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A probabilistic modelling concept for the quantification of flood risks and associated uncertainties

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Abstract: Flood disaster mitigation strategies should be based on a comprehensive assessment of the flood risk combined with a thorough investigation of the uncertainties associated with the risk assessment procedure. Within the 'German Research Network of Natural Disasters' (DFNK) the working group 'Flood Risk Analysis' investigated the flood process chain from precipitation, runoff generation and concentration in the catchment, flood routing in the river network, possible failure of flood protection measures, inundation to economic damage. The working group represented each of these processes by deterministic, spatially distributed models at different scales. While these models provide the necessary understanding of the flood process chain, they are not suitable for risk and uncertainty analyses due to their complex nature and high CPU-time demand. We have therefore developed a stochastic flood risk model consisting of simplified model components associated with the components of the process chain. We parameterised these model components based on the results of the complex deterministic models and used them for the risk and uncertainty analysis in a Monte Carlo framework. The Monte Carlo framework is hierarchically structured in two layers representing two different sources of uncertainty, aleatory uncertainty (due to natural and anthropogenic variability) and epistemic uncertainty (due to incomplete knowledge of the system). The model allows us to calculate probabilities of occurrence for events of different magnitudes along with the expected economic damage in a target area in the first layer of the Monte Carlo framework, i.e. to assess the economic risks, and to derive uncertainty bounds associated with these risks in the second layer. It could be shown that the uncertainty caused by epistemic sources significantly alters the results obtained with aleatory uncertainty alone. The model was applied to reaches of the river Rhine downstream of Cologne.

Keywords: flood risk assessment, uncertainty estimation, probabilistic model

1. INTRODUCTION

Flood defence systems are usually designed by specifying an exceedance probability and by demonstrating that the flood defence system prevents damage from events corresponding to this exceedance probability. This concept is limited by a number of assumptions and many researchers have called for more comprehensive design procedures (Plate, 1992; Bowles et al., 1996; Berga, 1998; Vrijling, 2001). The most complete approach is the risk-based design approach which balances benefits and costs of the design in an explicit manner (Stewart and Melchers, 1997). In the context of risk-based design, the flood risk consists of the flood hazard (i.e. extreme events and associated probability) and the consequences of flooding (i.e. property damages). Ideally, a flood risk analysis should take into account all relevant flooding scenarios, their associated probabilities and possible damages as well as a thorough investigation of the uncertainties associated with the risk analysis. Thus, a flood risk analysis should finally yield a risk curve, i.e. the full distribution function of the flood damages in the area under consideration, ideally accompanied by uncertainty bounds.

Following these concepts the working group 'Flood Risk Analysis' of the German Research Network on Natural disasters (DFNK) investigated the complete flood disaster chain from the triggering event to its consequences: 'hydrological load – flood routing – potential failure of flood protection structures – inundation – property damage'. Complementary to applied determistic models a simple stochastic model consisting of modules each representing one process of the flood disaster chain was developed. The advantages for flood risk assessment of the simple approach are mainly: First, significantly less CPU time is needed which allows application of the approach in Monte Carlo simulations. Second, the simpler model structure makes it easier for the analyst to understand the main controls of the systems.

The simple stochastic model represents two fundamentally different types of uncertainty, aleatory and epistemic uncertainty. Aleatory uncertainty refers to quantities that are inherently variable over time, space, or populations of individuals or objects. According to Hall (2003) it can be operationally defined as being a feature of populations of measurements that conform well to a probabilistic model. Epistemic uncertainty results from incomplete knowledge of the object of investigation and is related to our ability to understand, measure, and describe the system under study.

The simple stochastic model allows the risk and uncertainty analysis through a Monte-Carlo-framework. In line with the distinction of aleatory and epistemic uncertainties, the Monte-Carlo-framework was hierarchically structured, with each of the two layers representing one of the two types of uncertainties (two-dimensional or second-order Monte-Carlo–simulation, Cullen and Frey, 1999). The first layer represents aleatory uncertainty and assumes that the variability of the system is perfectly known and correctly quantified, e.g. by known parameter distributions. The result of this first layer of Monte Carlo simulation is a risk curve for the target area. The second layer of Monte Carlo simulations represents the uncertainty caused by our incomplete knowledge of the system. This distinction into the two uncertainty classes has important implication for the results of the risk assessment. The uncertainty bounds derived by this method cannot be interpreted as steady-state and may narrow down as more knowledge about the processes and parameters under of the model is obtained (Ferson and Ginzberg, 1996).

In this paper, the feasibility of this modelling approach combined with the hierarchical uncertainty analysis is illustrated for a reach of the river Rhine in Germany.

1.1 Investigation area

The investigation area of this study was the reach of the Rhine between Cologne and Rees with a focus on the polder at Mehrum. For this polder the actual risk assessment was performed. The polder at Mehrum is a confined rural area of 12.5 km², which is only inundated if the protecting levee system fails.

Two levee breach locations were exemplarily selected along the reach for the simulation. They differ significantly in their storing capacity. At Krefeld the large unbounded hinterland provides a retention basin with a practically infinite retention capacity whereas the polder at Mehrum is strictly confined to a comparatively small volume. The levees at the two breach locations are similar in structure, but at Mehrum the levee crest is higher, i.e. larger flood waves are required to overtop the levee at Mehrum as compared to Krefeld (Figure 1).

Through the selection of a longer reach of the main river along with the main tributaries the risk assessment implicitly considers the hydrological behaviour of a complete watershed. Additionally the selection of the two breach locations with their different hinterlands enables a risk assessment under consideration of possible levee breaches and their impact on flood wave propagation.

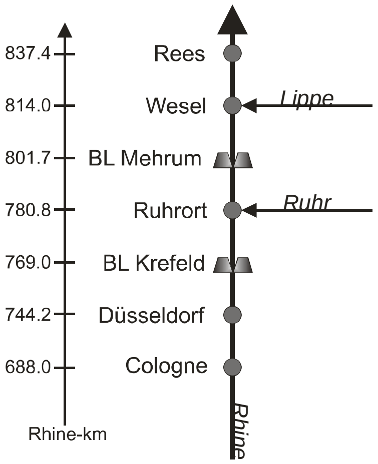

Figure 1: Sketch of the investigation area with the main tributaries Ruhr and Lippe and the selected breach locations (BL) Krefeld and Mehrum

2. MODULES

The risk analysis for the flood disaster chain is based on the following modules: Hydrological load, flood routing, levee failure and outflow through levee breach and finally the damage estimation. The following sections describe the modules briefly, followed by a description of the Monte-Carlo-framework in section 3. More details are given in Apel et al. (2004a) and Apel et al. (2004b).

2.1 Hydrological load

The hydrological load was derived from the flood frequency curve of the gauge Cologne/Rhine based on the annual maximum series from 1961 to 1995 (AMS 1961-1995). Four distribution functions were fitted to the AMS 1961-1995: Gumbel, Lognormal, Weibull and the Pearson-III distribution. The four distribution functions were weighted by a Maximum Likelihood method to construct a composite probability distribution function (Wood and Rodríguez-Iturbe, 1975). Figure 2 shows the four individual distributions along with the composite distribution.

In order to determine the occurrence of levee breaches and inundation levels of the polders it was necessary to generate flood hydrographs in addition to the maximum discharge. Hence typical flood hydrographs (Apel et al., 2004b) were generated for the gauge Cologne based on non-dimensional hydrographs in combination with cluster analysis.

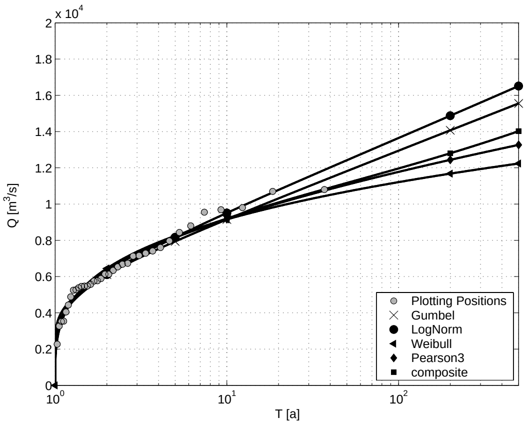

Figure 2: Different distribution functions fitted to the annual maximum flood series 1961-1995 of the gauge Cologne/Rhine.

The results of the cluster analysis are seven types of typical, realistic hydrographs: single peaked hydrographs and various multiple peaked hydrographs. A similar procedure was applied to the main tributaries Ruhr and Lippe, using the corresponding flood hydrographs for the chosen events to the main river.

2.2 Flood routing

The second module of the flood disaster chain is a routing module consisting of the Muskingum routing method for flood waves in river channels (Maidment, 1992). The required parameters were estimated for the defined river reaches from the 35 flood events of the years 1961-1995.

2.3 Levee failure

In this case study we defined two levee breach locations and derived probabilities of breaches for these two points. For the calculation of the point-failure probability of a levee, a general engineering technique was applied in which a breach condition is defined as the exceedance of a load factor over a resistance factor. This concept was applied to levee failures caused by overtopping of the levee crest which is the most common failure mechanism of modern zonated levees. The breach criterion was defined as the difference between the actual overflow q_a [m^3/s] (the load factor) and the critical overflow q_{crit} [m^3/s] (the resistance factor). For the calculation of q_a and q_{crit} the approaches of Kortenhaus & Oumeraci (2002) and Vrijling (2000) were used, respectively. These are based on overtopping height and overflowing time as independent variables and on the geometry of the levees. The only non-geometric parameter used in this formulae is the turf-quality parameter *fg* (Vrijling 2002), which is of subjective nature and hence was given particular attention in the uncertainty calculations (cf. section 3).

From this intermediate complex deterministic model a probabilistic model representing the conditional failure probability depending on overtopping height and time was derived analogously to USACE (1999). The outflow through a levee breach is calculated from an empirical outflow formula presented in Disse et al. (2004).

2.4 Damage estimation

The last module estimates direct monetary losses within the polder at Mehrum. Since the size and location of the inundated areas are not estimated directly by the simple model presented here, a damage function that relates the damage in the inundated areas of the polder at Mehrum to the inflow of water volume after/during a levee failure had to be determined. This was done by assuming the filling of the polder in 0.5 m steps up to the levee crest and intersecting each inundation layer with the land use map. The damage of the inundated land use types was estimated by combining assessed replacement values and stage-damage curves.

For all sectors, with the exception of private housing, unit economic values were determined from the economic statistics of North Rhine-Westphalia from 1997 (data of the gross stock of fixed assets according to the system of national accounts from 1958 and land use information from the statistical regional authorities in North Rhine-Westphalia). The replacement values were scaled to the year 2000 by data on the development of gross stock of fixed assets in North Rhine-Westphalia and adjusted to Mehrum by comparing the gross value added per employee in that region with that of entire North Rhine-Westphalia. Damages were determined using the step-damage-function of MURL (2000).

3. RISK AND UNCERTAINTY CALCULATIONS

For the risk and uncertainty analysis a hierarchical Monte Carlo framework was developed. In the first level of the analysis the Monte Carlo simulations represent the variability of the system, i.e. the aleatory uncertainty. This results in frequency distributions of floods at the outlet of the investigation area and risk curves for the target area, the polder at Mehrum. We randomised the following variables in the first level 10^5 times:

- the annual maximum discharge of the Rhine
- the correlation of the maximum discharge of the Rhine with the tributaries Ruhr and Lippe

The second level of Monte Carlo simulations represents the uncertainty associated with the results of the first level. In this level, uncertainty distributions of the flood frequency distributions and risk curves were calculated and used to construct the confidence bounds. The uncertainty sources covered in this analysis were the selection of the extreme value statistics functions and the parameter estimation of the stage-discharge relationship at the levee beach locations.

However, it was not possible to include all uncertainty sources as for some of them only insufficient information was available. These uncertainty sources include the width of a levee breach after a levee failure and the turf quality parameter involved in the calculation of the probability of failure. In these two cases statistics such as mean values, coefficients of variation and distribution types were not available. Because of this, the width of the breach and the turf quality parameter were not incorporated in the MC-framework but examined in scenario calculations. The values for the breach width in the scenarios were set to 100, 200, 300 and 400 meters according to expert knowledge of the local flood defence authorities and historical records. Additionally a zero breach scenario for the location Krefeld was calculated in order to assess the effect of upstream levee breaches on the risk in the investigation entirely. The turf quality scenarios were set according to the minimum, maximum and mean of the range of value given in Vrijling (2000). The scenarios apply to both levels of MC-simulations.

4. RESULTS

4.1 Risk analysis

Without any upstream breaches (K0), the levee at Mehrum failed up to 99 times (failure rate 0.99 ‰) in the Monte Carlo simulations. When breaches at Krefeld were allowed, this figure was significantly reduced to only one failure of the levee at Mehrum in the case of a breach width of 400 m at Krefeld irrespective of the value of the turf parameter *fg*. In addition to the breach width at Krefeld, the turf quality has an important effect on the number of breaches, if the breach width is in the range of 100-200 m: The lower is the turf quality, the higher is the number of breaches at both locations.

The flood frequency curve at Rees, the most downstream gauging station of the reach examined here, is also influenced by the number of upstream levee breaches and the breach width at Krefeld. Figure 3 shows the flood frequency curves at Rees derived from the output of the routing module for a fixed turf quality and varying breach widths at Krefeld. Overall, the exceedance probabilities of extreme events are reduced by upstream levee breaches while the exceedance probabilities of discharges at the critical levels are increased. This effect is caused by the reduction of the peak flows of a number of floods that overtop the levee to discharges below the critical overflowing discharge. The effect is more pronounced the wider the breach at Krefeld is assumed.

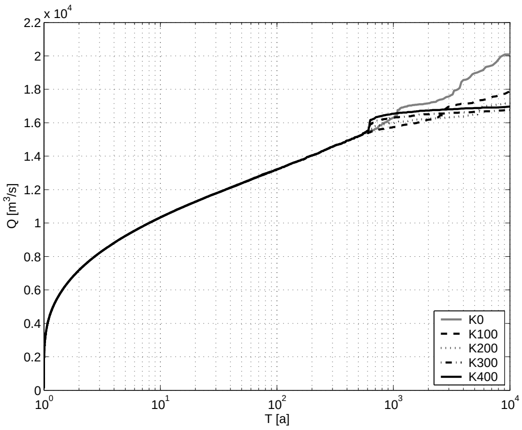

Figure 3: Frequency curves at the outlet of the investigation area (Rees at the Rhine): scenarios of different breach widths, *fg* = 1.05

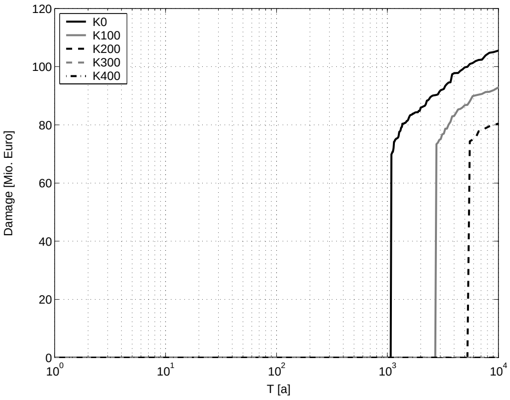

Figure 4: Risk curves for the polder Mehrum, scenarios with different breach widths; *fg* = 1.05

The risk curve for Mehrum was constructed from the calculated inflow volume of the polder for the different scenarios (Figure 4). The step-like trajectories of the risk curves are a result of the presence of the flood protection system as the damages only occur for discharges equal to or in excess of discharges causing levee failure. For breach widths at Krefeld larger than 300 m, the risk of damage at Mehrum is zero up to a return interval of 10^4 years which is a result of the high retention capacity of the upstream polder. This, again, emphasises the key role of upstream levee failures for the flood risk downstream.

4.2 Uncertainty analysis

The uncertainty analysis performed by the 2nd level of Monte Carlo simulations yielded confidence bounds for each scenario. As an example, the annual maximum discharge frequency curve at Rees for the breach scenarios with *fg* set to 1.05 are shown in Figure 5. It suggests that, for large events, the uncertainty decreases with the width of the breach at Krefeld. This is due to the large breach outflow combined with the almost infinite retention capacity of the polder at Krefeld. Most of the randomised discharges of the uncertainty distributions that produce a levee breach are reduced to the level of the levee base in the case of a 400 m breach, resulting in the upper confidence bound approaching the frequency curve at the level of the critical breach discharge.

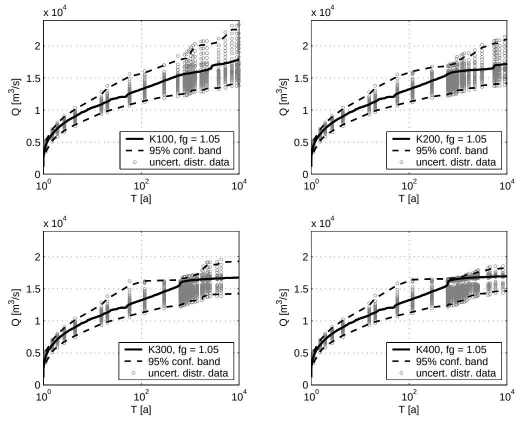

Figure 5: Uncertainty in the exceedance probability of annual maximum discharges at Rees caused by the distribution function type and the stage-discharge-relationship for the 4 breach scenarios. *fg* was set to 1.05.

The risk curves associated with the flood frequency curves in Figure 5 are shown in Figure 6. It shows that the uncertainty in damage is hardly reduced by the breach width which is in contrast to the results of the flood frequency curve. The uncertainty bounds (dashed lines in Figure 6) cover a wide range from zero damage to almost maximum damage above return intervals larger than about 200 years.

The presented results indicate that the uncertainty of the risk assessment is enormous. This is caused by two facts:

1. the large magnitude and duration of floods required to cause levee failures,
2. the comparatively large uncertainty in the extreme value statistics for the annual maximum discharges with return intervals > 200 years (cf. Figure 2).

The combination of these two facts results in uncertainty distributions that are almost binary. For floods associated with return intervals > 200 years either levee failures producing very high damages can occur, or if the levees happen to resist the flood, the polder is protected from any damage. The confidence intervals calculated from these uncertainty distributions are consequently enormous. For return intervals as high as 10^4 years it is possible that the levee resists the flood and protects the polder or it fails and causes disastrous damages. This enormous uncertainty is mainly attributed to the uncertainty in the annual maximum discharge.

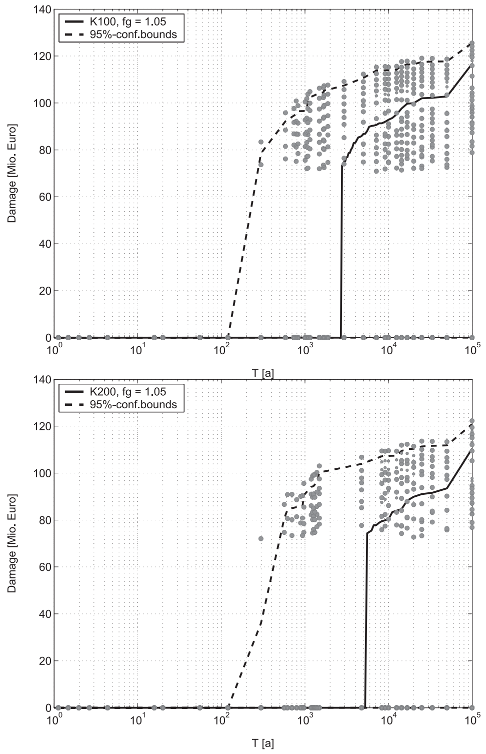

Figure 6: Exceedance probability of damage at the polder at Mehrum (solid lines) and associated uncertainty (dashed lines) caused by distribution function type and stage-discharge-relationship for the K100 and K200 breach scenarios. *fg* was set to 1.05. The points show the Monte Carlo realisations.

5 Discussion and Conclusion

The proposed model allows us to perform a quantitative flood risk analysis including the effect of levee failures along with the associated uncertainty. Because of the simple structure of the model proposed here, a large number of Monte Carlo-simulations can be performed in a reasonable time which cover a wide variety of flood events.

The approach is therefore very well suited to integrated flood risk assessment.

Risk assessment (aleatory uncertainty)

The results obtained here suggest that, in the study reach, upstream levee failures significantly affect the failure probability downstream and, hence the risk curve of the target area. The simulations also illustrate the effect of the retention volume of a polder. Because of the very large retention capacity of the hinterland at Krefeld, the levee failure probability at Mehrum is significantly reduced and the flood frequency curve at Rees is attenuated if levee failures at Krefeld are allowed. The size of the polder at Mehrum controls the shape of the flood risk curve. The step-like shape of the risk curve results from the small volume of the polder at Mehrum and the high magnitude of the events overtopping the levee. However, in case of upstream breach widths larger than 300 m at Krefeld the risk equals zero for return intervals up to 10^4 years. Taking the zero breach scenario at Krefeld as the worst case scenario for the target area, the results indicate that the flood protection structures at Mehrum are sufficient to resist floods up to return intervals of >1000 years, if the uncertainty of the results is neglected.

Uncertainty analysis (epistemic uncertainty)

Due to the large uncertainty caused by the epistemic uncertainty sources the statement that the flood protection structures at Mehrum are sufficient to protect the area from a 1000-year flood has to be corrected. From the uncertainty bounds of the zero breach scenario, being the worst case for the polder Mehrum, and the 100 and 200 m breach width scenarios shown in Figure 6 it can be concluded that the flood protection structures are likely to protect from floods with return intervals of less than 200 years. For larger floods, the uncertainty is mainly attributed to the extreme value statistics of the annual maximum discharge and yields that both complete failure and no failure may occur producing a range of possible damage from zero to maximum damage.

The results suggest that a more reliable extreme value statistics is crucially important for reducing the uncertainty of the risk assessment. A major prerequisite for that are longer time series of annual maximum discharges. The used series of 35 years is clearly too short to obtain reliable risk assessments of events with associated return intervals of more the 200 years. Also, the uncertainties associated with the breach module are considerably large. Better knowledge about the breach development and the distribution of the turf quality on natural levee systems would most likely reduce this unknown component of uncertainty in the risk assessment. The comparison of the results of the risk analysis with the results of the uncertainty analysis clearly emphasises the necessity of uncertainty analysis in flood risk asessment procedures.

Due to its modular structure and the universal nature of the methods used here, the proposed model system should be transferable to other river systems provided the required data sets are available. In addition, single parts of the model system may be applied independently, e.g. to investigate the probability of levee failure at a given location. It is therefore believed that the system may be profitably used for a number of additional purposes, e.g. as a tool for cost-benefit analysis of flood protection measures, and as a decision support system for operational flood control. Another possible application is the flood management and control during a severe flood for which estimates of the effects of upstream levee breaches on the shape and propagation of the flood wave and thus on inundation risks at the reaches downstream may be useful. Real time simulations of such scenarios could facilitate the emergency management and enhance the efficiency of planned levee failures or weir openings. However, a prerequisite for these applications is an accurate calibration of the model system to a given reach. Clearly, this needs to be done prior to a severe flood event. This implies that, ideally, the flood management system should be applicable to both long-term planning tasks and operational decision support.

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