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Flood risk in coastal regions

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Abstract

An essential part of flood risk assessment at rivers under tidal conditions is the determination of flood zones. The paper presents approaches at different levels for its determination. The most simple method is the identification of areas lying below the storm surge water levels not taking into account the distance from the coastline. A more detailed approach is a semi-dynamic computation of a water intrusion into the hinterland in case of failure of coastal defences based on continuity equation in combination with the Manning-Strickler equation for the computation of flow velocities. Finally a fully dynamic simulation of the time-dependent flooding process is shown. The different approaches are analysed with respect to uncertainties in bottom friction.

1 Introduction

The management of coastal defences in Germany is under change. While today the damage due to flooding in case of storm surges is not taken into account future management concepts will do on the basis of risk analysis. The risk analysis comprises on the one hand side the determination of the failure probability $p_{failure}$ of coastal defences and on the other hand side the estimation of the loss C_{damage} in case of failure using the following concept to determine the
risk R:

$$R = p_{failure} \cdot C_{damage} \tag{1}$$

At the German North Sea coast the most important coastal defence is the dike with breaching in case of wave overtopping being the main failure mechanism [1]. The loss in case of failure is then related to flooding of the hinterland. It is calculated from the property in the hinterland introducing a damage factor φ depending on the inundation characteristics. E.g. the CUR [2] gives a parameterisation of the damage factor depending on the inundation depth. To determine the inundation depth three different approaches are known. In the following these will be worked out for the coastline between the German estuaries Jade and Weser near the seaports of Wilhelmshaven and Bremerhaven.

2 Determination of flood zones – three different approaches

Within a first straight forward approach the topography is superimposed by a constant storm surge water level. This does not take into account the propagation of the flood wave after a failure of coastal defences. Nevertheless this procedure is very common, e.g. the IPCC [3] proposed it within studies on climate change. Figure 1 gives an example of this static approach assuming a storm surge water level of 2m above German datum.

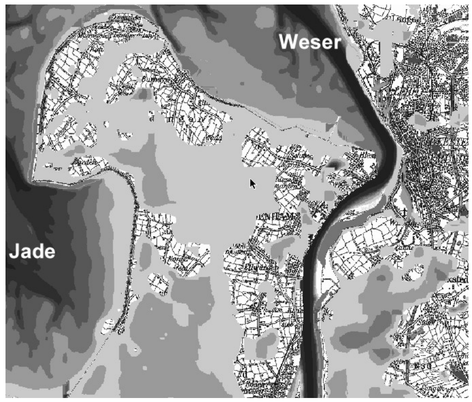

Figure 1: Determination of the inundation depth by a static approach,
storm surge water-level 2 m above German datum

A more detailed approach than the static one is a semi-dynamic computation based on the continuity equation (eqn (2)) in combination with the Manning-Strickler equation (eqn (3) and (4)):

$$\frac{dd}{dt} + d \cdot \frac{dv}{dr} = 0\,, \tag{2}$$

$$v = k_{St} \cdot d^{2/3} \cdot I^{1/2}\,, \tag{3}$$

$$I = \frac{d\zeta}{dr} \tag{4}$$

with the flow velocity v, the Strickler coefficient k_{St}, the water depth d, the hydraulic gradient I, the surface elevation ζ, the time t, and the horizontal distance r. The semi-dynamic approach assumes a semi-circular propagation of the flood wave in case of a dike breach. Important model parameters are the width of the dike breach and the bottom friction, analysed in section 3 of this paper. Figure 2 exemplifies the semi-dynamic approach at the Jade estuary nine hours after a dike breach. The width of the dike breach was set to 200m. This is typical as former dike breaches revealed. The time series of the water level in the Jade was taken from a storm surge in 1976.

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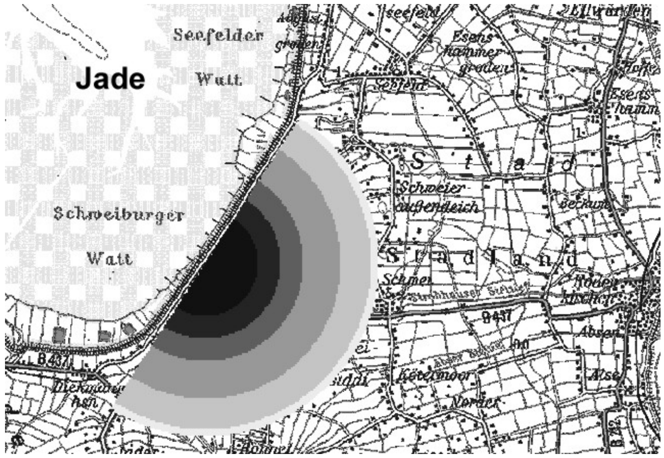

Figure 2: Determination of the inundation depth by a semi-dynamic approach, nine hours after dike breach at the Jade estuary

Further improvement can be achieved by solving the full Navier-Stokes-eqns (5) and (6) and the continuity eqn (7) numerically:

$$\begin{aligned} &\frac{\partial\left(d \cdot v_x\right)}{\partial t}+\frac{\partial}{\partial x}\left(d \cdot v_x^2\right)+\frac{\partial}{\partial y}\left(d \cdot v_x \cdot v_y\right)= \\ &\qquad -g \cdot d \cdot \frac{\partial \zeta}{\partial x}-\frac{F_{bottom,x}}{\rho_w}+\frac{F_{eddy,x}}{\rho_w}+\Omega \cdot d \cdot v_y \end{aligned} , \tag{5}$$

$$\begin{aligned} &\frac{\partial\left(d \cdot v_y\right)}{\partial t}+\frac{\partial}{\partial y}\left(d \cdot v_y^2\right)+\frac{\partial}{\partial x}\left(d \cdot v_x \cdot v_y\right)= \\ &\qquad -g \cdot d \cdot \frac{\partial \zeta}{\partial y}-\frac{F_{bottom,y}}{\rho_w}+\frac{F_{eddy,y}}{\rho_w}-\Omega \cdot d \cdot v_x \end{aligned} , \tag{6}$$

$$\frac{\partial \zeta}{\partial t}+\frac{\partial\left(d \cdot v_x\right)}{\partial x}+\frac{\partial\left(d \cdot v_y\right)}{\partial y}=0 \tag{7}$$

with the components of velocity v_x and v_y, of bottom friction $F_{bottom,x}$ and $F_{bottom,y}$ and of the shear stress $F_{eddy,x}$ and $F_{eddy,y}$ in x- and y-direction, the water density ρ_w, the gravity g, and the Coriolis parameter Ω. To keep the computational time in reasonable limits two-dimensional computations were carried out using the model MIKE 21 HD [4]. Within MIKE 21 the bottom friction is parameterised using the formulation of Manning (eqn (8)):

$$\begin{pmatrix} F_{bottom,x} \\ F_{bottom,y} \end{pmatrix}=\frac{g \cdot \sqrt{v_x^2+v_y^2}}{M^2 \cdot d^{1/3}} \cdot \begin{pmatrix} v_x \\ v_y \end{pmatrix} \tag{8}$$

where M is the Manning number. The turbulent shear stress F_{eddy} is calculated after Smagorinsky analysed in [5]. Figure 3 shows a result of the numerical simulation for the same conditions (location, storm surge, width of the dike breach) presented in figure 2.

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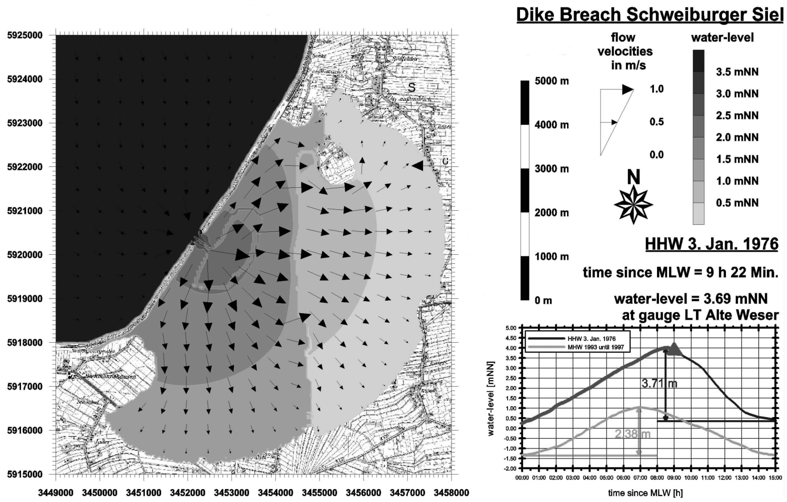

Figure 3: Determination of the inundation depth by numerical simulation,
nine hours after dike breach at the Jade estuary [6]

The comparison of the different approaches reveals significant differences. While the semi-dynamic and the numerical simulations lead to almost the same inundated area and inundation depth the static approach overestimates the area flooded. Especially dips surrounded by areas higher than the storm surge water level are indicated as flooded. Nevertheless there are also differences between the semi-dynamic and the numerical computations. These occur especially in strongly structured topographies [7] like in Bremerhaven as shown in figure 4. The results of both approaches are influenced by the bottom friction.

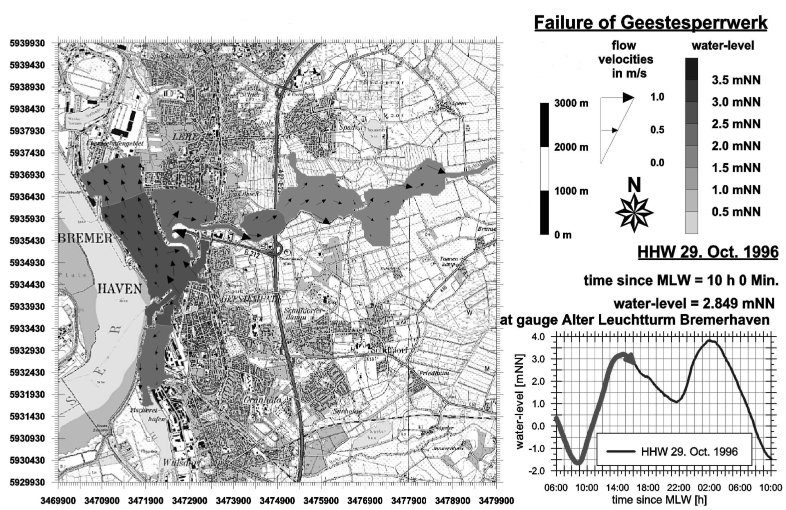

Figure 4: Flooding of a structured hinterland

3 Influence of bottom friction

A sensitivity study on the influence of the bottom friction on the inundation process was carried out for the dike breach at the Jade estuary, as shown in the figures 2 and 3, using the numerical approach. Within this study the Manning number was varied in the range of $M = 15.5m^{0.33}/s$ and $M = 26.0m^{0.33}/s$. According to DHI [8], proposing a Manning number of

$25m^{0.33}/s$ for estuaries, this is reasonable. However also Manning numbers of $100m^{0.33}/s$ can be found [9]. The results were analysed with respect to the area flooded (figure 5) and the water volume inundating (figure 6).

In figure 5 it can be seen that the maximum extend of the area flooded does not depend on the Manning number. For a width of a dike breach of 200m the maximum extend equals $60km^2$ in case of the storm surge in 1976, which has been the most severe so far. The duration of flooding depends on the Manning number. It varies from 10 hours for $M = 26.0m^{0.33}/s$ to 12 hours for $M = 15.5m^{0.33}/s$. In contrast to the area flooded figure 6 shows that the maximum water volume inundating is related to the Manning number. It varies from $0.034km^3$ for $M = 15.5m^{0.33}/s$ to $0.042km^3$ for $M = 26.0m^{0.33}/s$. Therefore the average inundation depth varies from 0.56m to 0.70m.

Within the risk analysis changes in the average inundation depth lead to changes in the estimated loss in case of inundation, because according to the CUR [2] the average damage factor φ corresponding to a Manning number $M = 15.5m^{0.33}/s$ equals 8% and corresponding to $M = 26.0m^{0.33}/s$ equals 14%.

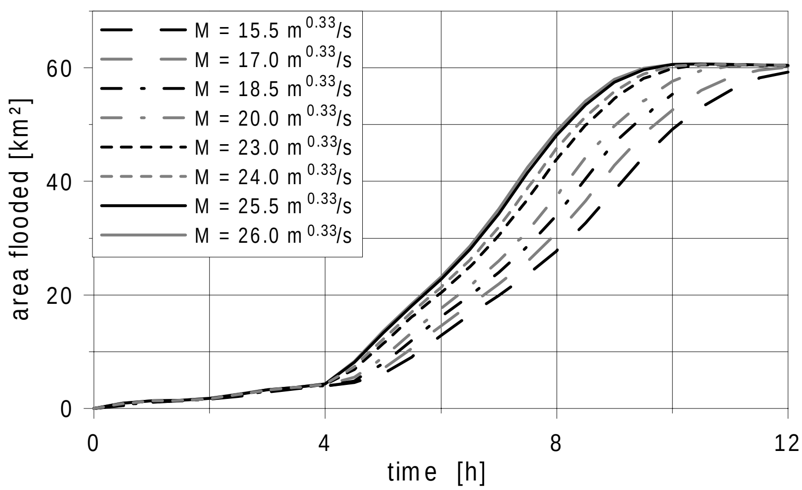

Figure 5: Influence of Manning number on the area flooded

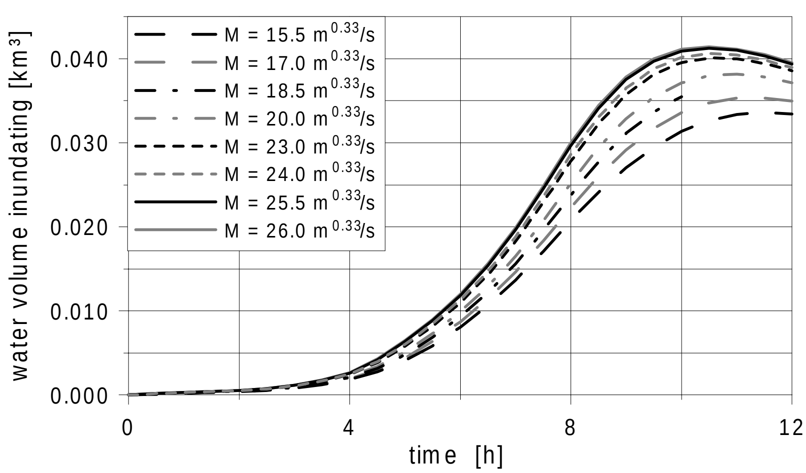

Figure 6: Influence of Manning number on the water volume inundating

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4 Conclusion

For the estimation of the area flooded in case of a failure of coastal defences, which is an important part of the risk analysis, three different methods are presented. While dynamic approaches lead to comparable results the traditional static approach overestimates the are flooded significantly. Future flood risk management should therefore use only dynamic approaches and overcome the traditional static method e.g. used in Germany in the moment. To improve the dynamic calculation of flood zones further calibration of the bottom friction is necessary, e.g. using information gathered during former flooding processes like the dike breach near the Oder river at the border between Germany and Poland.

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