A Storm Surge Management System for the German Coast

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Abstract

Future storm surge management will be based on risk analyses including the determination of failure mechanisms of coastal defenses and their probabilities of occurrence as well as the calculation of losses due to inundation. This paper presents an example of a risk analysis carried out for the coastal region between the two major ports Wilhelmshaven and Bremerhaven. In order to supply the decision-makers and stakeholders with easily accessible information on storm surge management the results of the risk analysis were introduced into a Geographical Information System (GIS) called RISC – Risk Information System Coast.

Introduction

The traditional storm surge management at the German North Sea Coast is essentially based on deterministic approaches. Due to economic restrictions, climate changes and altered land uses methods of risk assessment are now introduced into storm surge management systems (Mai and von Lieberman, 2000a). This is a common approach in all countries neighboring Germany, like the Netherlands (Jorissen, 2000), Denmark (Laustrup, 2000) and Great Britain (Purnell, 1999). The basic ideas are described in the report of the Technical Advisory Committee on Water Defenses (CUR, 1990). In order to ease the access for stakeholders and decision-makers the results of risk analyses are today available in Geographical Information Systems providing also management tools for the decision making process (de Kok et al., 1998 / Mai and von Lieberman, 2000b). The basic ideas of risk analysis and its implementation in a decision support system (DSS) are presented exemplary in the following for the coastal region between the ports Wilhelmshaven and Bremerhaven near the estuaries Jade and Weser (Fig. 1). The region is characterized by a hinterland lying at mean high water level which is protected by dikes as the main protection element. In front of the dikes forelands and large tidal flats can be found reducing especially the wave load on dikes. The tidal range is appr. 3.50 m with maximum water levels of appr. 5 m above German datum (appr. mean sea level) during storm tides.

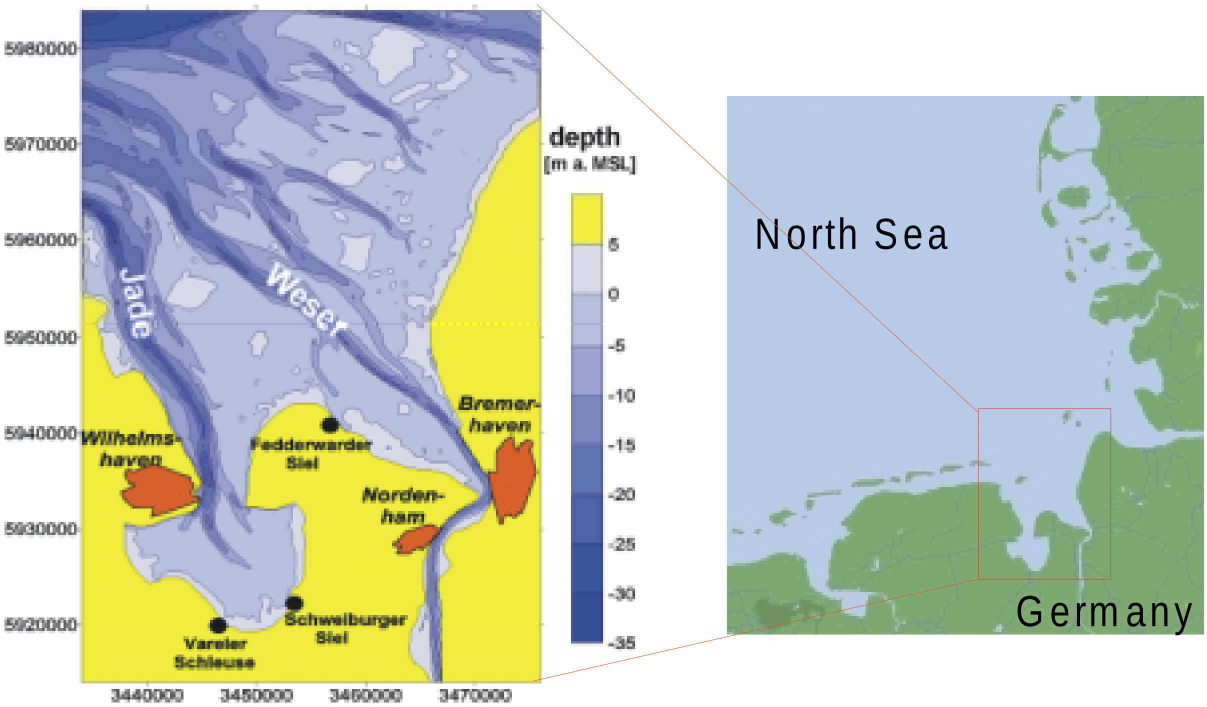

Figure 1. Focus area at the German coast.

Basic Ideas of Risk Analysis

Risk comprises the failure probability of the coastal defense system and the losses to be expected in case of failure.

$$R = \int_{Z<0} p_{(Z)} \cdot C_{(Z)} dZ \tag{1}$$

with
R risk
$p_{(Z)}$ probability density function of the reliability Z
$C_{(Z)}$ loss in case of failure (i.e. $Z < 0$)

The failure of coastal protection systems at the German coast is related to dike breaches. The main cause for dike breaching is wave overtopping as former storm events revealed. A mathematical formulation of these failure modes is given by (CUR, 1990 / Reeve, 1998)

$$Z = h_D - HW - R_{98\%} \tag{2}$$

with
h_D height of the dike
HW tidal high water level
$R_{98\%}$ wave run-up

The probability of breaching $p_{Z<0}$ is calculated taking into account the statistics of tidal high water levels and wave run-up. The probability respectively the recurrence interval $T_{Z<0}$ is calculated by

$$\frac{1}{T_{Z<0}} = p_{Z<0} = \int_{-\infty}^{0} p_{Z(Z)} dZ = \int_{-\infty}^{\infty} \int_{h_D - HW}^{\infty} p_{(HW, R_{98\%})} dR_{98\%} dHW \tag{3}$$

The statistics of wave run-up were deduced numerically from the statistics of wind and wave climate. The loss in case of failure $C_{(Z)}$ is derived from the maximum possible loss C_{total}:

$$C_{(Z)} = \varphi_{(Z)} \cdot C_{total} \tag{4}$$

The damage factor $\varphi_{(Z)}$ is a function of the degree of failure represented by Z. In case of dike breaches the damage factor is related to the inundation characteristics, like area flooded and inundation depth. Figure 2 shows a typical dependence of the damage factor on the inundation depth. This is based on field surveys in the Netherlands during the storm surge in 1953. Unfortunately comparable data is not available for the latest storm surge in Germany in 1962. Within the analysis different values at risk, like agriculture, dwellings and capital stock, are distinguished. In the following the concept outlined is applied at the coastal region shown in figure 1 and introduced into a DSS using the GIS ArcView.

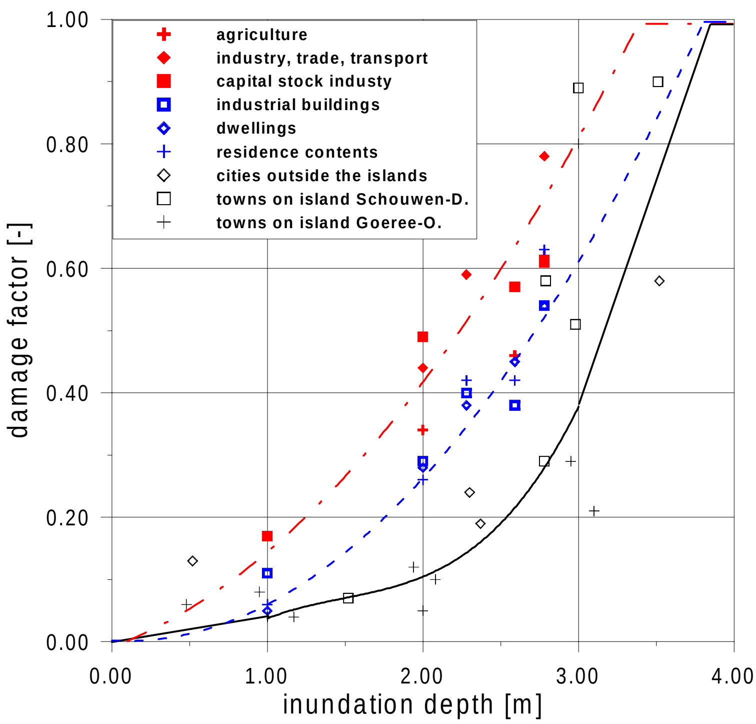

Figure 2. Damage factor as a function of inundation depth (CUR, 1990).

Implementation of Risk Analysis in DSS

Among others the failure analysis presented in eq. 2 requires the knowledge of the statistics of the tidal high water level HW and the design parameters of the dike. Thus these parameters were collected and included into the DSS. Figure 3 shows a screenshot of the DSS which presents information on dikes and other coastal defenses like sluices, locks and storm surge barriers. The height of the dike and statistics of HW being necessary parameters to calculate the reliability Z can also be found. The wave run-up $R_{98\%}$ is calculated from wave parameters using the formulation of van der Meer and Janssen (1995). Because of the lack of long-term statistics on wave climate wave statistics are derived from wind and water level statistics using the numerical model SWAN, which was calibrated with data of wave buoys (Mai et. al., 2000). The wave conditions, i.e. significant wave height and mean wave period, for various sets of wind and water level can be looked up in the decision support system RISC (fig. 4).

Using the information on the dikes and the statistics of water levels and waves resp. wave run-up the failure probability is calculated according to eq. 3.

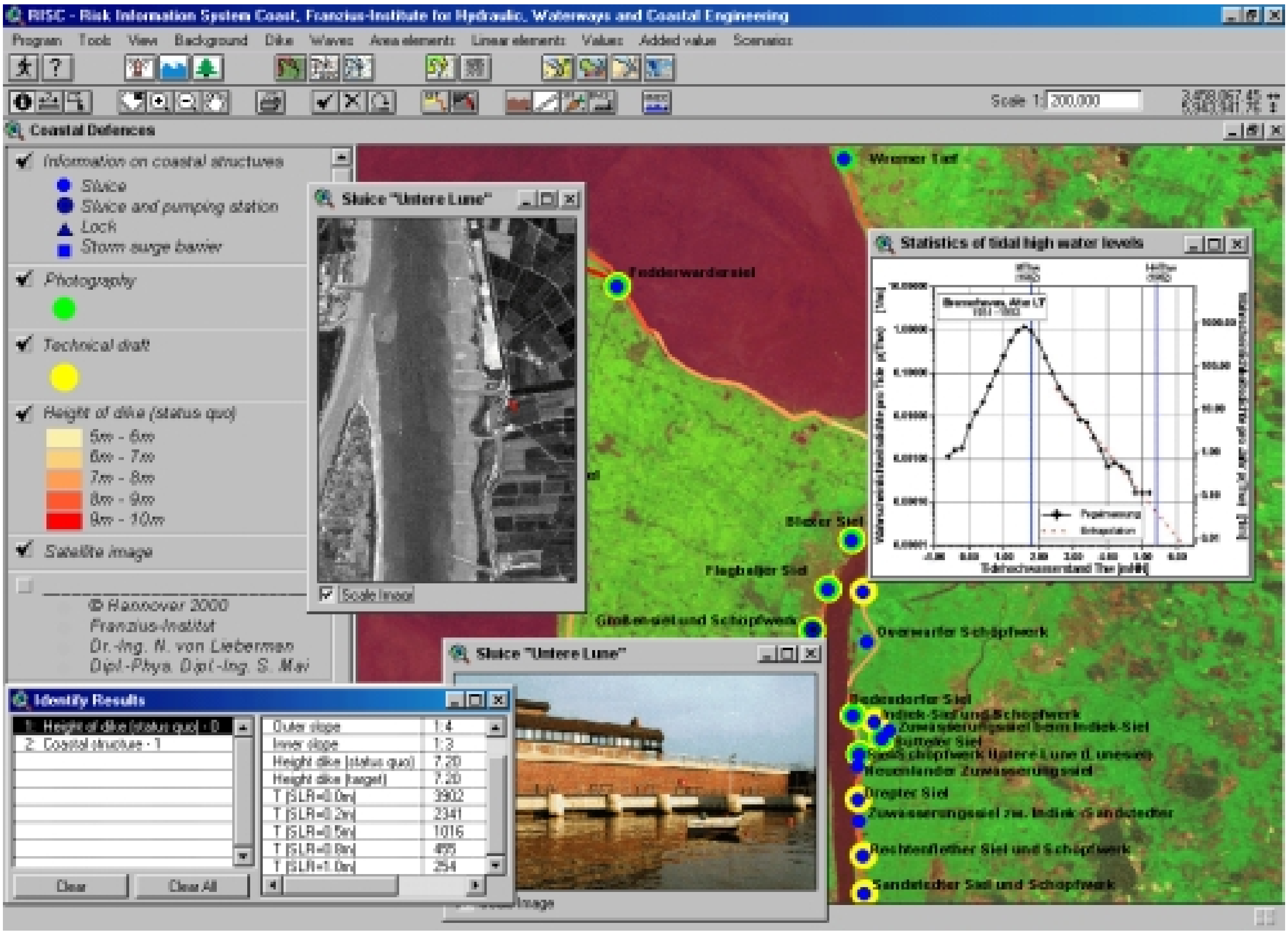

Figure 3. Screenshot of RISC, information on coastal defenses (Mai and von Lieberman, 2001).

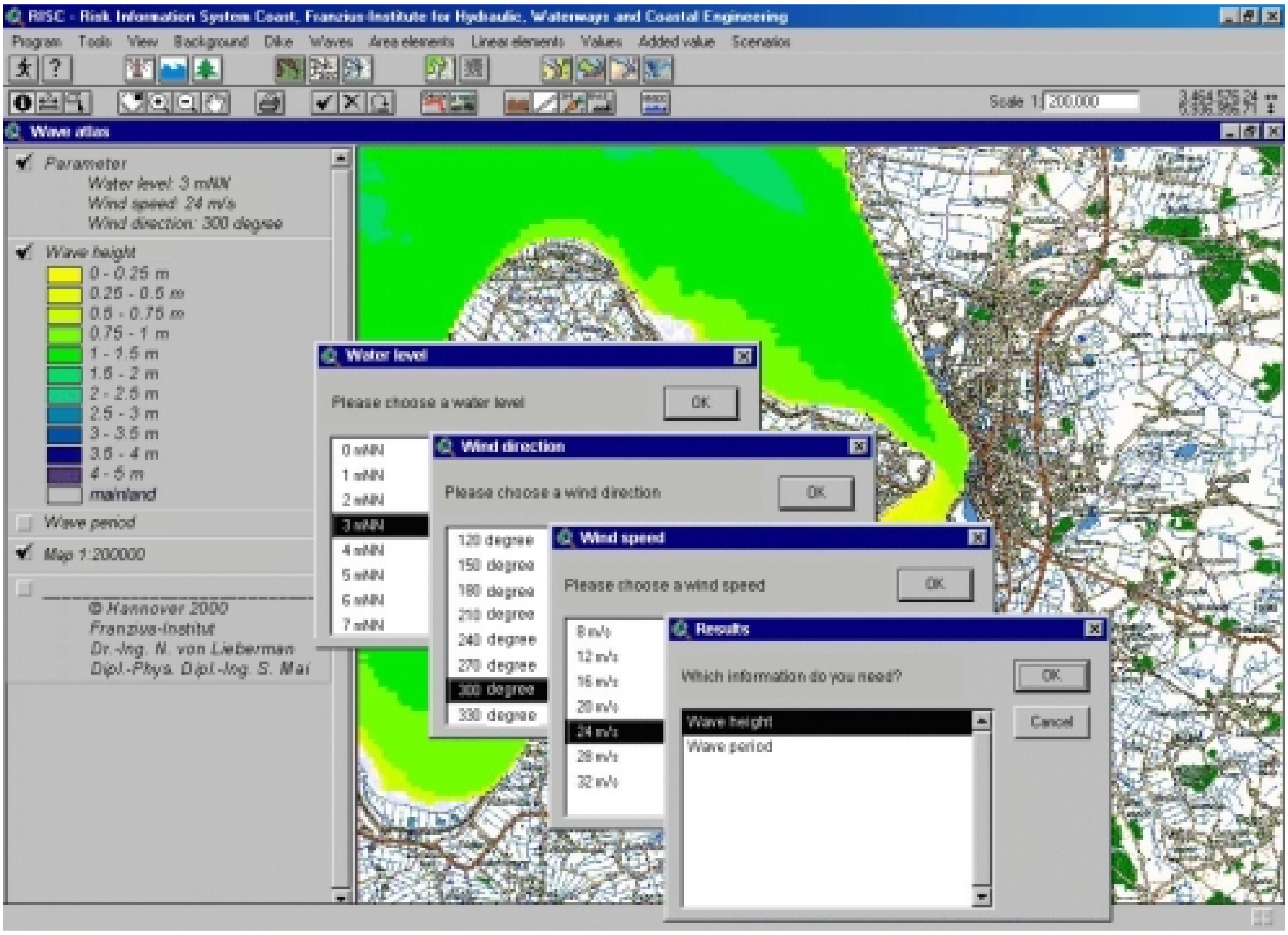

Figure 4. Screenshot of RISC, wave atlas (Mai and von Lieberman, 2001).

The resulting probability of failure at the German coast ranges from 1 in 400 years to 1 in 4,000 years depending on the location at the coast. In the City of Bremerhaven the average failure probability is 1 in 4,000 years. As shown in figure 2 this information is also included in RISC. Besides today's situation possible climate changes, leading to an increase of water levels and winds, are also taken into account calculating failure probabilities. In case of a water level rise of 0.50 m today's probability of dike failure is reduced to a fourth (Mai and von Lieberman, 2000c).

Another part of the risk analyses is the calculation of the loss in case of inundation after a dike breach, see eq. 1. This requires the determination of the extend of inundation. The areas of inundation are calculated by two-dimensional numerical simulations with the model MIKE21-HD for the low lying hinterland. Figure 5 presents a result of the inundation process in case of a dike breach in the City of Bremerhaven. The width of the dike breach was estimated on the basis of historic dike breaches with 200 m. This leads to a flooded area of appr. 19 km² (6 km² in the City of Bremerhaven) with a water depth up to 2.5 m during one storm tide assuming an average bottom friction of 24 $m^{1/3}/s$. A sensitivity analysis carried out by von Lieberman and Mai (2001) revealed only little influence of the bottom friction on the flooded area. A change in bottom friction of 50 % reduces the flooded area by 15 %.

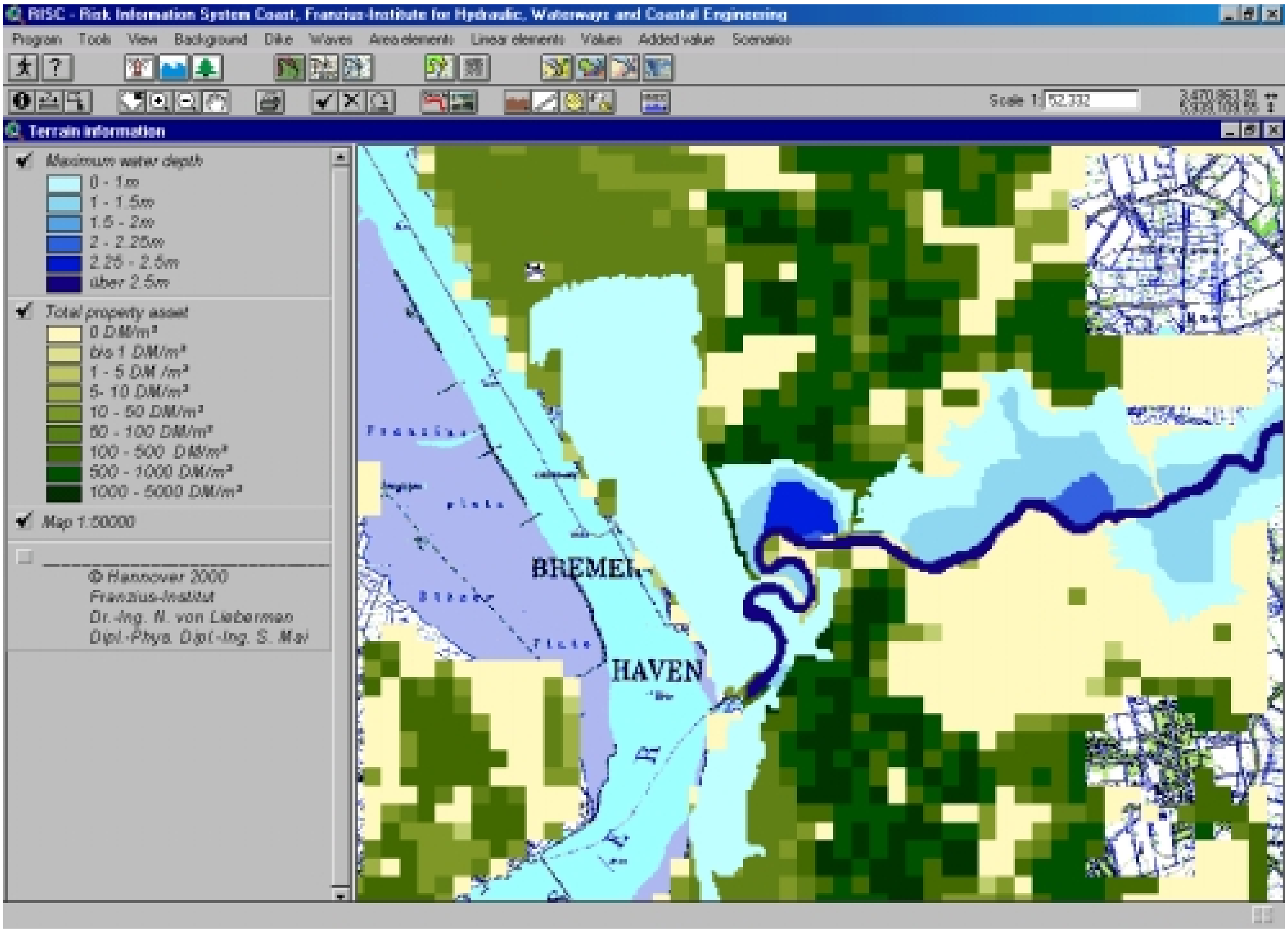

Figure 5. Screenshot of RISC, inundated area after dike breach (Mai and von Lieberman, 2001).

Besides the inundated area figure 5 shows the spatial distribution of the total economic value (maximum possible loss) in the City of Bremerhaven. The total economic value within the area of inundation is derived from official statistics including number of inhabitants, gross value, residential, industrial, and agricultural areas for the municipalities affected. The distribution of the parameters within the municipalities is derived by a top-down approach analyzing topographical maps with respect to housing, traffic (railroad, autobahn, highway, waterway), communication / power lines, agriculture (grassland, field), and protection works (dike, sluice, pump station) (von Lieberman and Mai, 2000).

The total loss per area is calculated by superposition of maximum possible loss and the damage factor being a function of the inundation depth (see eq. 3). The spatial distribution of the total loss per area is shown in figure 6. The total loss per area in Bremerhaven is appr. 200 DM/m² (≈ 100 $/m²). The integration of the total loss per area results in the total loss. This loss for the anticipated dike breach in Bremerhaven is appr. 1.2 Billion DM (≈ 0.6°Billion $).

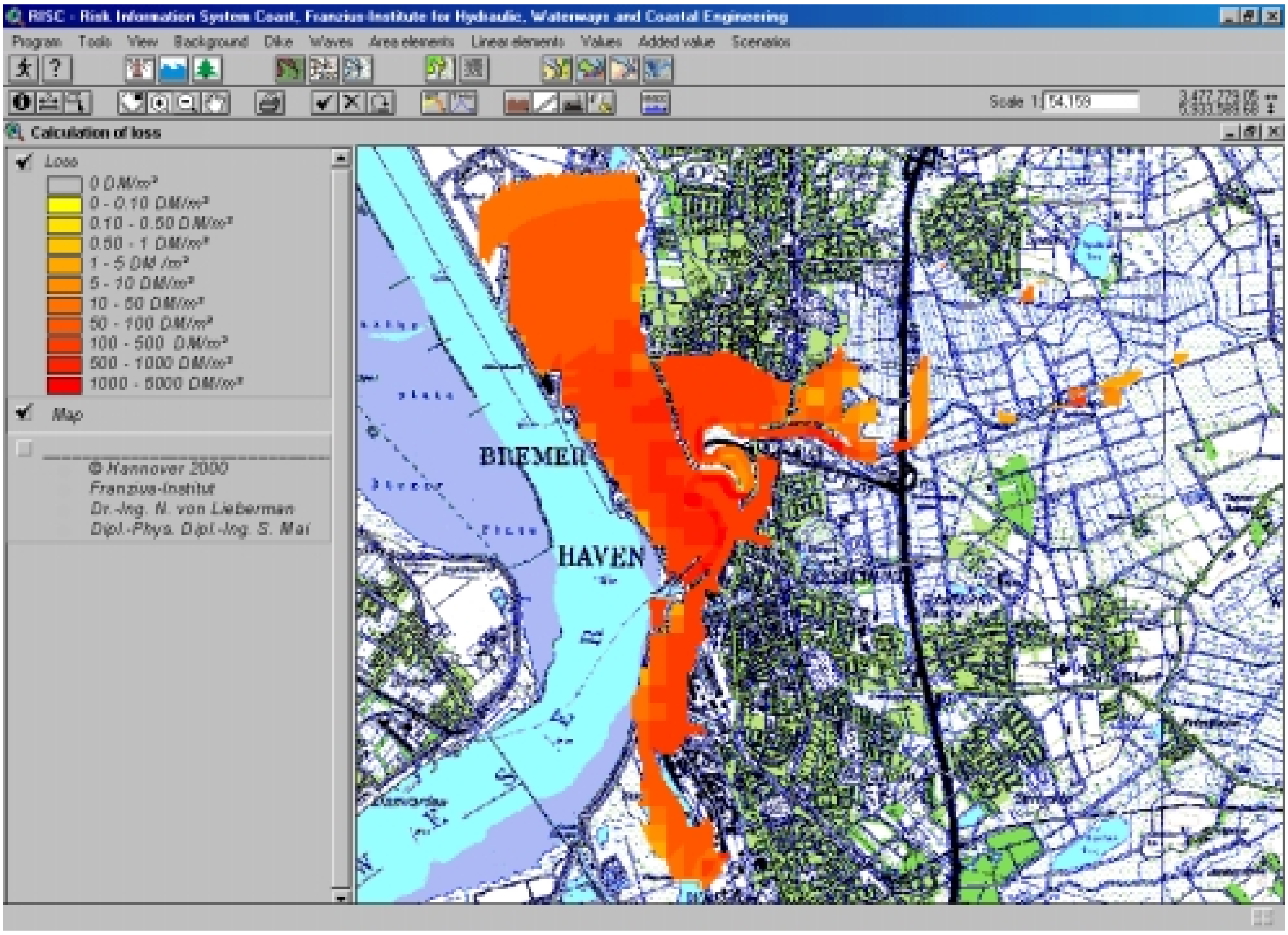

Figure 6. Screenshot of RISC, calculation of loss (Mai and von Lieberman, 2001).

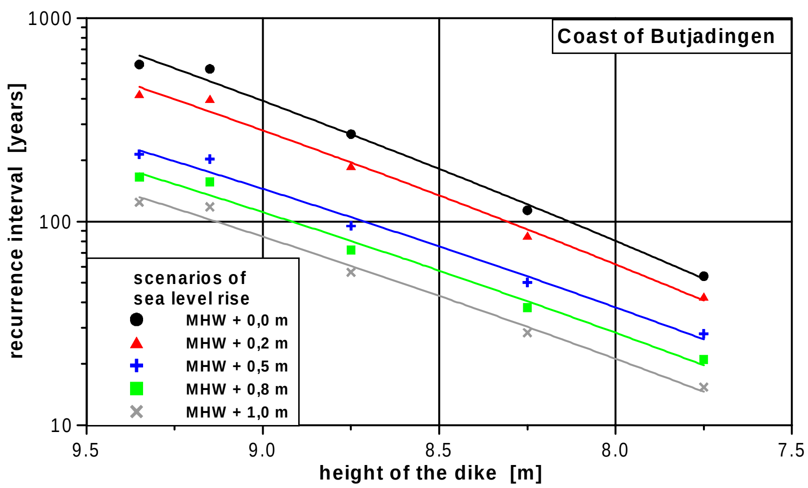

Figure 7. Recurrence interval of dike failure as a function of the height of the dike (Mai and von Lieberman, 2000c).

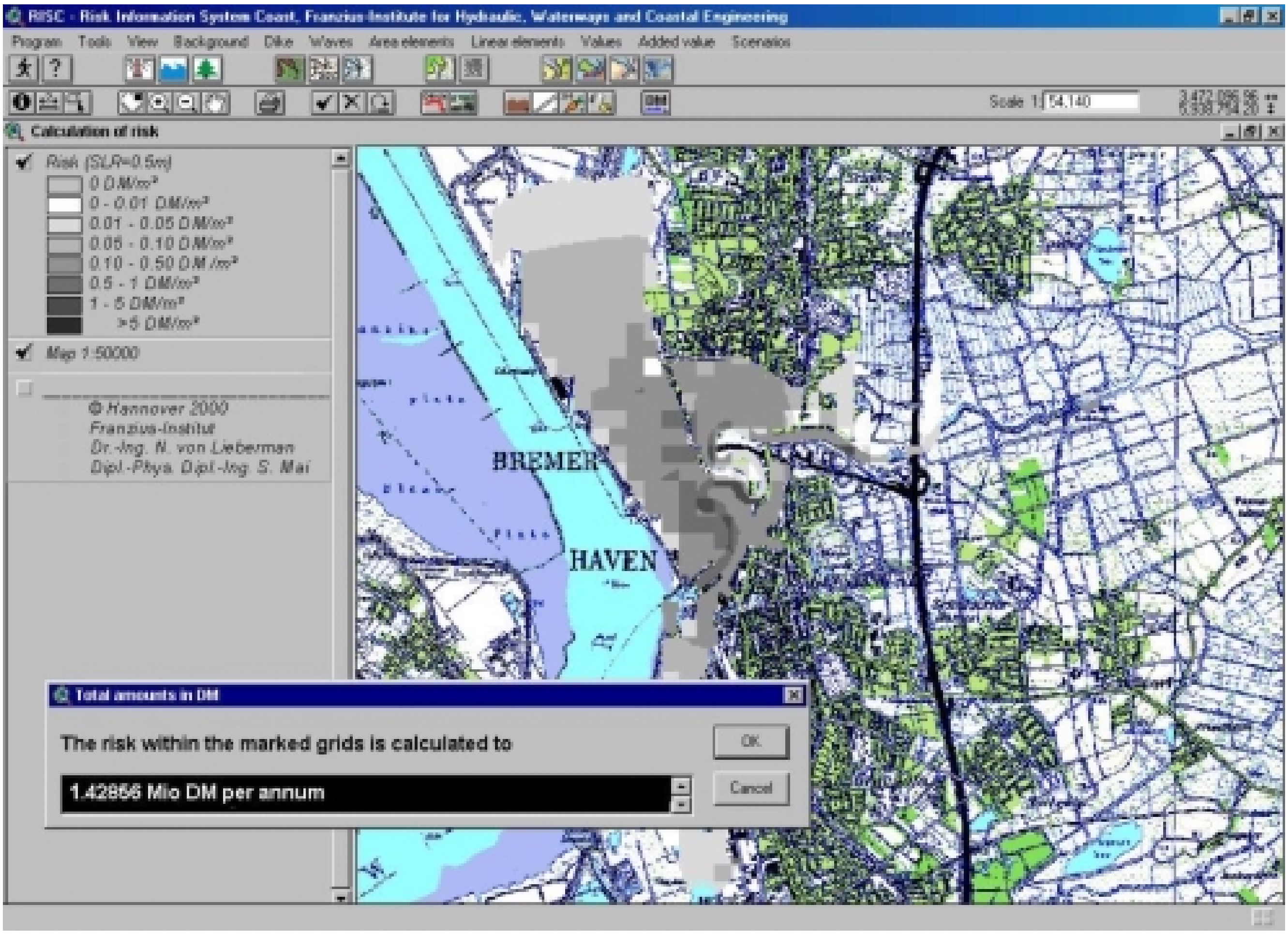

Figure 8. Screenshot of RISC, calculation of risk (Mai and von Lieberman, 2001).

According to eq. 1 the risk is calculated from the probability of failure and the total loss. Thus the flood risk for the City of Bremerhaven is today appr. 0.35 Million DM per year (≈ 0.18°Million $ per year) and increases to 1.4 Million DM per year (≈ 0.7°Million $ per year) in case of a sea-level rise SLR of 0.5 m. The spatial distribution of the risk is shown in figure 8 (risk maps).

Besides the analysis of today's coastal defenses under increased stress, e.g. SLR, caused by climate changes different actions improving the coastal defense, like the heightening of dikes, the construction of storm surge barriers and the set-up of a second dike line were compared on the basis of risk maps. Figure 7 provides information on the influence of the height of the dike on the recurrence interval of dike failure, i.e. the inverse of the probability of failure, for different scenarios of SLR. The recurrence interval of failure is appr. reduced to a fifth for a heightening of 1 m.

Conclusions

The developed decision support system RISC helps to analyze the reliability of today's coastal defense management. They can help decision-makers and stakeholders to optimize the allocation of investment in coastal defense in order to get the same standard of safety – in terms of risk – along tidal coasts.

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