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ASSESSMENT AND OPTIMIZATION OF FLOOD CONTROL SYSTEMS: THE UNSTRUT RIVER CASE STUDY

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ABSTRACT: The disastrous floods in Europe in 2002 and several other extreme floods worldwide during recent years call for integrated assessment and optimization methodologies of existing flood control structures to reduce the vulnerability of societies to flooding. Hydrological and hydraulic modelling form the basis of the approach introduced here to thoroughly assess flood control systems. A detailed evaluation protocol is followed, whereby different system states, combined with different hydrological scenarios and a set of operational and structural measures make it feasible to include uncertainty. Since measurements are generally available for a rather short time period only and in order to provide a broad range of hydrological loads for system assessment and optimization, a stochastic rainfall generator has been developed. Long time series of precipitation are in turn used as input for a hydrological model. Hydrologic loads with a broad range of recurrence intervals, hydrograph shapes and volumes serve as input for the combined 1-D/2-D hydraulic model, which allows for accurate determination of inundation areas, flow velocity, stage and flood duration. Six system states, the current state, a flood control system with improved structural components and four extended flood control systems are investigated. The evaluation is further supplemented by socio-economic analysis and integrated in a GIS-based decision support tool. This methodology allows for detailed evaluation of flood control systems for an extensive range of hydrological loads. As a result, structural system adjustments are shown for the Unstrut watershed in Mid-East Germany (6343 km^2). However, due to their flexible structure the approach and the tools developed here can readily be applied to assess other flood control systems.

Key Words: flood damage, vulnerability, rainfall generation, hydrologic/hydraulic model, GIS

1. INTRODUCTION

The assessment and optimization of flood control systems requires detailed knowledge about the hydro-meteorological regime of the catchment under investigation. Furthermore, possible future flood scenarios need to be considered to reduce flood risk and to provide a sound knowledge base for decision makers. To support this, Collier and Fox (2003) proposed a methodology for recognizing extreme rainfall and flood events based upon a conceptual model of causal meteorological conditions and upon a question and answer assessment procedure. Extreme floods are also often estimated using a stochastic weather generator in combination with a rainfall-runoff model (e.g. Leander et al., 2005). In various studies the hydrological model is further combined with a hydraulic model to determine the inundation areas caused by flooding (e.g. Anselmo et al., 1996). Knowledge about the extent of the inundated area allows for an assessment of damage. Förster et al. (2005) investigated the effect of retention areas on damage caused by flooding for two different scenarios, whereby the controlled flooding of polders and floodplain areas has been simulated and assessed with cost-benefit analysis. In the approach introduced here the three different levels of risk management put forth by Plate (2002) are supported: the operational level, the project planning level and the project design level. To consider the important spatial aspect in the approach for flood control system assessment introduced here, a stochastic rainfall generator has been adopted to provide long time series of precipitation, whereby great care has been taken to account for spatial correlation and to allow for extrapolation. First the stochastic rainfall generator is introduced. Next the stochastically generated rainfall time series are used as input for a hydrological model, which is coupled with a reservoir and dam model. Selected hydrological time series, combined with several states of the flood control system are further processed with a hydraulic model to determine and evaluate the inundation areas. Lastly, results from the socio-economic analysis are shown.

2. METHOD

Figure 1 shows the elements of the assessment methodology and their dependencies.

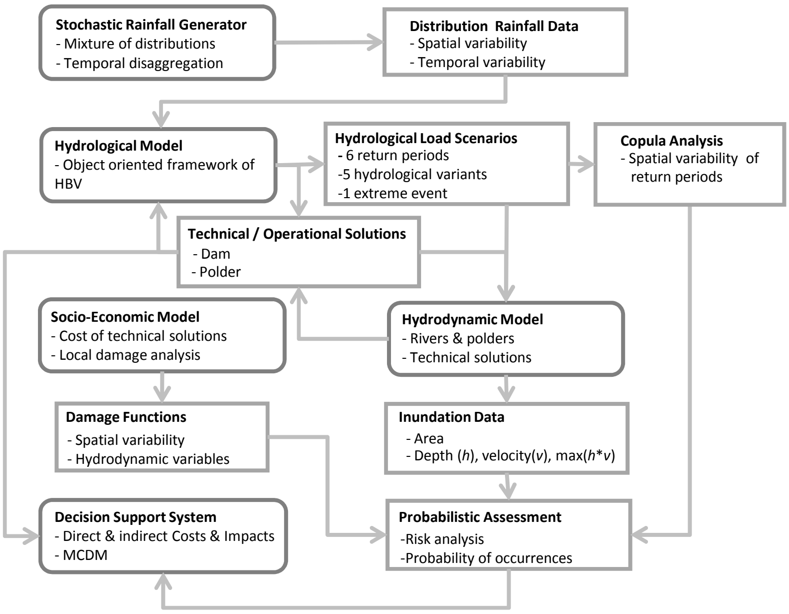

Figure 1: Flowchart of the main Elements of the Assessment Method and their Dependencies

Since measurements are available for a rather short time period only that do not allow for the required broad range of hydrological loads for system assessment and optimization, a rainfall generator is needed. Long time series of precipitation are in turn used as input for a hydrological model that includes a dam and reservoir module for controlled and uncontrolled operation of reservoirs. Hydrological loads for a wide range of recurrence intervals, hydrograph shapes and volumes serve as input for a hydrodynamic model, which allows for accurate determination of inundation areas, flow velocity, stage and flood duration. Since computer resources are generally expected to be limited, i.e. no supercomputing time is allotted for the assessment, a certain number of pre-defined system states is investigated (e.g. the current state, improvements of the current state and extended flood control systems). The evaluation, following an evaluation protocol, is based on socio-economic analysis and a GIS-based probabilistic decision support instrument.

2.1 Stochastic rainfall generator

The basic requirements of the weather generators used for the purpose of assessing flood control systems are that they must be able to reproduce the statistical properties of the historical rainfall series at each site and the spatial covariance structure between sites. Although a single type of distribution has frequently been implemented to model the amount of daily precipitation with seasonally varying parameters, it can sometimes be inadequate to capture some of the statistical properties of the daily rainfall that have relevance for the purpose the model is sought for. Here a stochastic model for the generation of daily time series of rainfall at multiple locations is employed, in which the amount of daily rainfall is modelled by a mixture of two different probability distribution functions (Hundecha et al., 2008). Figure 2 shows the model structure of this stochastic rainfall generator.

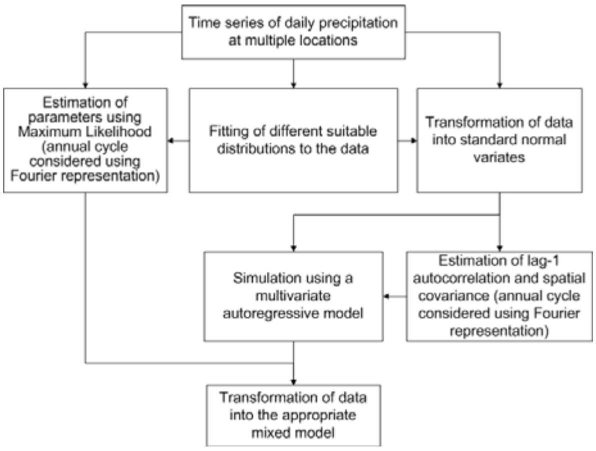

Figure 2: Flowchart Describing the Steps Involved in the Stochastic Generation of Rainfall in this Study

A two stage modelling procedure is implemented. In the first stage, a multivariate autoregressive model is used to model the local probability of occurrence of rainfall and the amount, while keeping the inter-site covariance structure using a truncated and power transformed normal distribution. In the second stage, the amount simulated using the power transformed normal distribution is further transformed so that it can be regarded as coming from a mixture of Gamma and Pareto or Gumbel distribution. Time periods within the time series of daily precipitation that are selected for hydrologic load generation are disaggregated into hourly time steps by means of two multivariate models that have been proposed by Koutsoyiannis and Onof (2001) and Koutsoyiannis et al. (2003).

2.2 Hydrological model

An adapted semi-distributed hydrological model, based on an object-oriented framework and following the concept of HBV-96 (Lindström et al., 1997) is coupled with a dam and reservoir module for controlled and uncontrolled reservoir operation to generate runoff scenarios from the precipitation time series.

2.3 Hydraulic model

A state of the art coupled 1D-2D hydraulic model has been developed (Kamrath et al., 2006). The 1D model is based on the St.-Venant-equations, whereas the 2D model has been implemented using an “initially dry land” approach that embodies storage cells. The model is simplified as ODE system, leading to a stiff system of equations. An implicit integration scheme is used to further improve computational efficiency. The coupling of 1D-1D / 1D-2D is bidirectional. Figure 3 shows an illustration of the representation of the model domain.

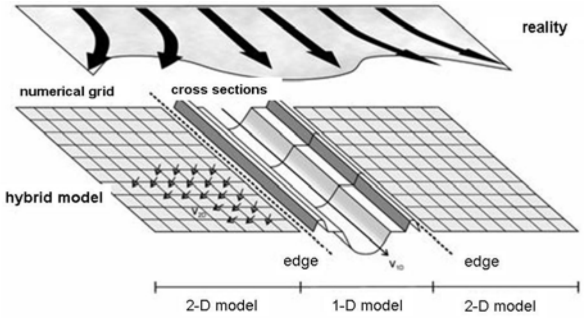

Figure 3: Representation of the Model Domain in the Hydraulic Model

The following parameters are computed and thereafter used for further analysis and assessment of the flood control system: (i) inundation area, (ii) maximum water level, (iii) maximum flow velocity, (iv) maximum product of water level and flow velocity, (v) total duration of the flood event and (vi) duration of exceedance of threshold water levels.

2.4 Socio-economic analysis

The classical approach for this type of cost-effect analysis is to estimate the costs of the planned measures, including the direct costs of flooding agriculturally used polders and to compare these costs to the possible reduction in damages as a result of uncontrolled flooding. We typecast and quantified the local socio-economic values in order to make a monetary and geographical estimate of the site-specific damage potential. Since pecuniary damage varies with flooding-specific parameters, the absolute or relative degree of damage is estimated using value and land-use type specific damage functions.

2.5 Evaluation protocol

In order to evaluate and compare different flood control systems states, each component of risk should be analysed for each particular measure. Adverse effects are estimated as the combination of intensity and vulnerability. Neither probability nor intensity or vulnerability is geographically homogeneous distributed. Therefore a geographical differentiation scheme has been implemented.

Based on intensity and probability estimates of the rainfall generator data, a representative set of river basin typical instances is selected, characterized by different hydrological scenarios and return periods. For each system state (i.e. combination of different measures), these instances are processed by the hydraulic model for grid cells (see Figure 3), providing the variables used for further assessment. Since a coarse resolution of the hydraulic model has been chosen for computational efficiency reasons, unwanted effects of the hydraulic load, e.g. on the boundaries of the flood area, have been eliminated through flood volume redistribution using a high resolution digital terrain model, thus technically enhancing the resolution to a resolution level comparable to the economic data.

The probabilities for the selected set of instances may vary geographically, as could be expected for mesoscale river basins. Therefore, different sets of probabilities, in this approach supplemented by copula analysis, need to be used, depending on the geographical location of possible damages.

Next the ascertainment procedure of vulnerability analysis is carried out. Socio-economic analysis provides local community-specific pecuniary values, distributed over capital assets (e.g. residential capital, household assets and invested capital), infrastructure and agriculture. This analysis is linked to the national German topographical and cartographical information system (ATKIS) to provide an area-specific vulnerability assessment. Vulnerability in this case is defined here as a combination of exposure (geographical location) and potential damage. Pecuniary damages are then calculated for each single land use type in each grid cell, based on the value-specific damage functions in relation to the hydraulic parameters and site-specific socio-economic conditions, thus resulting in the factor “severity of adverse effects”.

Subtracting the possible damage for a certain system state from the possible damage for the current state yields the possible reduction in damage as a direct consequence of the flood control system. This can be done for each of the scenarios of different pre-defined return periods. The reduction in damage can be analyzed for the entire river basin, or for individual geographic areas.

This vast amount of geographical and probabilistic data is summarized and represented in a DSS, where manipulation and combination of different datasets and the subsequent damage analysis is automated using GIS.

3. APPLICATION

The River Unstrut catchment with an area of 6343 km^2 in Thuringia and Saxony-Anhalt, Germany, has been chosen as a test case for the assessment approach. The Unstrut catchment is highly prone to flooding and the region suffered from severe damage during both historical and recent flood events. The present flood retention system consists of two dams, a flood channel and four polders with a total retention volume of about 100 million cubic meters (Figure 4).

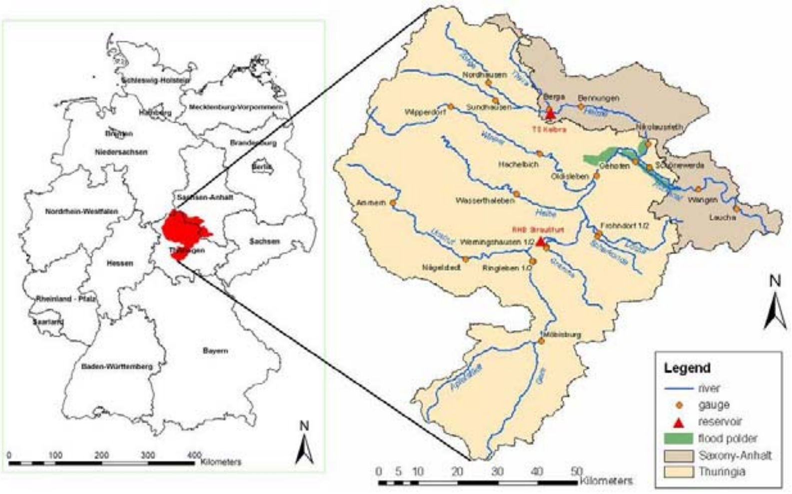

Figure 4: The River Unstrut Catchment in Thuringia and Saxony-Anhalt, Germany

The flood control system is operated according to flood response guidelines of the states Thuringia and Saxony-Anhalt. Three cases are to be distinguished: (i) flooding caused in the Helme subcatchment, i.e. the northern part; (ii) flooding caused in the Unstrut subcatchment, i.e. the southern, western and central part and (iii) flooding caused in both the Helme and Unstrut subcatchments.

Six different system states are being considered in this study: the current state, the improvement of the current system so that all technical features are fully functional and four different extensions of the current flood control system. Briefly, the following measures are implemented: (i) optimization of the inlet and outlet structures (no controlled operation), (ii) controlled operation of the inlet and outlet structures, (iii) subdivision of the existing polders into compartments and (iv) development of new polders. Optimized dam operation is not considered in this study, since a pre-evaluation has shown that the positive effect of the dams for flood control vanishes for return periods exceeding 50 years.

4. RESULTS

Ten precipitation time series of 1000 years have been generated. The most important statistical feature that needs to be reproduced in the context of this assessment study is the extremes of daily precipitation. No single distribution fitted to the daily precipitation series was able to reproduce the extreme statistics of the daily precipitation at most stations. Our rationale in using a mixture of two distributions to simulate the daily precipitation was based on circumventing this problem. Figure 5 shows a comparison of the distribution of the observed annual maximum daily precipitation for two selected stations and the entire catchment with the upper and lower bounds for 10 simulations of the distribution of the corresponding simulated annual maximum daily values.

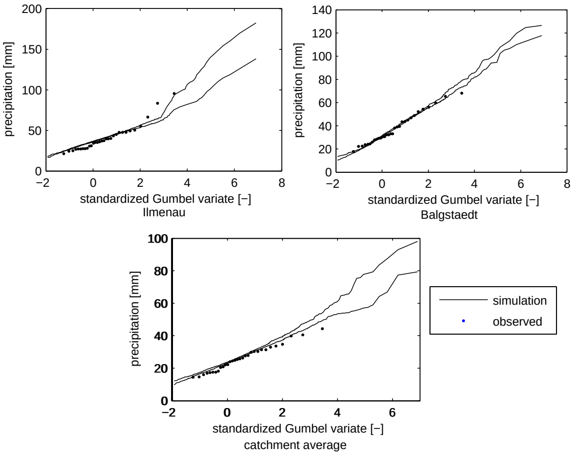

Figure 5: Comparison of the Distribution of the Observed Annual Maximum Daily Precipitation with the Upper and Lower Bounds of the Distribution of the Corresponding Simulated Annual Maximum Daily Values for two Stations (top row) and the Entire Catchment (bottom row).

Both the spatial structure and the seasonal variation of historic events have been preserved in the events that were selected from the entire time series for further evaluation, but obviously also events that have not been observed yet were included to guarantee a comprehensive assessment of the flood control system. Figure 6 shows an example comparison between simulated rainfall data and measurements for one of the most common spatial structures, where intense precipitation mainly in the South induces the flood event.

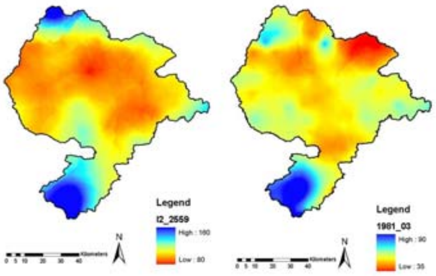

Figure 6: Example of the Spatial Distribution of Simulated (left) and Measured (right) Precipitation

From the analysis of historical data it was found that about 20% of the flood events occurred during the summer period and 80% occurred during the winter period. This has been taken into consideration for the selection of the events in the flood control system assessment.

A representative sample of the population of possible flood events is required to evaluate the flood control system. Here six different return periods are considered (25, 50, 100, 200, 500, 1000 years). The damage is not only related to the flood peak, since different hydrograph shapes (e.g. multi-peak floods or floods with long duration and large volume) will result in different damage levels. The selection of hydrological loads was therefore further supported by cluster analysis of historical events to determine typical hydrograph shapes and volumes. In total 5 different hydrological variants were selected for each return period, which encompass various spatial distributions of rainfall and the effect of snow. Furthermore, one event that has a return period of more than 1000 years is evaluated, which may be regarded as the probable maximum flood. All together 31 hydrological loads were selected from the entire time series. In Figure 7 the selected events for a return period of 200 years are shown as an example.

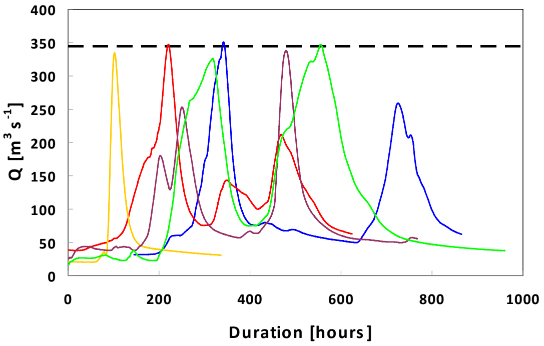

Figure 7: Discharge Scenarios Generated from Stochastic Precipitation Time Series Used for Evaluation of the Flood Control Measures (Return Period of 200 Years shown as Dashed Line)

The inundation parameters were computed with the hydraulic model for a total of 186 flood events (31 scenarios for six different return periods and the probable maximum flood), combined with socio-economic analysis and used for the assessment. Figure 8 shows an example for the spatially distributed evaluation of flood damage for one system state and a flood scenario with a return period of 100 years. The assessment is embedded in a DSS, which is described elsewhere (Pahlow et al., 2008).

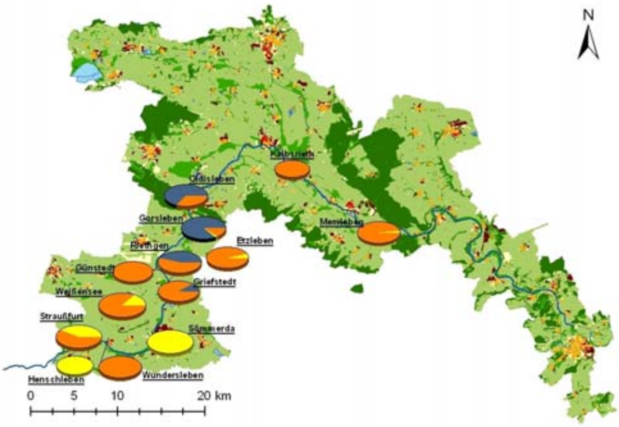

Figure 8: Spatial Distribution of Damage for one Selected Region for a Flood Scenario with a Return Period of 100 Years. The Pie Charts show the Spatial Distribution of Damage for Households (yellow), Industry (blue) and Mixed use (orange). The Pie Chart Size Represents the Damage Level

5. SUMMARY

A methodology that can be used for assessment and optimization of flood control systems has been developed. The main elements of this methodology comprise a stochastic rainfall generator, a hydraulic model that is coupled with a dam and reservoir module, a 1D-2D hydraulic model and socio-economic analysis, embedded in a GIS-based DSS. An example for evaluation of a flood control system in Mid-East Germany is shown. The methodology can be adopted to evaluate other flood control systems due to the flexible structure of the individual elements.

6. ACKNOWLEDGEMENTS

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