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A rainfall-runoff database to support flood risk assessment

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Abstract: A comprehensive rainfall-runoff database for the Mulde catchment in Central Germany was developed to support flood risk assessment and flood management. A large number of randomly generated 20-day rainfall scenarios and several combinations of model initialization states are the basis for the simulation of basin response by applying a metric conceptual rainfall-runoff model. The rainfall scenarios are divided into three periods; a five day initialization period to represent pre-conditions, a two day storm period representing a rainfall extreme event, and a final period characterized by low rainfall volumes to study streamflow recession behaviour. The rainfall-runoff database can be used as an effective tool to easily assess possible streamflow situations assuming different rainfall volumes for the following days. The benefit of the database approach is that it can be easily used by persons who are not necessarily familiar with hydrologic modelling, because the modelling step has already been accomplished. The study area was strongly affected by the extreme flood event in August 2002. In order to study the rainfall-runoff models' capabilities to capture this extreme event it was calibrated to training sets of input data including and not including this event. The model was calibrated using different objective functions, the Nash-Sutcliffe efficiency and a modified Nash-Sutcliffe efficiency adapted to high flow conditions. Only simulations with model settings calibrated to time series including the extreme event were capturing the flood event sufficiently. Due to the growing complexity in rainfall-runoff modelling during seasons affected by snowmelt processes, the applicability of the database in the current state is limited in snow affected catchments to the warm season.

Keywords: Rainfall-runoff database; Flood risk management; Random rainfall generator; Parsimonious.

1. INTRODUCTION

The frequency of large floods has increased substantially during the twentieth century and has a significant positive trend (Milly et al., 2002). Moreover, floods have the greatest damage potential of all natural disasters worldwide (Smith and Ward, 1998). Recent large floods, such as in the Elbe basin in summer 2002 lead to increased interests in research and highlight the necessity of improved flood forecasting techniques and flood risk assessment. To account for this development programs like the European Flood Directive (Directive 2007/60/EC) have been implemented to assess and manage flood risks.

In this paper we present the development of a comprehensive rainfall-runoff database as a tool for flood risk management. For this purpose a rainfall scenario generator was developed generating flood-relevant rainfall events. These events serve as input for the simulation of runoff by using the metric conceptual rainfall-runoff model IHACRES (Identification of unit Hydrographs and Component flows from Rainfalls, Evaporation and Streamflow data) (Jakeman et al., 1990; Jakeman and Hornberger, 1993). The IHACRES model was calibrated to the Mulde catchment in Central Germany that was strongly affected by the devastating flood event in August 2002. IHACRES was chosen because of its parsimonious approach to model parameterization and because of the simplicity to initialize the model. The rainfall-runoff scenarios are directly exported to an object-relational database management system (PostgreSQL, www.postgresql.org) in order to handle the data in a proper way.

Flood risk management includes flood forecasting with oftentimes only sparse information available such as observed streamflow and precipitation data of the last days as well as the weather forecast. The rainfall-runoff database can be used here as an effective tool to easily assess possible streamflow situations assuming different rainfall depth for the following days. First, a database query must be performed to select all scenarios where the five day initialization rainfall patterns or depth are similar to the real rainfall pattern of the previous five days. The next step is scenario based where the water manager selects all simulations where the rainfall storm event is in a certain range (rainfall depth in mm). Due to the large number of available simulations in the database the result is a variety of simulated hydrographs, reflecting the uncertainties of rainfall forecasts and model results. A benefit of this approach is the minimal time required by the database queries to achieve the desired results. The database was tested for several flood events that occurred during the period 1983 to 2002 achieving good results.

2. STUDY SITE

The Mulde river basin in Central Germany is one of the major tributaries of the Elbe River with an area of approximately 5,400 km² (at gauge Golzern) and consists of three larger sub-basins: The Freiberger Mulde draining the Central Ore Mountains, the Zwickauer Mulde which drains the western Ore Mountains and the Vereinigte (unified) Mulde. The altitudes in the basin reach between below 50 m to above 1200 m.a.s.l. 60% of the basin is used as farmland with high proportions of drainage-tiled areas, followed by forests with 17%, urban areas with 10%, pasture with 10% and 3% for others. Several flood protection measures have been implemented in the basin because of an increasing number of catastrophic floods during the last decades (especially in the year 2002). Extremely high discharge events, originating in the large mountainous parts of the upper Mulde catchment area after intensive rainfall events, have been always the basis of hydrological and landscape-forming development of the river course and its adjacent countryside.

3. METHODS

3.1 Rainfall scenario generator

The basis of the development of the rainfall-runoff database for flood events are rainfall scenarios of a length of 20 days. Hlavcova et al. (2005) state that there is no real preference for a certain method to estimate design rainfall events until now. Furthermore, the rainfall-runoff model used in our study requires only average catchment time series of precipitation and temperature to simulate streamflow. Thus, it was not necessary to apply sophisticated methods to generate distributed rainfall events as has been accomplished for instance by Gabellani et al. (2007). For this reason we used a random number generator to produce the required rainfall scenarios. The scenarios are divided into three periods where the length of the periods and the rainfall amounts can be defined by the user. We chose a length of five days for the first period - the initialization period - and allowed rainfall depth to range between 0 and 80 mm (representative values for the study area). The rainfall initialization period is not to initialize the model, as described in the following section, but to capture uncertainties in rainfall patterns and measurements. The random generator first defines for each scenario a rainfall depth for the initialization period between 0 and 80 mm and distributes the value randomly over the five days. Thus, a five day rainfall period is generated, representing a variety of artificial (or not yet occurred) as well as real rainfall events, capturing a large spectrum of different volumes and intensities. Following the initialization period a two day storm event is calculated randomly based on the same approach. We defined possible rainfall depth for the storm event in the range of 40 to 180 mm to be distributed over the two days. Instead of two days the user could also define a different duration of the storm event. An analysis of the rainfall time series in the Mulde showed that the duration of two days for the storm event is adequately representing the natural conditions. In order to study the streamflow recession behaviour a third period was introduced characterized by low rainfall events. We chose the duration of 13 days with rainfall depth of 0 to 20 mm over this period. The rainfall scenario generator was implemented in the programming language C++ and was equipped with a database interface. The 20-day rainfall scenarios are directly exported to an object-relational database management system (PostgreSQL).

Due to the large number of rainfall scenarios, both artificial rainfall patterns and natural rainfall patterns are captured, although the scenarios are generated randomly: Figure 1 shows an example of the observed rainfall event during the flood in August 2002 as well as two generated scenarios from the database capturing the pattern of the observed event.

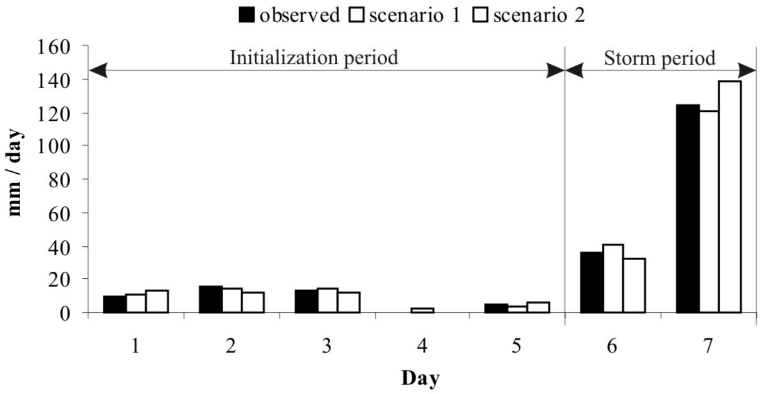

Figure 1. Randomly generated rainfall scenarios capturing the observed rainfall event in August 2002 in the Mulde catchment

Additionally a 20-day time series of daily mean temperature is produced by the generator. Here we focus on flood events during the summer period and calculate a time series representing typical temperatures in the months June, July, August and September.

3.2 Rainfall-runoff modelling

The IHACRES metric conceptual rainfall-runoff model (Jakeman et al., 1990; Jakeman and Hornberger, 1993) has a parsimonious approach to model parameterisation. The version used in this paper has six free calibration parameters. IHACRES has been applied to catchments with a wide range of climatologies and sizes (Croke et al., 2004). It has been used to predict streamflow in ungauged catchments (Kokkonen et al., 2003; Post and Jakeman, 1999; Post et al., 1998), to study land cover effects on hydrologic processes (Croke et al., 2004; Kokkonen and Jakeman, 2002), and to investigate dynamic response characteristics and physical catchment descriptors (Kokkonen et al., 2003; Sefton and Howarth, 1998).

Due to the minimal data requirements IHACRES can be applied in many catchments without spending a long time to prepare necessary input data. The model requires only time series of precipitation and temperature to simulate catchment runoff. Observed streamflow data are used for calibration. As illustrated in figure 2 a rainfall (r_k) time series is converted to effective rainfall (u_k) in the non-linear loss module (Jakeman and Hornberger, 1993). In order to achieve this, a catchment wetness index or antecedent precipitation index, representing catchment saturation is calculated for each time step. In the linear routing module the effective rainfall is converted to streamflow (x_k). We used a storage configuration of two parallel storage components, a quick (x^q) and a slow component (x^s). The parameter (α) is the recession rate for the quick and slow storage component and parameter (ß) represents the fractions of effective rainfall (u_k) for peak response. A comprehensive description of the model functions used in our study is given in Jakeman and Hornberger (1993). In order to avoid long model warm-up periods, the streamflow simulations based on each rainfall scenario are calculated starting with different initial model states. These model states represent a variety of possible pre-conditions (wet to dry) at time step zero (t_0). The parameters required for model initializations are the *antecedent precipitation index* (API) and *streamflow* (Q). Initial combinations of these parameters are stored in a table where for instance the first combination is Q = 10 m^3/s and API = 0.1, the second combination Q = 10 m^3/s and API = 0.2 and so on. In our case we used 220 pre-condition combinations. Thus, for each rainfall scenario 220 streamflow simulations were performed. The model initialization should not be mixed up with initialization period of the rainfall scenario described in the previous section.

The IHACRES model was implemented as a module for the open source GIS SAGA (www.saga-gis.org) and has been equipped with a calibration tool based on the Monte Carlo approach which is appropriate to calibrate six free parameters in a short time. Due to the parsimonious parameterization of the model and the minimal data requirements, a simulation of a long time series can be calculated in a few seconds for instance. These are optimal conditions to realize thousands of simulations within a short time which was necessary to develop the rainfall-runoff database.

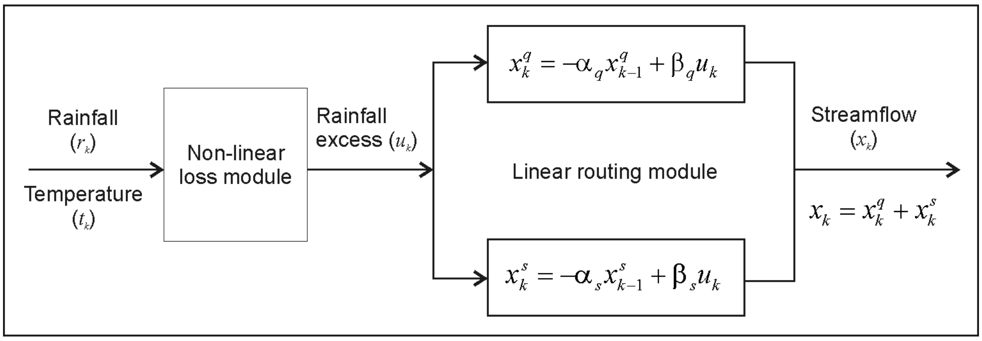

Figure 2. IHACRES model (after Jakeman and Hornberger, 1993; Croke et al., 2004)

Calibration

The model was calibrated at gauge Golzern with a catchment size of 5400 km^2. Arithmetic mean time series of all available precipitation and temperature gauges in the catchment served as model inputs. The period 1995 to 2002 (period 1) was chosen, because it includes the extreme flood event in August 2002 and consists of a variety of hydrologic conditions, namely wet, dry and normal years, as shown in table 2. In order to learn about the models' capabilities to capture extreme events with magnitudes not included in the training set, period 2 (1995 to 2001), not incluing the 2002 extreme event, was used to calibrate the model with a second set of parameters adjustments. For model validation the period from 1983 to 1994 was selected. The performance of the model calibration was measured on a daily time step using three objective functions, the Nash-Sutcliffe efficiency (NSE) (Nash and Sutcliffe, 1970), a modified Nash-Sutcliffe efficiency (Hoffmann et al., 2004) adapted to high flow conditions (ANSE) and the PBIAS in [%].

For each calibration period the model was calibrated focussing on the objective functions NSE and ANSE. Hence we obtain four simulations characterized by different model parameter settings. To distinguish the different model versions the nomenclature shown in table 1 is used in the following.

Table 1. Nomenclature of model versions

	NSE	**ANSE**
Period 1	NSE_P1	ANSE_P1
Period 2	NSE_P2	ANSE_P2

Model performance

Reasonable model performance for all model versions was obtained for the calibration period in all years (Table 2). Only in the years 1996 and 1997 the efficiency dropped below 0.6. In the validation period the performance is also reasonable except for the years 1983-85 and 1990 where the Nash-Sutcliffe efficiency is below 0.5. Noticeable is that these years can be characterized as dry years. Generally the model performs much better in the Mulde catchment in wet years than in dry years. During the wet years mean Nash-Sutcliffe efficiencies of 0.83 were obtained (NSE_P1), however in dry years the mean NSE was with 0.54 considerably lower. It should be emphasized here that the model versions calibrated for period 2 seem to be more robust than the versions calibrated for period 1, particularly in the validation phase. An explanation for this phenomenon could be that the enormous runoff volume during the storm event in 2002 (not included in calibration period 2) corresponds approximately to the volume of 60 to 70 days of mean discharge. Thus, the 2002 flood event is influencing model calibration considerably distorting the parameter settings towards the achievement of a good fit to this event.

Table 2. Model performance and comparison

	NSE_P1			**ANSE_P1**			**NSE_P2**			**ANSE_P2**		
Year	**NSE**	**ANSE**	**pbias**	**NSE**	**ANSE**	**pbias**	**NSE**	**ANSE**	**pbias**	**NSE**	**ANSE**	**pbias**
Cal.												
1995 w	0.79	0.85	-3.9	0.72	0.78	-5.5	0.80	0.80	-2.6	0.81	0.83	-5.9
1996 n	**0.59**	0.74	14.1	**0.41**	0.62	10.0	**0.55**	0.71	16.6	**0.54**	0.70	18.1
1997 d	**0.52**	0.50	5.5	**0.44**	0.41	5.4	0.68	0.69	6.1	0.69	0.71	5.8
1998 w	0.77	0.81	2.9	0.72	0.78	0.1	0.77	0.80	2.8	0.84	0.86	1.2
1999 n	0.84	0.86	3.5	0.85	0.90	5.5	0.91	0.94	1.8	0.85	0.89	5.4
2000 w	0.88	0.91	-18.3	0.88	0.91	-16.9	0.89	0.90	-12.5	0.91	0.92	-8.3
2001 d	0.60	0.68	-7.7	**0.47**	0.57	-11.3	0.64	0.72	-8.1	0.71	0.77	-4.5
2002 w	0.93	0.96	6.3	0.95	0.98	2.8	0.74	0.72	12.5	0.77	0.73	9.6
Mean	**0.74**	**0.79**	**7.8**	**0.68**	**0.74**	**7.2**	**0.75**	**0.79**	**7.9**	**0.77**	**0.8**	**7.4**
Val.												
1983 d	**0.37**	0.49	-35.3	**0.13**	0.24	-37.1	0.76	0.87	-14.9	0.76	0.89	-18.6
1984 d	**0.37**	0.52	12.3	**0.25**	0.45	11.7	**0.24**	0.46	12.6	**0.34**	0.45	19.9
1985 d	**0.44**	0.56	7.5	**0.34**	0.50	6.1	**0.24**	0.37	4.9	**0.40**	0.53	14.5
1986 d	0.66	0.69	-12.4	0.65	0.74	-13.4	0.66	0.73	-5.2	**0.47**	0.41	-1.5
1987 w	0.76	0.80	1.3	0.81	0.85	1.5	0.73	0.76	1.7	0.70	0.70	13.9
1988 w	0.83	0.84	-3.2	0.78	0.79	-5.4	0.86	0.88	-4.0	0.82	0.83	12.3
1989 d	0.77	0.82	-5.2	0.63	0.70	-6.4	0.83	0.87	-3.6	0.80	0.83	1.0
1990 d	**0.23**	0.37	-6.7	**0.06**	0.23	-7.6	**0.49**	0.62	-1.7	**0.58**	0.66	-2.2
1991 d	**0.51**	0.57	-3.2	**0.32**	0.41	-6.4	**0.57**	0.66	-1.1	**0.59**	0.68	4.1
1992 d	0.67	0.69	-13.3	0.60	0.61	-12.7	0.76	0.77	-10.4	0.77	0.76	8.3
1993 d	**0.54**	0.61	-9.5	**0.37**	0.46	-9.8	**0.51**	0.65	-11.6	0.63	0.67	-2.3
1994 d	0.80	0.84	-11.1	0.77	0.83	-10.6	0.80	0.83	-11.8	0.83	0.85	-11.6
Mean	**0.58**	**0.65**	**10.1**	**0.48**	**0.57**	**10.7**	**0.62**	**0.70**	**7.0**	**0.64**	**0.69**	**9.2**

w = wet, n = normal, d = dry

Flood event modelling

With regard to the objective of our study it was important to analyze the model performance for flood events. During the period 1983 and 2002 three floods in 1983, 1995 and 2002 occurred in the summer periods with daily discharge values exceeding 500 m^3/s. The hydrographs shown in figure 3 and 4 are not simulation results obtained from the rainfall-runoff database, but from a simulation period starting in 1975. Figure 3 is illustrating the model results for the flood events in 1983 and 1995 with maximum discharge values of about 700 m^3/s. The model versions calibrated to period 1 tend to overestimate runoff peaks and the versions calibrated to period 2 are underestimating peak flow. Both events are represented best by averaging the four simulations, an approach comparable to the multi-model approach proposed for example by Goswami and O'Connor (2007). The simulation results of the extreme flood event in 2002 are different. Version ANSE_P1 captures the flood peak perfectly and NSE_P1 adequately. Both versions calibrated to period 2 are underestimating the extreme flood peak dramatically, simulating only 50% of peak discharge, see figure 4. This leads us to the assumption that the IHACRES model is not able to capture events of extreme magnitudes if no comparable event occurred in the calibration period or training set, respectively. Thus, from the modellers point of view we are "fortunate" that an extreme event with a recurrence interval of 500 to 1000 years (LfUG, 2002), such as the flood in 2002, occurred and data are available from several streamflow gauges. Hence it was possible to train the model with this information and to gain the capability to better represent comparable events in the future. This is an important prerequisite for the development of a “reliable” rainfall-runoff database for the Mulde catchment, because at least statistically the probability of recurrence of a larger event is relatively low.

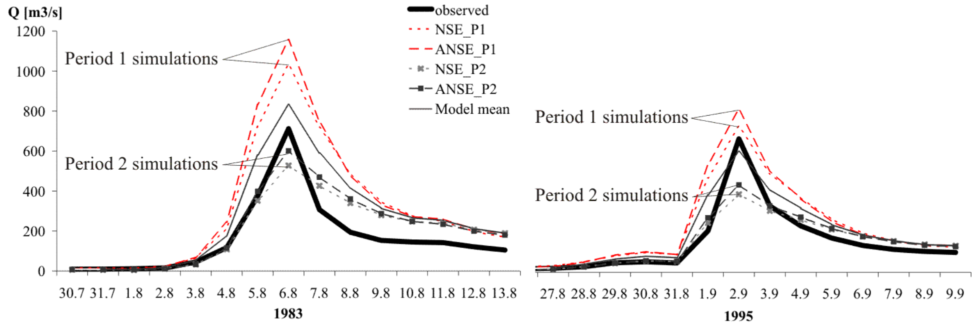

Figure 3. Flood event simulations of the years 1983 and 1995

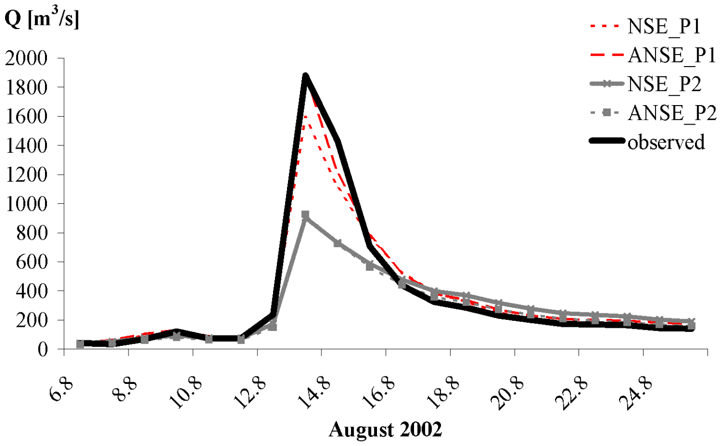

Figure 4. Extreme flood event in the Mulde catchment at gauge Golzern in August 2002

3.3 The rainfall-runoff database

With the development of the rainfall-runoff database our objective was to support applied flood risk management providing a large set of 20-day rainfall-runoff simulations. The number of runoff simulations depends on the number of rainfall scenarios and the number of combinations of initial model states (parameters API and Q). We generated 10,000 rainfall scenarios and 220 API-Q-combinations. Hence the number of runoff scenarios in the database is 2.2 Million. Three categories of tables exist in the database: rainfall and temperature scenario tables, tables with initial model conditions (initial API and Q values), and tables containing the runoff simulations.

Figure 5 shows an example runoff result set, where only runoff simulations, based on rainfall scenarios that are comparable to the 1995 flood, are displayed. Therefore, a database query in the form of:

SELECT *all simulations*
FROM *runoff simulation table*
WHERE *rainfall volume in the initialization period is* > 45 and < 50
AND *rainfall volume in the storm period is* > 90 and < 100
AND *initial streamflow is* < 30 m^3/s
AND *initial antecedent precipitation index is* > 0.1 and < 0.4

was performed.

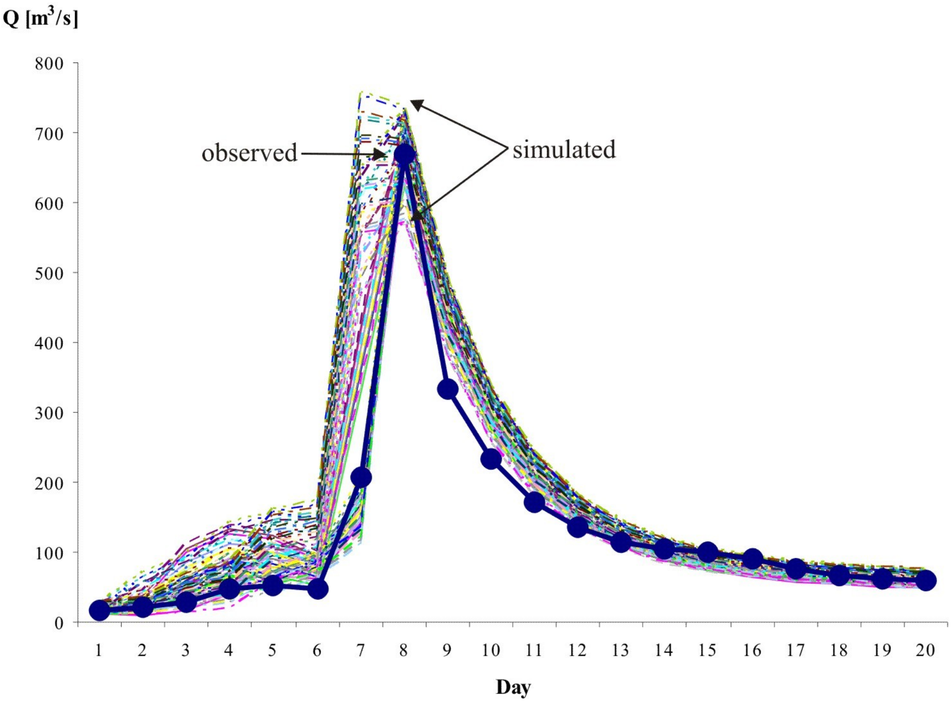

Figure 5. The 1995 flood event captured by the database simulation result set

The example shows that the runoff simulations capture the 1995 flood event, where some simulations are underestimating and some are overestimating the flood peak. The differences between the lowest simulated flood peak and the highest simulated flood peak can be considered as an uncertainty range.

4. CONCLUSIONS

Sources of uncertainties in the flood forecasting process are manifold, starting from uncertainties in precipitation measurements, followed by the uncertainty attributable to the internal states of the hydrological and hydrodynamic models, the initial conditions and relevant process parameterizations (Arduino et al., 2005). With the development of the rainfall-runoff database we are able to show the uncertainties related to precipitation measurements and forecasts as well as uncertainties related to initial conditions. The results of our studies in the Mulde catchment showed that the generated rainfall scenarios are representing a variety of artificial (or not yet occurred) as well as real rainfall events, capturing a large spectrum of different volumes and intensities. Moreover, we demonstrated that flood events can be captured by the range of the result set of runoff simulations.

By using database queries the water manager is able to produce flood risk scenarios, depending on short-term rainfall forecast. The database can be used by persons who are not familiar with hydrological modelling, because the modelling step has been accomplished already. By linking the simulation results (minimum and maximum peak flow) with a hydrodynamic model a water manager is able to delineate flood inundation areas.

Due to the growing complexity in rainfall-runoff modelling during seasons affected by snowmelt processes, the applicability of the database in the current state is limited in snow affected catchments to the warm season. In order to better account for seasonality in climate scenarios we propose to use more sophisticated weather generators, such as the EARWIG (Kilsby et al., 2007) based on a Neyman-Scott point process model (Cowpertwait, 1991), or stochastic models as the WGEN (Richardson and Wright, 1984) or LARS-WG (Semenov et al., 1998; Semenov and Brooks, 1999), to produce design rainfall and related temperature events.

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