_c deducted over lifetime t_l:

$$R_c \;=\; C_c \;/\; t_l \tag{6}$$

The optimal design of sea dikes is achieved for the total annual costs being minimized.

Study area

The optimisation of the height of the sea dike is exemplified for the coastal zone north of Bremerhaven, Germany. This part of the coastline of the estuary Weser is characterised by tidal flats with a width of 100 m to 4000 m, forelands of 100 to 500 m and in some places additional summer dikes in front of the sea dike (Mai and von Lieberman, 2002). The tidal range amounts to approximately 3.70 m and the highest water level was recorded with 5.37 m a. MSL in Bremerhaven and 5.45 m a. MSL in Wremertief 30 km north of Bremerhaven.

The coastal hinterland is used for agriculture, housing, tourism and to a very little extent for industry. The width of the hinterland affected from flooding ranges from 5 km to 10 km. The height of the terrain varies from 2 m a. MSL to 4 m a. MSL.

Implementation of risk analysis into a DSS

Probability of failure of sea dikes

All steps of the risk analysis described above are included in a geographical information system based on the platform of Arc/View 3.1. The standard functionality of the system called Risk Information System Coast (RISC) is extended and adapted to risk analysis by Arc/Avenue (von Lieberman and Mai, 2002). Figure 1 (left) shows a screenshot of RISC providing the essential information on the coastal defences and their probability of failure.
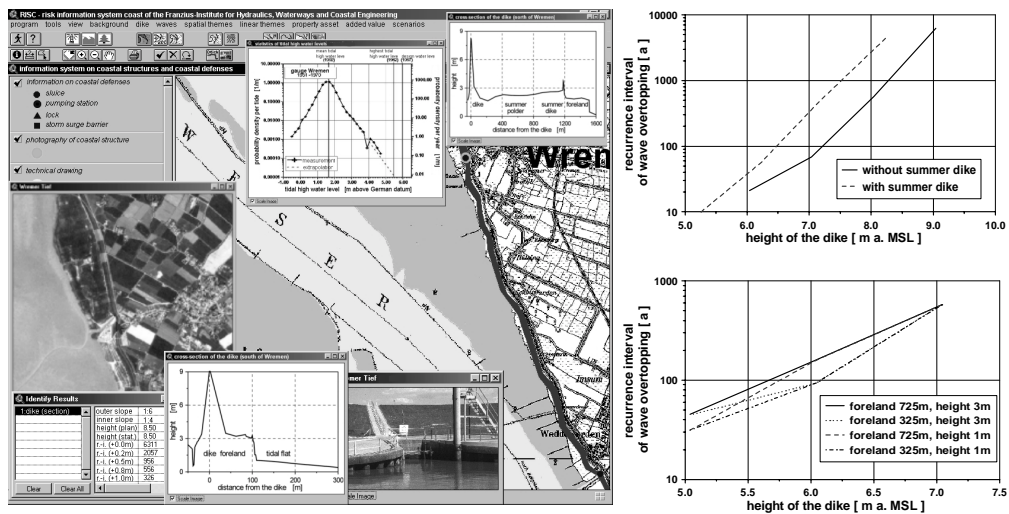
Figure 1 Screenshot of RISC: Locations, profiles and photographies of sea dikes at the estuary Weser (left) and recurrence interval of wave overtopping at sea dikes with or without an additional summer dike (top right) and with different geometries of the foreland (bottom right).

The statistics of water levels (see figure 1, left) are derived from the historical data-sets recorded for more than 100 years (Mai and Zimmermann, 2000). In contrast to that the wave statistics is determined transferring the wind statistics by numerical simulation of the wave propagation in the whole coastal zone (Mai and von Lieberman, 2000b). Within the numerical simulation using the model SWAN (Booij et al., 1999) also additional features, like forelands and summer dikes, in front of the sea dike are recognized (von Lieberman and Mai, 2000a). Figure 1 displays two typical cross-sections through the sea dike with a foreland of a width of 60 m and a width of 1500 m with respectively without a summer dike. The height of the dike is approximately 9 m a. MSL for the coastal defence system without summer dike located 5 km north of Bremerhaven in the south and 8.5 m for the system with summer dike located 30 km north of Bremerhaven. The recurrence interval of failure of today's coastal defence system amounts to 6000 years at the dike (with additional summer dike) and 600 years at the dike (without additional summer dike). The influence of the height of the dike on the recurrence interval is outlined in figure 1 (right). Besides that the recurrence interval is calculated for a dike with and without an additional summer dike as well as for a dike with different foreland geometries using experimental data of Mai et al. (1999) and of von Lieberman and Mai (2000b).

Mapping flood zones

In case of failure of the coastal defence system the hinterland is inundated. Typical ways to characterize the inundation are the identification of low-lying areas in a digital terrain model (static approach) or the numerical simulation with simplified models (semi-dynamic approach) or complex models (dynamic approach) (Mai and von Lieberman, 2001). These concepts of mapping flood zones are all realised in RISC.

In case of a dike breach 5 km north of Bremerhaven an area of 77 km^2 is flooded as a numerical analysis shows. The area inundated is visualized in figure 2 (left). The maximum water depth during flooding is more than 3 m within 19,4 % of the flooded area, more than 2 m within 64,8 % of the area and more than 1 m within 92,6 % of the area. Using classifica-

tions derived from historic flood events (CUR, 1990) the inundation water depth d of 1 m, 2 m and 3 m is transferred to a degree of damage $\varphi(d)$ of 8 %, 28 % and 60 % for houses and industry respectively 15 %, 42 % and 80 % for farm land.

An analysis of a digital landscape model reveals the use of the flood zone. RISC distinguishes between two-dimensional uses, like agriculture or housing, and one-dimensional uses, like streets or railways. For two-dimensional uses the results are listed in figure 2 (right).

Calculation of loss

An appraisal of the value of the different uses within the coastal hinterland is based on county statistics including the total value of different uses $v_{tot,i}$. The total area $A_{tot,i}$ of the different uses is determined as well. The maximum possible loss MPL calculated with equation 6 is tabulated in figure 2 and amounts to 3771 million EUR. Besides that figure 2 includes the loss L calculated with equation 4 taking into account the degree of damage $\varphi(d)$.

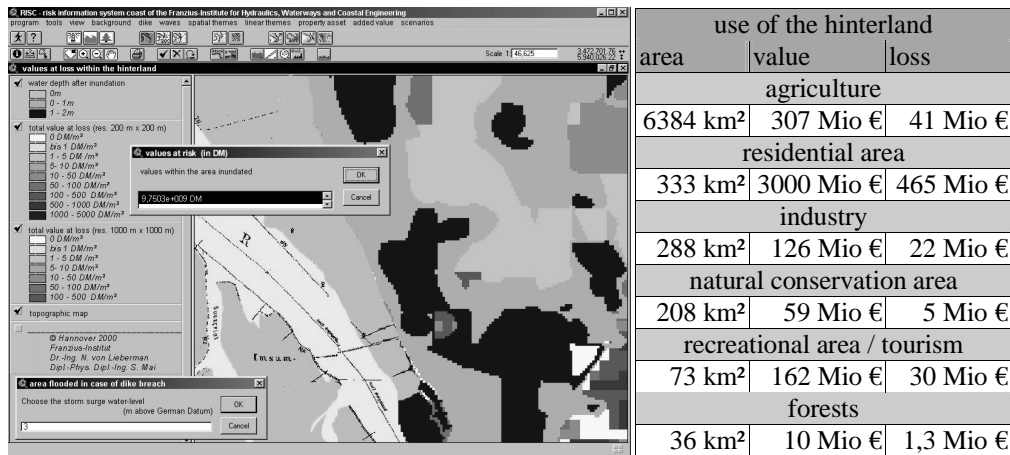| use of the hinterland		
area	value	loss
agriculture		
6384 km²	307 Mio €	41 Mio €
residential area		
333 km²	3000 Mio €	465 Mio €
industry		
288 km²	126 Mio €	22 Mio €
natural conservation area		
208 km²	59 Mio €	5 Mio €
recreational area / tourism		
73 km²	162 Mio €	30 Mio €
forests		
36 km²	10 Mio €	1,3 Mio €

Figure 2 Screenshot of RISC: map of values at risk within the hinterland in case of inundation (left) and economic uses within the hinterland related to maximum possible loss respectively expected loss in case of inundation (right).

Mapping of risk zones

The risk per unit area dR_f/dA is calculated using the probability of failure p_f of the coastal defence system and the loss per unit area. The spatial integration of the risk per unit area defines the total risk of the hinterland R_f. The total risk of the hinterland north of Bremerhaven protected by a dike without additional summer dike amounts to 325000 EUR / year. The same system with additional summer dike leads to a risk of 170000 EUR / year.

The mapping of risk zones directly identifies the extremely exposed areas, i.e. the zone of high risk per unit area. It is therefore valuable identifying the need for extra object oriented coastal defences, e.g. polders. RISC provides a tool to introduce these additional object oriented coastal defences into the defence system and to recalculate the total risk in order to study the effect of object oriented measures.

Decision support in dike design

The annual construction and maintenance costs R_c of the different coastal defence systems stand opposite to the risk of the coastal hinterland R_f. The life-time t_l of coastal defences is typically estimated with 75 years (LAWA, 1993). The construction costs of a dike are approximately proportional to its length and its height. For sea dikes with slopes of 1:6 the construction costs per m length and m height are 500 EUR / m / m while polder dikes with slopes of 1:4 cost 300 EUR / m / m and summer dikes with slopes of 1:10 800 EUR / m. A more detailed analysis of construction costs can be found in Ohle and Dunker (2001).

The components of the total annual costs R_{tot} are visualized in figure 3 presenting also the optimisation procedure of the coastal defence system with respect to the height of the dike. For the sea dike without a summer dike the optimal height comes to 7.0 m, i.e. 9.0 m a. MSL. This height is reduced to 6.0 m a. MSL in case of a summer dike located in front of the sea dike. However the sea dike without summer dike is economically advantageous because of its smaller total costs.
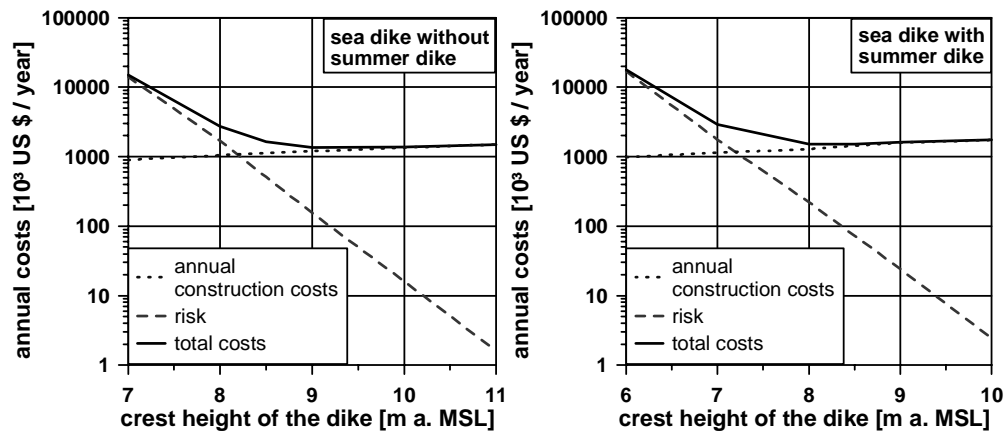

Figure 3 Components of the total costs of flood hazards and the measures of their mitigation.

Conclusion

The Risk Information System Coast (RISC) provides a method to optimise the coastal defence system by means of minimizing the total costs, i.e. the construction costs and the flood risk. This concept will significantly support the process of decision making in coastal defence management and helps to integrate other subject areas. Besides of the integration of economic consequences in case of flooding the method outlined in this paper may be extended by ecological (Kraft et al., 2002) and sociological consequences (Heinrichs and Peters, 2001). A first concept for this extension is put forward by Hahn et al. (2002).

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