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GENERATION OF SEVERE FLOOD SCENARIOS BY STOCHASTIC RAINFALL IN COMBINATION WITH A RAINFALL RUNOFF MODEL

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ABSTRACT: Design events with a given return period and corresponding peak flows are commonly used for the evaluation of flood protection systems. However, for sustainable flood management a risk-based approach with consideration of all possible features of flood events, their spatial distribution and local characteristics, as well as their conditional probabilities is necessary. Historical data offers insufficient information about this complex issue because of short time series of records. For this reason a stochastic rainfall model generating daily values of precipitation at multiple locations, maintaining the spatial covariance structure, by a mixture of two different probability functions is proposed. To obtain rainfall and discharge at finer time scales, a multivariate spatial-temporal rainfall disaggregation model is applied to the generated daily values for selected events. A time series of 1000 years of rainfall is generated as input for a rainfall runoff model of the Wupper catchment in Mid-West Germany. The results verify good performance of the rainfall model in terms of reproducing observed and producing unobserved but physically possible precipitation data according to local temporal and spatial characteristics. The simulated hydrograph, based on daily as well as hourly precipitation data, shows the required broad range of flood scenarios with different characteristics of peaks, shapes and volumes as well as spatially differentiated occurrences of floods. This data pool allows for verification of the efficiency of the local reservoir system and adapted planning of flood management by using Bayesian networks.

Key Words: rainfall generation, multivariate statistics, flood management, rainfall runoff modeling, disaggregation

1. INTRODUCTION

Flood protection measures like dams and facilities of water resources management such as reservoirs are often evaluated by using design events. In general, their probability of occurrence and hence the applied level of protection is often defined by a single discharge peak. This selected threshold, e.g. a discharge peak with a return period of 100 or even 1000 years, is calculated by statistical methods with input of available annual flows of a few decades of data. This insufficient information and the missing investigation of the spatial flood development lead to uncertainty in the level of protection. Furthermore, recent planning is meant for risk-based flood management, which demands a sustainable consideration of different kinds of events (Begum et al., 2007). For a representative estimation of flood probability and evaluation of local protection measures it is therefore necessary to include a broad range of features of extreme events depending on the variety of peak flows and wave shapes, the spatial distribution of discharge and their corresponding conditional probabilities.

For this reason a technique for generating severe hydrological scenarios of differentiated occurrence is employed by coupling a stochastic rainfall model with a deterministic rainfall runoff model. The approach adopted here includes a newly developed model based on a concept proposed by Hundecha et al. (2008). Subsequently, the precipitation data is disaggregated by a multivariate model, proposed by Koutsoyiannis et al. (2003), to derive spatially consistent hourly rainfall series, which are required for detailed modeling of hydrological processes at finer time scale.

The paper is divided into three sections. The first section presents the methodology and implementation of the stochastic rainfall generator. In the second part the spatial-temporal disaggregation of the generated rainfall to finer time scale is shown. In the third part these models are applied to a mesoscale catchment in Germany to generate severe, unobserved rainfall and flood events to evaluate the local flood-control system that consists of several reservoirs. The study concludes with an evaluation of the efficiency of the local reservoir system according to the simulated events and proposals for further analysis of the generated scenarios.

2. THE STOCHASTIC RAINFALL MODEL

The requirements of weather generators used in terms of risk assessment during flood events are that they should be able to reproduce the statistical properties of the historical rainfall series at each site and their spatial covariance structure. Therefore a model based on a concept proposed by Hundecha et al. (2008) is applied. Here the amount of daily rainfall is modelled by a mixture of two different probability distribution functions, Gamma and Pareto.

[1] $$f\left(z,u\right)=a\left(u\right)\frac{\left(\frac{z}{\beta\left(u\right)}\right)^{\alpha\left(u\right)-1}\exp\left(\frac{-z}{\beta\left(u\right)}\right)}{\beta\left(u\right)\Gamma\left(\alpha\left(u\right)\right)}+\left[1-a\left(u\right)\right]k\left(u\right)\frac{z_m^{k\left(u\right)}\left(u\right)}{z^{k\left(u\right)+1}}$$

f(z,u) is the probability density function of the daily precipitation *z* at location *u*, *k(u)(…)* is the density function of the Pareto distribution corresponding to location *u* and *a(u)* is the mixing coefficient. Γ is the Gamma function and α and β are the shape and scale parameter, respectively.

Based on a two stage process, the local probability of occurrence of rainfall and the amount of a transformed precipitation are simultaneously calculated by a multivariate autoregressive model, using a normal process at each location and assuming no precipitation for negative values. Subsequently the simulated amount is further transformed so that it is described by the shown mixture of distribution functions. The annual cycles of the amount as well as the temporal and spatial correlations are incorporated using a Fourier representation. The objective of this approach is the reproduction of the extreme statistics of the daily precipitation as well as the annual cycle of the monthly mean precipitation and the monthly variability of precipitation at each station.

3. THE DISAGGREGATION MODEL

To simulate the hydrological processes in detail, the generated precipitation series have to be disaggregated while considering the temporal statistics and the spatial correlation between the stations. A methodology proposed by Koutsoyiannis et al. (2003) combines several univariate and multivariate rainfall models in a disaggregation framework called MuDRain. Hereby a simplified multivariate model, based on an AR(1) process,

[2] $X_S = a \cdot X_{S-1} + b \cdot V_S$

generates a synthetic hourly series of rainfall while a transformation model modifies these series in order to be consistent with the given daily values. $X_S := [X_S^1, X_S^2, \ldots, X_S^n]^T$ represents the hourly rainfall at time (hour) s at n locations, a and b are (n × n) matrices of parameters and V_S ($s = \ldots, 0, 1, 2, \ldots$) is an independent identically distributed sequence of size n vectors of innovation random variables. However, to get spatial-temporal consistent rainfall series at several locations by using this method, at least one or more stations with hourly information are required. Therefore a univariate rainfall model, proposed by Koutsoyiannis and Onof (2001) and implemented in the computer software Hyetos, is applied to selected stations. It is based on a Bartlett-Lewis process (incorporating a Poisson cluster process), which generates a synthetic rainfall series in combination with a proportional adjusting procedure:

[3] $X_S = X_S{}' \left(Z / \sum_{j=1}^{k} X_j{}' \right)$

Here the initially generated values X_S' are modified to get the adjusted values X_S, where Z is the lower-resolution variable (i.e. daily) and k is the number of higher-resolution variables (i.e. hourly) within the lower-resolution period (with $s = 1, \ldots, k$). This procedure modifies the generated values in order to be consistent with the given daily values, without changing the stochastic structure implied by the rainfall model. Hence the required time series at finer time scale are obtained independently.

Daily rainfall data at 28 locations were generated for the case study in section 4. At three stations with historical daily and hourly data, the generated daily time series were temporally disaggregated using Hyetos. During the next stage these stations act as reference stations for the spatial-temporal disaggregation of daily time series at all other stations within the catchment using MuDRain. The procedure is outlined in Fig. 1.

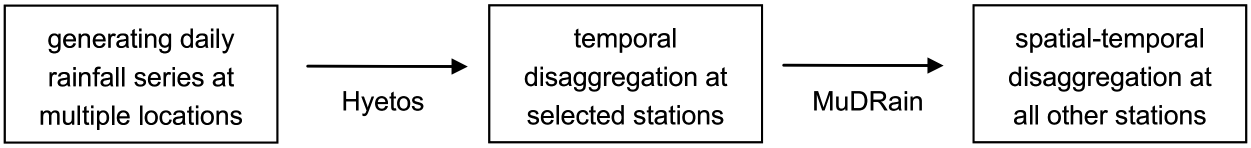

Figure 1: Process Flow of Spatial-Temporal Disaggregation of Selected Rainfall Events

4. CASE STUDY

The techniques described in section 2 and 3 are applied to the mesoscale catchment of the river Wupper with an area of 813 km² (Fig. 2). It is located in the western part of Germany and is a subcatchment of the Rhine basin. The technical flood control system consists of 17 reservoirs (Fig. 2). Four of them are used seasonal for flood control during winter. The largest one is the Wupper reservoir with a flood detention volume of 9.9 mio. m³. Historical flood peaks, in particular extreme ones, emerged mostly during winter from November to March at gauge Kluserbrücke downstream of the Wupper reservoir (see Fig. 2). This gauge is an essential point of the local flood management system because its records indicate whether danger of flooding is given and urgent measures have to be initiated.

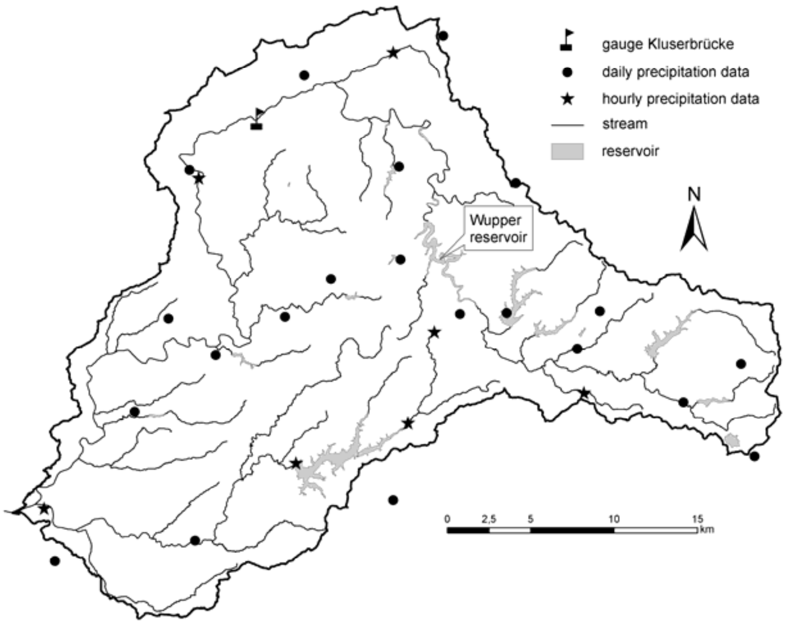

Figure 2: Wupper Catchment with Location of Reservoirs, Rainfall Stations and Gauge Kluserbrücke

To verify the performance and efficiency of the reservoir system, unobserved but possible extreme flood scenarios have to be generated. For this reason a combined rainfall runoff model and storage model of the catchment was set up. To generate the required events, the model was applied with precipitation data of the fitted stochastic rainfall model (section 2) as input. For selected events of the resulting hydrograph the corresponding daily rainfall time series were disaggregated to obtain discharge time series at finer timescale. The objective of this approach (see Fig. 3) is to simulate several extreme flood events of different (spatial) occurrences with at least one event with a return period greater than 500 years.

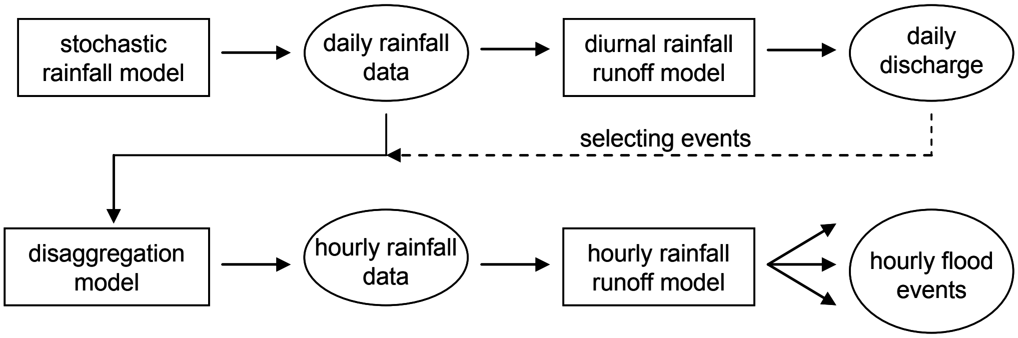

Figure 3: Process Flow of Generating Selected Extreme Flood Events

4.1 Generating rainfall time series

According to Eq. 1 rainfall time series were generated from a combination of Gamma and Pareto distributions. In Fig. 4 the reproduction of seasonal means and variances of 1-day- and 3-day-rainfall is shown for one sample station. The annual maximum precipitation of the generated 1000 years at each station were compared with observations and with values of the "KOSTRA-Altlas" (German Weather

Service, 2000), which displays the results of extreme value statistics for precipitation in Germany for different durations and return periods based on records from 1951 to 2000 of about 4500 rainfall stations. Figure 5 displays the observed and generated distributions of the described 1-day- and 3-day-maxima.

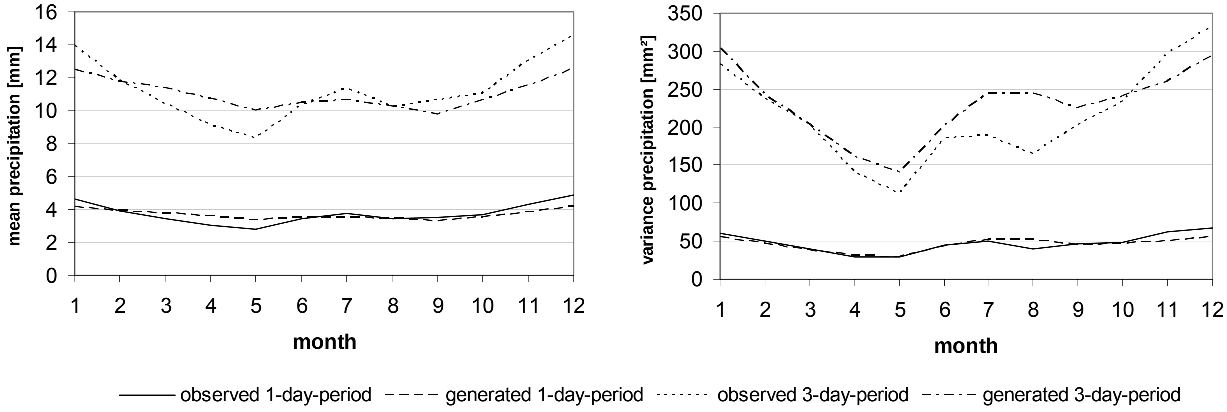

Figure 4: Monthly Statistics of Generated and Observed Daily Rainfall at one Sample Station

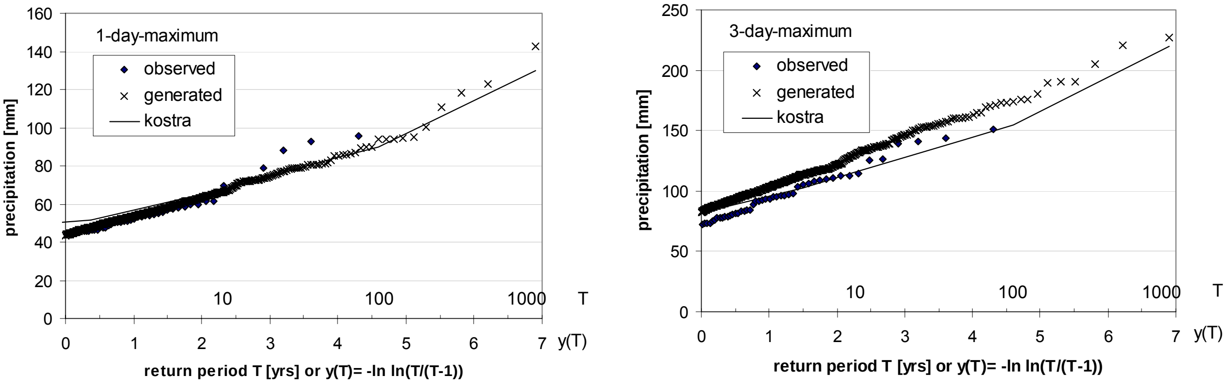

Figure 5: Maximum Annual Precipitation at one Sample Station for Observed and Generated Values and According to Intense Rainfall Data of KOSTRA-DWD-2000

The model shows good performance in terms of reproducing the statistics of the annual cycle of historical records (Fig. 4). The historical annual maximum values are also reproduced quite well by the model, even in case of the 3-day maximum (Fig. 5). With regard to the longer return periods where observed data are not available, the generated values fit the intense rainfall records of KOSTRA well, which are extrapolated up to a return period of 1000 years. To ascertain that these generated values are still in the range of physically possible amounts for this region, they are also compared with values of the maximum regional precipitation (MGN) which are deduced from the possible maximum precipitation (PMP). For Germany it has been estimated that the value of the MGN is at least two times the value of the 100 year return period of KOSTRA data (Schmidt, 1997). Therefore is has been proven that at each station the generated precipitation is physically possible.

4.2 Simulation of flood scenarios

To simulate possible flood scenarios, the generated values of 1000 years of daily rainfall are used as input for a calibrated rainfall runoff model (NASIM), which embodies a coupled storage system and the operation rules of the reservoirs. The evaluation of the efficiency of the local reservoir system considers the features of all simulated events as well as their conditional probabilities, i.e. comparing the spatial distribution of flow and the corresponding inflow at the Wupper reservoir, while accounting for the available flood control storage at the beginning of each event. Limited by the coarse temporal resolution of daily time steps the basic relationships between inflow, initial storage volume and resulting effects of the flood retention can be shown approximately in Fig. 6, considering only events where the main runoff originates from watersheds upstream of the reservoir. It displays that the initial storage content of the reservoir has a significant impact on flood retention. The 90%-quantile ranges of discharge at gauge Kluserbrücke are separated for three initial states of flood control storage. It is shown that the initial state becomes less important if the inflow to the reservoir increases, indicated by the more and more overlapping ranges. Above a certain inflow level it becomes less relevant if the initial storage content is half or even completely filled, the resulting distributions of discharge remain almost the same.

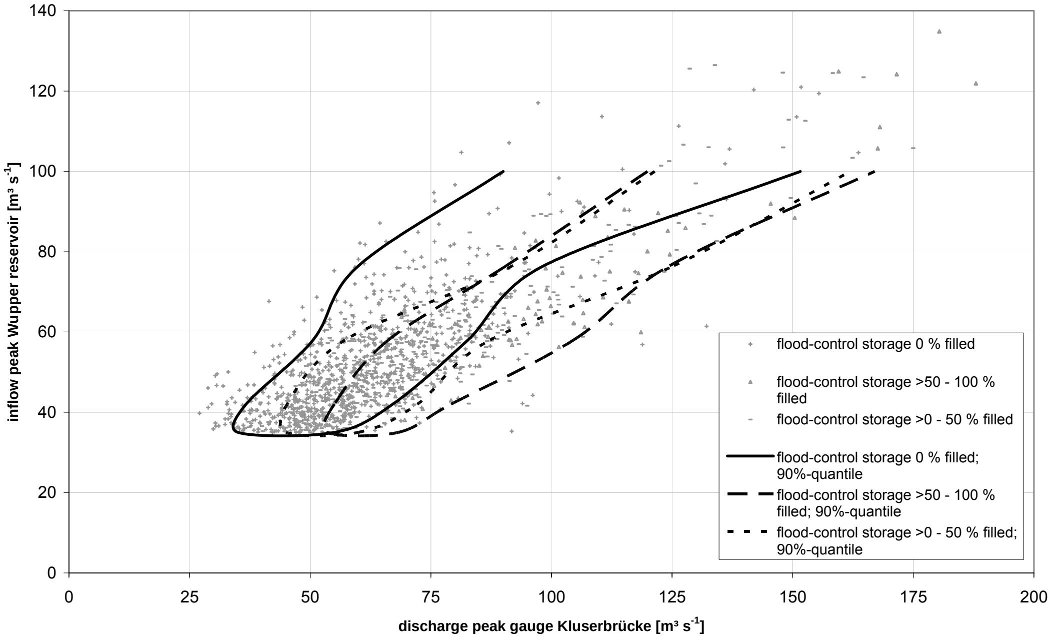

Figure 6: Dependency Between Annual Maximum Discharge at Gauge Kluserbrücke and Corresponding Inflow to the Wupper Reservoir

These analyses were done at a daily time step to specify the interesting range of events where a disaggregation of rainfall and a simulation of the reservoir behaviour on an hourly scale have to be done. The resulting hourly hydrographs will differ slightly from the daily simulated ones in terms of shape and peak and underline the dynamic characteristics of rainfall and corresponding discharge at finer time scales. For risk-based flood management it is necessary to consider the combined probabilities of different features during a flood event, as mentioned above. Thereby the flood risk at different locations downstream the reservoir can be estimated, considering the interactions between river basin and reservoir, for different conditions. This can be done, for instance, with a Bayesian network. Hereby the risk downstream of the reservoir is characterized as the result of conditional probabilities which can be derived from long term simulations. In Fig. 7 an example of such an analysis is sketched where probabilities of reservoir efficiencies are estimated depending on initial flood control storage and inflows.

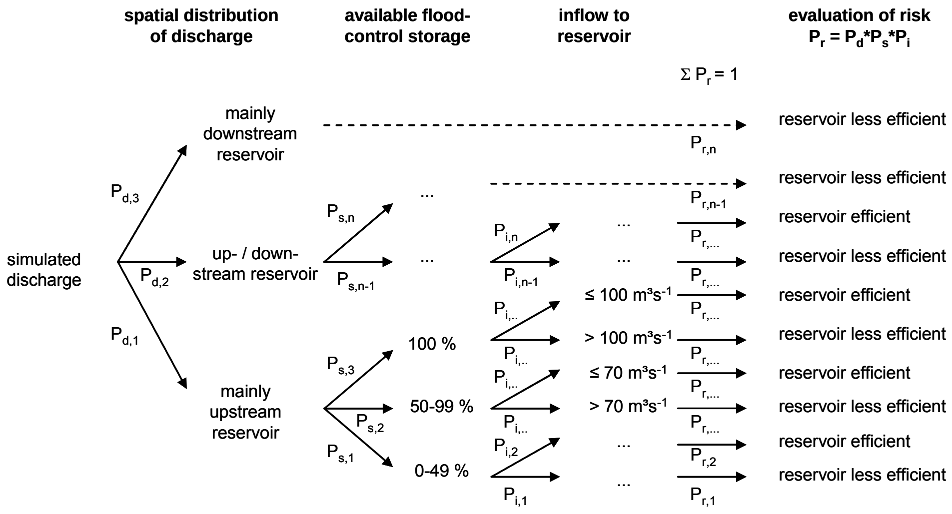

Figure 7: Sketch of Risk Calculation for the Reservoir System Based on a Bayesian Network

Fig. 8 shows empirical probability functions of simulated annual maxima of discharge at gauge Kluserbrücke for different initial storage contents. The right fat tails of the distributions base on the operating rules of the reservoir. The objectives of flood control increase stepwise from 80 to 100 up to 150 or even 210 m³ s^{-1}, depending on the free storage. A flood peak of 100 m³ s^{-1}, for instance, is reached more often if the initial flood control storage is filled with more than 50 %.

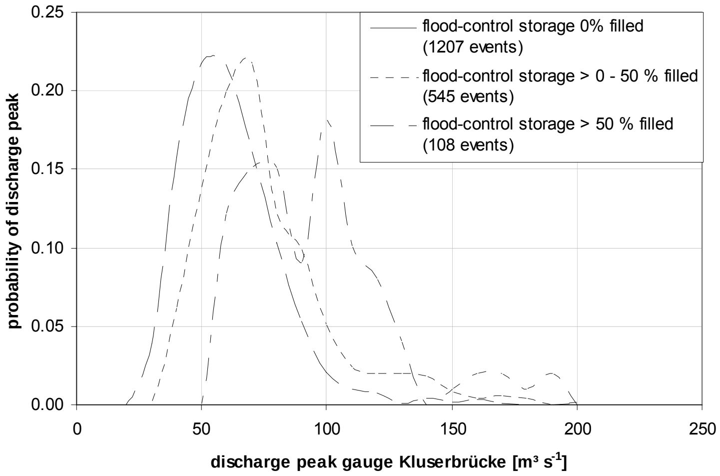

Figure 8: Probabilities of Discharge at Gauge Kluserbrücke Considering the Initial Flood Control Storage

5. SUMMARY AND CONCLUSIONS

Sustainable flood management demands a risk-based approach with consideration of all possible features of flood scenarios, depending on the spatial distribution of rainfall and discharge and the variety of the peak flow and wave shape. For this reason a stochastic rainfall model generating daily values of precipitation is applied (Hundecha et al., 2008), whereby these values are described by a joint Gamma and Pareto distribution. For evaluation the employed methodology is applied to the mesoscale catchment of the Wupper in Mid-West Germany. A time series of 1000 years of stochastic rainfall is generated as input and a statistical analysis of the produced precipitation as well as the simulated hydrograph is carried out. The results show good agreement between historical and generated rainfall values in terms of the annual cycle statistics and the return period of annual extreme events. The simulated discharge yields reasonable flood events, even in the extrapolation range, with the demanded variety of spatial distribution and shape features, which proves the performance of the local reservoir system for unobserved extreme floods. The analysis is done on daily time steps for preparation of selecting and disaggregating several events. It is necessary to disaggregate the generated daily rainfall for these events temporally and spatially consistent to hourly rainfall series. Herewith the complex hydrological processes of floods are represented in a more realistic manner by the rainfall runoff model, showing the differing dynamic of discharge at finer time scale compared with daily simulations. The probability of efficiency of the local reservoir system and hence the flood risk are defined by several features, e.g. the spatial distribution of discharge and the initial flood control storage and their corresponding probabilities. This can be displayed, for instance, by Bayesian networks, which set up a joint probability distribution of a set of related but independent variables as the product of their conditional probability distributions. The resulting probability of a selected event, i.e. the efficiency of a reservoir system, is characterized by all conditional probabilities describing this event. Another possible way is a bivariate flood frequency analysis such as a copula model (Shiau et al., 2006), which investigates the dependence between two random but correlated variables, i.e. flood peak and volume, to construct a bivariate distribution (Klein et al., 2008).

6. ACKNOWLEDGEMENTS

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