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DEVELOPMENT OF AN INTEGRATED AND INTERDISCIPLINARY FLOOD RISK ASSESSMENT INSTRUMENT

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ABSTRACT: Modern flood control concepts are commonly based on interdisciplinary approaches, i.e. coupling of hydrologic and hydraulic analyses with socio-economic assessment and decision theory. Furthermore, a risk-based approach to flood management demands the consideration of extreme events with low probabilities and high impacts instead of assessments based on single return periods which were used in safety-oriented concepts before. A decision support system (DSS) is applied to evaluate the effectiveness of complex flood control systems subject to a probabilistic assessment of different hydrological loads and the resulting consequences. These hydrological loads encompass a broad range of scenarios with flood events of different peak return periods, hydrograph shapes and volumes. The hydrological loads serve as input for a hydrodynamic model. To evaluate the system, different alternative flood management schemes are investigated. Improved management of existing flood retention facilities has to be compared with structural measures to extent the flood control system. The hydrodynamic modelling is the prerequisite to estimate a set of inundation scenarios, which forms the basis of the socio-economic assessment, considering direct and indirect benefits and costs. The complexity of hydrological loads is considered by probabilities resulting from copula analyses. Thus multiple dimensions of flood risk can be considered. This enables the analyst and decision maker to gain additional insight and to make a more informed decision when considering different policy options and the respective overall risk at basin scale in a distributed manner. The DSS is based on an activity and object model of the planning and decision process. It provides tools for different interactive analyses and negotiation of decision criteria. If-then analyses can be used to reduce the set of measures and/or scenarios according to the preferences of the users, e.g. local focus points, administrative units or seasonal flood events. For multi-criteria analysis the Analytic Network Process is implemented. With these tools the system can contribute to the solution of conflicts between different groups of interest such as upstream/downstream or rural/urban stakeholders.

Key Words: flood control, vulnerability, uncertainty, risk, DSS

1. INTRODUCTION

In recent years Europe was affected by a large number of floods. The EU flood directive has been implemented in 2007 to support a thorough assessment and management of flood risk. Other entities and organizations also have implemented programs to foster activities to adequately cope with flood risk. As an example, integrated flood management is promoted by the Associated Program on Flood Management (APFM, 2004).

The objective of this study is to develop a methodology to evaluate flood control of complex systems. Hereby options of usage, improvement and extension of the system have to be investigated and assessed to be able to optimize the flood control system. In order to achieve this, both local and regional flood protection goals need to be considered. Often several administrative offices are responsible for the water management of different regions of the flood control system and this matter is further complicated by involvement of various stakeholders.

2. METHODOLOGY

A decision support system is being developed to support the planning process and to ease decision making for the participating parties. The complex information load is aggregated and prepared for those who are responsible for making final decisions. The DSS provides tools for the negotiation of attainable risk reduction on different spatial and administrative levels. The users can filter the possible alternatives to a reasonable number of acceptable solutions.

2.1 Framework for integrated flood risk assessment

The components integrating inundation data and probability analysis in the flood risk assessment instrument developed here are summarized in Figure 1.

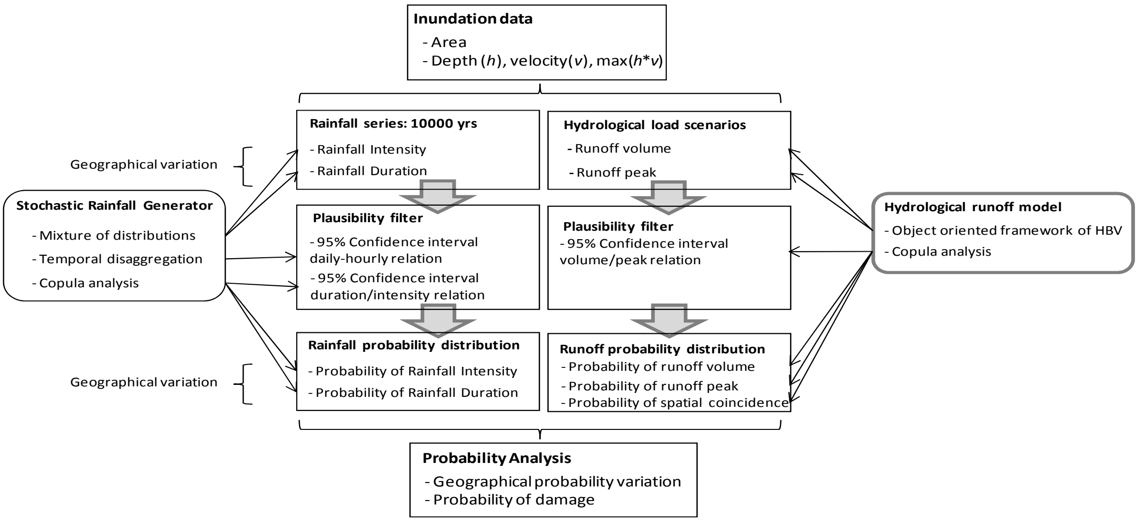

Figure 1: Components of the integrated flood risk assessment instrument

To account for the geographical pattern of rainfall intensity and duration, a rainfall generator was built into the interdisciplinary flood risk assessment instrument and linked to a rainfall-runoff model. Using a mixture of distributions, the rainfall generator was set up to generate daily precipitation for a long time series. For detailed flood risk investigations a disaggregation of the generated data into finer time scales is necessary. Due to the uncertainty related to discharge computation when using different time steps using a hydrological model, implausible combinations of daily and hourly occurrences are filtered by a 95% confidence interval.

To analyse the complexity of flood generation within the river basin the peak and volume of the flood events are analyzed for different geographic locations using copula analysis (Nelsen, 2006; Pahlow et al., 2008). Also the coincidences between the flood events of different tributaries were described by copula analyses. Particularly in large river basins return periods may show a large geographical variation that is not represented in the "classical" flood return period, which most of the time is based on a limited number of discharge measurements at a limited number of locations. Joint probabilities resulting from copulas describe the multiple dimensions of floods in a river basin in a better way than statistics of annual maximum discharge values at single gauges. Stochastic-deterministic data generation is the prerequisite for such analyses. To become more specific: it is impossible to describe the efficiency of a flood retention reservoir just by the peak of the inflowing wave. Its shape or volume is needed as well. In a river basin the interaction of tributaries has to be considered. Downstream of confluences the flood risk results from coincidences of floods in the tributaries. The resulting bivariate distribution can be characterized also by copula analysis. With these tools it becomes feasible to determine a comprehensive data base for the DSS.

2.2 Decision support system

Flood management problems are inherently complex. DSS may aid in managing and reducing this complexity by combining value judgements and technical information in a structured multi-criteria decision framework.

2.2.1 Providing access to the information

Two structural analysis models have been formulated in the notation of the Unified Modelling Language (UML). The first model describes planning and decision making processes using activity models, whereas the second one uses class diagrams for structuring the geospatial information related to these processes. The different hydro-meteorological scenarios are modelled as driving forces, whereas inundation is modelled as a pressure, which causes damage as an impact on society. The different flood management schemes are modelled as alternative responses to the respective cause-effect chains.

The DSS was designed as an internet application. Logging in to the DSS, the user is required either to open an existing decision-path or to start a new one (see Figure 2). A new decision path offers the user three main entry points, depending on his focus: a system-, geographically- or probability-oriented request. System oriented requests will guide the decision maker towards answers to the question "what is the effectiveness of a certain flood management scheme?" Geographically-oriented users are more interested in questions such as "what management scheme is the best for this region?" and probability-oriented decision makers want to analyse a specific return period for differing management schemes and locations. The user's selection is displayed both in graphic and in tabular form and, given an aggregation parameter, can be summarized. This transparent application assures the decision maker full access to the data so he can acquaint himself with the study area and the different types of data before proceeding to the actual decision making. Participatory learning based decision procedures should reduce complexity in the negotiation. The DSS separates planning and negotiation, thus simulation models are not included in the DSS. Instead alternative strategies were composed from the combination of hydro-meteorological scenarios and management schemes. These build up a decision space.

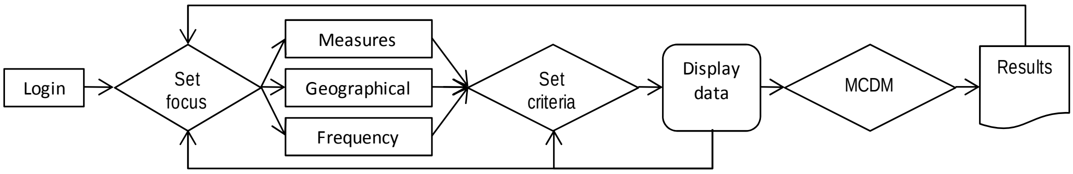

Figure 2: Decision Path of the DSS

2.2.2 Integrating probabilities

A wide range of information can be offered to the decision maker. Since the major problem for the decision maker remains one of information overload (Haimes 1998), the question remains how to incorporate manifold probabilities into an integrated DSS. In this study two strategies were used to cope with the probabilistic data load: the ensemble approach, where relevant data are depicted and analysed not as single data points, but as a set of probable occurrences, and secondly the artificial intelligence approach, where the DSS chooses only the relevant probabilities, based on the river network structure to calculate risks.

In flood protection planning and decision-making, the classical approach is to use design floods where the probability of the hourly measured peaks defines the return period. This approach, because of it's widespread acceptance and familiarity, is still used throughout this study as the primary classification of probabilities. A set of flood events varying from a return period of 25 to 1000 years (with regard to the flood peak) was used. However, differing rainfall patterns give rise to differing design floods and therefore to differing damage estimates. To reflect this meteohydrological variance, for each return period the damages for 5 design floods with different shapes and volumes were calculated. This results in a large variance of damages for every classical return period, as experienced in the field (Apel et al, 2004).

Structural alterations to the natural water systems (like reservoirs) have a large influence on the variation of the discharge peak/volume relationship. Both the recurrence of a high discharge peak and the recurrence of a large volume can cause flooding even if reservoirs are available. Copula analysis on daily values provides the bivariate relationship between the probabilities of both flood-inducing factors. Based on this analysis, a second probability classification was made which allows a categorisation of more and less likely events within a classical return period by their bivariate probabilities specified with copulas.

Each tributary, with differing retention structures and properties, has their specific relationship between peak and volume. Where data is available, the DSS selects the individual classical probabilities and copula generated probabilities for each geographical area under consideration. At the confluence, the combined probabilities of both tributaries can be used. Here the coincidence of flood waves from tributaries defines more or less critical events. It can be considered also by probabilities, based on copulas.

2.2.3 Multi-criteria decision analysis

In a participatory negotiation process, technical flood reducing solutions were grouped together to form a manageable amount of management schemes and criteria (e.g. flooded area, number of affected people, psychological effects or ecological effects) on which the decision maker would like to base his decision. Some of these criteria tend to be intangible, non-linear and subjective. . The Analytic Hierarchy Process (AHP) and its generalisation, the Analytic Network Process (ANP) are formal multi-criteria decision analysis techniques that allow for the incorporation of strongly differing types of criteria in relative scales. They have shown to be highly effective for improving flood hazard assessment (Levy, 2005).

The ANP uses the same theoretical background as the AHP, but generalizes the basic hierarchic structure into a network, which allows for interdependence and feedback among the decision criteria. The ANP is capable of working with intangible, subjective criteria. In Saaty´s (1977) work, he describes his fundamental scale in order to express the relationship between two elements. The decision maker defines the relationship in terms of “equal importance”, “moderate importance”, “strong importance”, “very strong importance” and “very, very strong importance”. Intensities of 1, 3, 5, 7, and 9 are attributed to these relationships. What happens if a decision maker is unsure of those comparisons, or, if the inherent imprecision of an estimate like the economic damage of a flood (Ahmad and Simonovic, 2001) cannot be indisputably classified in Saaty´s fundamental scale? Here, a fuzzy extension of the ANP might provide a solution (van Laarhoven and Pedrycz, 1983). Using fuzzyANP, we are able to retain the inherent impreciseness throughout the prioritisation.

3. APPLICATION OF THE METHODOLOGY

The methodology is applied to the Unstrut river catchment (6343 km^2) in Mid-East Germany. The study area is drained by two major river systems: one in the North (the river Helme) and one in the South (the river Unstrut). The flood control system consists of two flood detention basins, reservoir Kelbra in the North and reservoir Straussfurt in the central part of the catchment. Furthermore, a polder system and a flood channel have been implemented as flood protection measures.

For every return period (25, 50, 50, 100, 200, 500 and 1000 years), five distinct rainfall patterns were chosen out of the generated set. A Copula-analysis showed that the return period of the flood peak alone does not allow for a reliable estimate of the flooded areas and therefore of the possible damage. Depending on the generated type of discharge volumes and discharge peaks, although unlikely, it is throughout possible that a flood event with a peak recurrence interval of 200 years will result in a smaller flooded area than a 100 year flood (see Figure 3a and Figure 3b).

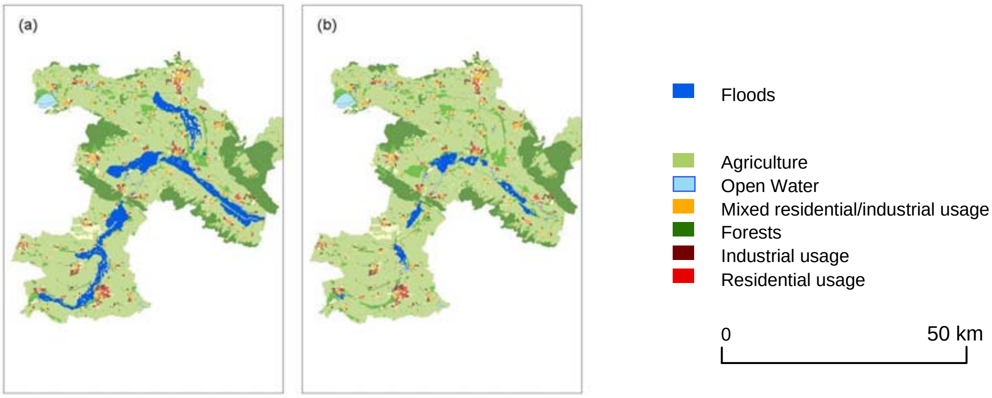

Figure 3: Inundation areas for different peak return periods (100-year flood (a), 200-year flood (b))

The corresponding discharge hydrographs for the inundation areas are shown in Figure 4. For a return period of 100 years the hydrographs at both Straussfurt and Kelbra have multiple peaks, large volume and long duration (Figure 4a) when compared to the flood peaks for the 200 year flood (Figure 4b).

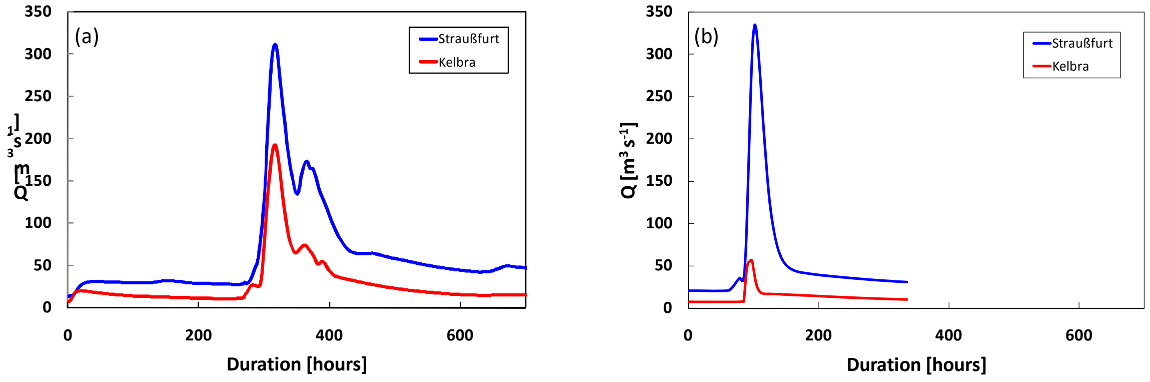

Figure 4: Corresponding discharge hydrographs for the inundation areas shown in Figure 3

3.1.1 Monetary Assessment

Hydrologic and hydraulic models generate flood area, water depth, flood duration and flow velocity. The latter three were combined by a multi-criteria damage function into direct economic damages for the area specific land uses in the floodplain. The accuracy of the damage function was tested against actual damages that occurred during the 2002 flood in Germany that were determined by Müller and Thieken (2006) (see Figure 5). The damage function used here compares well with actual damage data. However, the spread in damages displayed by the polls might also be of importance in the decision process. Further more, the computation of absolute damages is affected by uncertainty of potential damage estimation in the study area. Therefore we fuzzyfied the modelled damage data using the density function of the actual measured damages from the cited study.

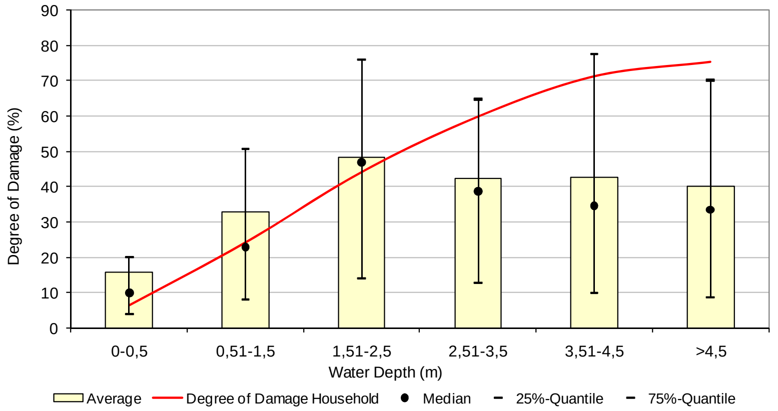

Figure 5: Damage-depth relationship used in this study (red line). Also shown are the data from Müller and Thieken (2006)

3.1.2 Multiple Criteria Decision Making

The ANP-scheme displays the criteria and its interdependencies used in the decision making algorithm (see Figure 6).

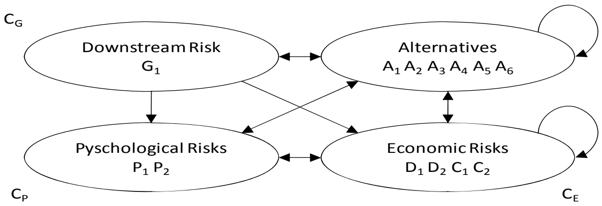

Figure 6: ANP Scheme used in this Study

By participation of the local authorities the wide range of possible flood reducing technical solutions was summarized into six different system states, e.g. alternatives. In short alternative 1 (A1) consists of the current situation “As Is”; Alternative 2 (A2) is an optimised management of the existing flood retention structures; A3 is similar to A2 including the construction of 4 Polders (Riethgen, Sömmerda, Schlüsselwiesen and Waltersdorf); A4 is similar to A2 including the construction of 4 Polders (Riethgen, Scherndorf, Wundersleben and Waltersdorf) that buffer water at a 10-year flood; A5 includes the same flood retention measures as A4, but constructed to react at 5-year flood; A6 is similar to A4, but the width of the inlet structures is doubled. The choice between these interdependent alternatives is based on three criteria groups: economic C_E, psychological C_P and downstream effects C_G.

The economical damages were separated into two parts: direct economic damages D_1, calculated using the multi-criteria damage functions and indirect economic damages D_2, estimated and described for each considered occurrence and each alternative. The costs were separated into recurring/yearly costs C_1 and construction and implementation costs C_2. Of course, both damage and costs factors are interdependent. Local social/psychological impacts of flooding were also separated in the number of affected people P_1 and the psychological damage P_2 of each occurrence. Impacts of the flood retention alternatives will most definitely have their effects further downstream from our study area. To differentiate between alternatives, we calculated the direct damages of a simulated 100-year flood 50 km downstream of the polder area at the town Wangen. Comparing these results with the effects of the other HQ´s and rainfall patterns, allows for a general estimate of the downstream effects in relation to the gauge in Wangen (G_1).

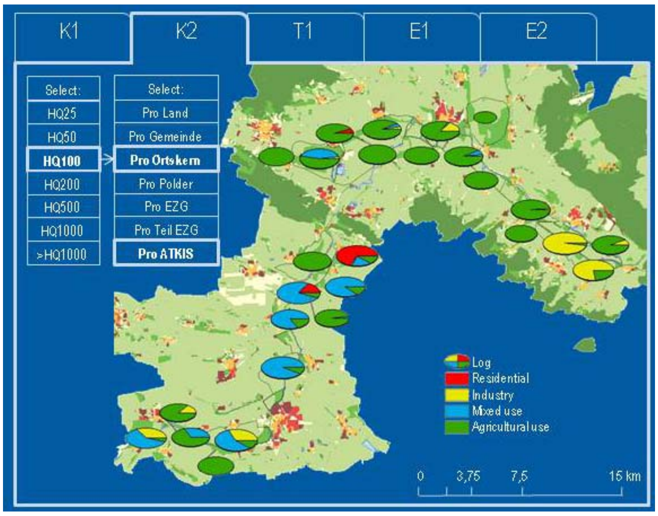

Figure 7: Distribution of Damages within the Catchment, as Displayed in the DSS

All seven criteria are made available to the decision maker in the DSS for all 6 return periods for 5 distinctive rainfalls patterns (equals 30 alternatives) and one return period greater than 1000 years for all 6 alternatives, resulting in 186 hydraulic calculations. The decision maker requires the MCDA to combine those data in order to arrive at a motivated choice between the 6 alternatives. Therefore, instead of working with flood peak return period and rainfall pattern, a combined (imprecise) probability factor is used, converting the damage criteria cited above to risk criteria.

The DSS allows the user to interactively browse the multitude of data and results generated in this study by selecting different implementation measures, geographical areas, return periods and displaying the results according to criteria like affected area, water level, damage or risk. Figure 7 shows an example for the distribution of damage for the regions upstream and downstream of the confluence of the river Helme and river Unstrut Since it is clear that the return period of the flood peak alone is inadequate as a basis for decision making (see Figure 3), these probabilities are handled as “imprecise values” characterised by the results of the Copula- analyses mentioned before. Within the DSS the different hydrological scenarios are weighted accordingly to the location of interest and their multivariate probabilities as described in paragraph 2.2.2. In this way the complex relationships between rainfall intensity & duration; run off volumes & peaks and impact/damage frequencies typical for the study area can be considered.

After valuating the MCDM criteria, the DSS prioritises the different management schemes, aiding the decision maker in his choice.

4. SUMMARY

The tools that form the basis for integrated flood risk assessment were introduced. An important aspect of the methodology is the incorporation of manifold probabilities by means of copula analysis. In this way it is possible to account for geographic variation that is not represented by the classical flood peak return period alone. Not only does the DSS allow for a probability-oriented analysis by the decision maker, but also for an analysis of sites of interest or system states.

5. ACKNOWLEDGEMENTS

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