WP 1.6

DELIVERABLE 1.6.5 (A)

INTEGRATING MONITORING AND MODELLING TO SUPPORT FLOOD RISK ASSESSMENT

Report of the NeWater project -
New Approaches to Adaptive Water Management under Uncertainty

www.newater.info

Title	INTEGRATED MONITORING AND MODELLING TO SUPPORT FLOOD RISK ASSESSMENT
Purpose	To summarize the experiences made and results obtained in AMIS implementation in the two NeWater case studies
Filename	D_165_a.pdf
Authors	Stefan Liersch, Raffaele Giordano, Michele Vurro
Document history	Version 1: 2008-10-31
Current version.	Version 1
Changes to previous version.	
Date	
Status	Draft
Target readership	WB1 partners
General readership	NeWater team
Correct reference	

Stefan Liersch[1], Raffaele Giordano[2], Michele Vurro[2]
[1] Helmholtz Centre for Environmental Research (UFZ) – Leipzig (Germany)
[2]National Research Council – Water Research Institute (CNR-IRSA)

October 2008

Prepared under contract from the European Commission

Contract no 511179 (GOCE)
Integrated Project in
PRIORITY 6.3 Global Change and Ecosystems
in the 6th EU framework programme

Deliverable title:	Integration of local and technical knowledge for adaptive water management
Deliverable no. :	D 1.6.5 a
Due date of deliverable:	Month 44
Actual submission date:	Month 46
Start of the project:	01.01.2005
Duration:	4 years

Policy Brief

Overview of the problem

Within the NeWater project, work packages 1.6 deals with the transition to advanced monitoring systems. The aim is to enhance current monitoring systems towards a better support of the learning process for adaptive management. Thus, a monitoring system must be able to support the identification of changes in system behaviour due to management actions and to provide tools to convert monitoring data into useful information according to management requirements.

Despite the fact, that the upper Tisza river basin is equipped with a number of automated climate stations, it can be considered as data poor. Only precipitation, temperature, and water level are measured. Currently, a rather complex hydrodynamic model is applied in order to provide information about flood risk. Obviously, there is a discrepancy between available data and the data requirements by the hydrodynamic model. Hence, the model results can be considered as highly uncertain.

This report aims to contribute to the current flood risk management in the upper Tisza river basin, by proposing an alternative hydrologic modelling approach and by the development of a rainfall-runoff database. The rainfall-runoff database can be used by water managers and requires no hydrologic modelling skills.

Policy recommendations

Flood risk management practiced under current conditions can be considered as not optimal. Beside a lack of financial resources to collect required data for hydrologic modelling or to implement technical flood protection measures, we identified as a major disagreement the discrepancy between data availability and data requirements for flood risk management.

Due to the fact that a financial support for data collection is not within the scope of the NeWater project, the contribution of deliverable 1.6.5a is to recommend strategies to adapt the current modelling approach to data availability. Therefore, we searched for “simpler” hydrologic models requiring only data provided by the current monitoring system (precipitation and temperature).

Two conceptual rainfall-runoff models were identified and tested. The report shows that both models are adequately simulating streamflow and thus, are useful (alternative) tools to support flood risk management. Moreover, one of the selected rainfall-runoff models was used to develop a comprehensive rainfall-runoff database. This database can be used

- to study catchment response to different rainfall events, in order to investigate the impact of different catchment pre-conditions (extremely dry, dry, medium, wet, and extremely wet) on flood extents, caused by rainfall volumes (storm events) in a certain range; and
- to contribute to flood risk assessment and flood forecasting by assessing possible streamflow situations for the following days, i.e. in order to decide whether predicted short-term climate scenarios might lead to dangerous flooding.

Table of contents

1 Introduction

The research activities carried out in WP 1.6 allowed us to define the conceptual architecture of an Advanced Monitoring System (Figure 0), able to support the Adaptive Water Management, being adaptive itself.

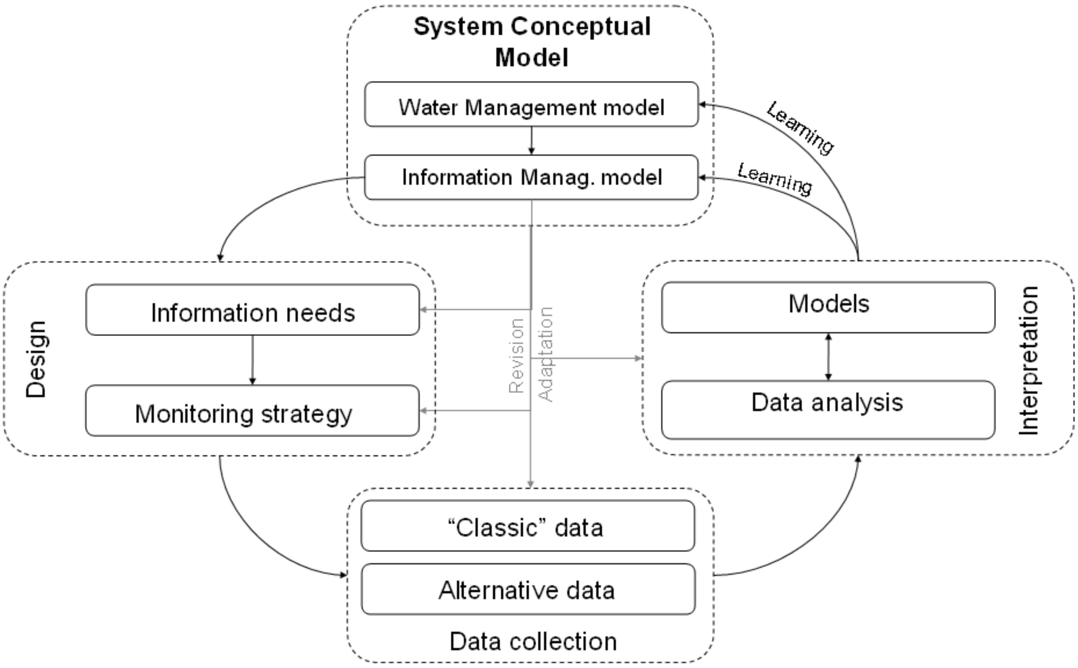

Figure 0. Conceptual architecture of the Advanced Monitoring Information System

The AMIS architecture consists of four main boxes, i.e. *Conceptual model elicitation*, *Design*, *Data collection* and *Interpretation*. The links between them represent the iterative process of monitoring design, which is at the basis of the AMIS. The figure was elaborated starting from the information cycle developed by Timmerman et al. (2000). This cycle depicts a framework where information users and producers communicate information needs that link the monitoring and decision processes. The monitoring program needs to be adapted to the different stages of the policy definition process, because each stage requires different types of information (Cofino, 1995) to make water management and governance adaptive.

Among the innovations introduced by the AMIS into monitoring system design and management, the iterative integration between system monitoring and system modelling is considered as fundamental for monitoring design and re-design. On the one hand, system modelling allows the main elements of the system to be managed and the most important relationships to be identified, taking into account the properties of complex systems, i.e. thresholds, inter-scale relations, etc. The integration between system monitoring and modelling allows to overcome the difficulties in understanding the dynamic feedback of the systems, which is particularly difficult in an environmental context because they are confounded by many factors. The integration between monitoring and modelling can prevent so-called "superstitious" learning, which is partly based on the premises that humans have a limited capacity to understand the complexity of feedbacks in ecological systems (Fazey et al., 2005). This leads to erroneous connections between causes and effects and, then, to wrong conclusions about the impacts of management actions. Conversely, models suggest which variables may be critical to monitor actions' impacts by posing elaborate hypotheses of which variables and relationships are critical to understanding the problem in question and then considering the dynamic implications of these hypotheses through the simulation of different scenarios. This allows monitoring networks to be designed (and re-designed) according to model results. The potentialities of models to simulate future scenarios can support the categorisation of the variables according to the speed of change, i.e. slow changing variables and fast changing variables. The scenario simulations can draw attention to the role of the slow variables influencing system dynamics. Often, managers ignore the slow variables and are frequently focused on fast variables (Walker et al., 2006). Moreover, the categorisation of variables according to the speed of changes influences the frequency of data collection in order to facilitate the definition of a variable's trend.

The integration between monitoring and modelling has to be considered as an iterative process. In fact, while the models can simulate system dynamics, allowing the identification of key variables, the availability of new data permits the revision and updating of models. This is also true for the speed of change of the variables. Thus, slow changing variables in the model can be detected fast by the monitoring system. A revision is needed both in modelling and in monitoring. Concerning the latter, the interval to sample has to be changed.

Modelling can, thus, support the interpretation of data, facilitating the learning process. Moreover, the AMIS is based on the integration of different sources of data, in order to fill the data gaps, which often hamper the definition of sustainable management policies for the environmental resources.

The present deliverable and the D1.6.5b are then focused on the description of the methodologies adopted in order to integrate alternative sources of information in the traditional monitoring system. Particularly, D1.6.5a describes the approach used to integrate the climatic data collected by a traditional monitoring system, with the information obtained by a model. The integration of these two kinds of data facilitates the use of models for flood risk assessment and preparedness in the Tisza river basin.

This work is organized as following. Section 2 describes the technical components of the AMIS architecture in detail; the case study is described in section 3. Unfortunately, the Ukrainian case study partners did not provide the required data for modelling, hence, the experimental implementation of the model has been made alternatively in a different river basin, as explained further in the text.

2 The Advanced Monitoring and Information System (AMIS)

Environmental monitoring can be considered as a producer of large amounts of data that need to be stored and administered adequately. Data on the environment are provided by different sources and thus occur in various formats, such as time series data provided by the monitoring network, remote sensing data, model results, reports, spatial information on geographic entities, etc. Appropriate tools are required that convert data into accessible, useful and tailor-made information according to the user's requirements. An important basis of decision making in the context of environmental resources management is information on the current state of the environment as well as information on trends and changes of different environmental variables in order to learn about the effects of implemented management actions. Both can be provided and supported by a well structured environmental monitoring and information system. In the following the system is referred to as AMIS (Advanced Monitoring and Information System) that can be considered as a software tool that provides different methods to deal with spatial and temporal data. Furthermore, the system was extended by specific tools tailored for two different case studies. For the first case study the functionality of the AMIS was enhanced towards hydrological modelling. For this purpose two conceptual rainfall-runoff models were implemented as modules into the AMIS. Moreover, tools were integrated into the system enabling the development of a rainfall-runoff database to support flood risk management. Actually it was planned to develop the rainfall-runoff database in the upper Tisza river basin (NeWater Tisza case study). Due to the problem that the Ukrainian project partners did not provide the required data up to now, the hydrological models and the rainfall-runoff database was alternatively tested in a German catchment. The German catchment is described in section 4.

In the focus of the second case study (NeWater Amudarya) is on supporting the current soil salinity monitoring by integrating local knowledge provided by farmers in Uzbekistan (see deliverable 1.6.5b). A user interface was developed that assists the estimation of soil salinity based on qualitative information as well as expert knowledge.

2.1 Components of the AMIS

Generally, the AMIS is composed of three main components fulfilling different tasks. The core of the system is the GIS SAGA, acting as user interface and providing functions for GIS-specific operations. The second component is a relational database management system used to store and administer available data. The database can be installed locally on a computer or, which is more straightforward, on a web server. The GIS-Database interface can be considered as the third main component enabling the GIS to exchange data with the database (see Figure 1). The interface is directly implemented in the GIS. Moreover, SAGA was equipped with additional components tailored for the two case studies, such as hydrologic models and an interface to input qualitative information based on local knowledge for soil salinity assessment. A more detailed description of the three main components is given in the following paragraphs.

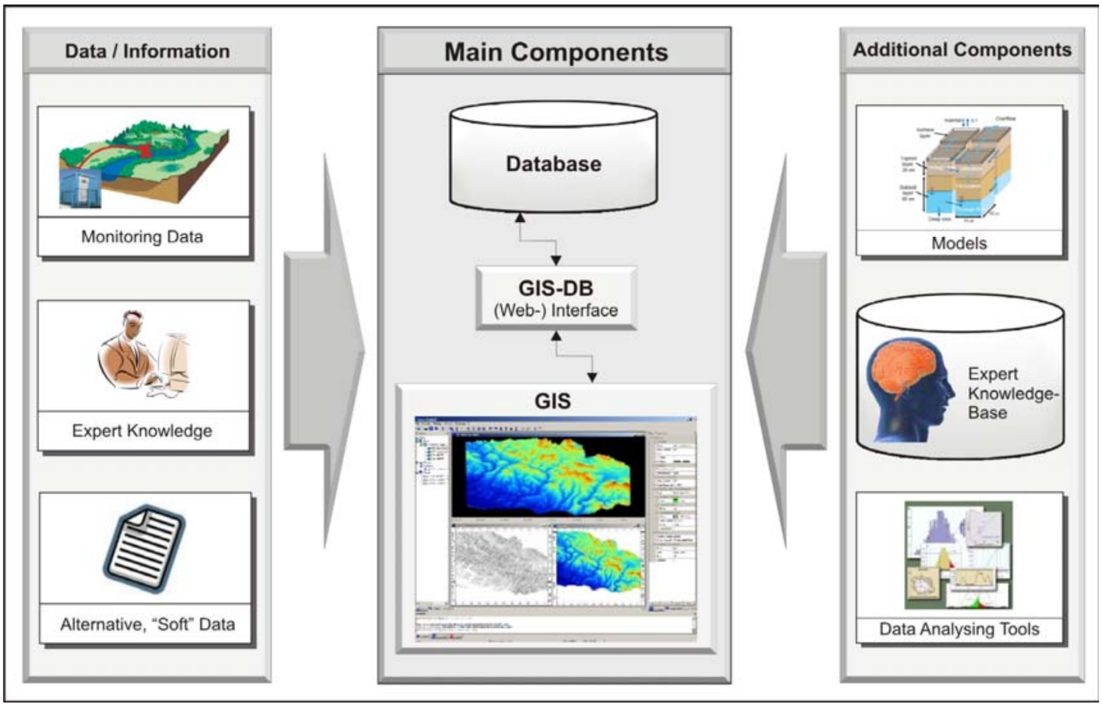

Figure 1. Structure of the AMIS

2.1.1 GIS

Almost all data and information used in environmental resources management have a spatial reference, which requires the usage of GIS technology. SAGA has been extended and adapted to the specific requirements of the case studies, described in NeWater deliverable 1.6.5.b and in section 6. Therefore, it was necessary to intervene in the SAGA API (Application Programming Interface) and SAGA GUI (Graphical User Interface). The OGC-conform Simple Feature format (OGC, 2005a) for geographic vector data was implemented as new data-object type in the SAGA API. Therefore, the new data-object type was derived from the existing type "Shapes" in order to inherit all implemented SAGA-Shapefile functions for Simple Features. In order to exchange data with the database an interface was developed and integrated in SAGA. A new menu called Database was implemented in the SAGA GUI (see Figure 2 below) providing import / export functions as well as specific AMIS functions that are related to the database.

SAGA has been selected as the basis of the AMIS because it is freely available, open source, platform independent and developed in an object oriented approach. Moreover it is rather user-friendly compared to other GIS with comparable functionalities and has a good performance in operating large datasets.

2.1.2 Database

The object-relational database management system PostgreSQL (http://www.postgresql.org/) is predominantly used to store environmental data, such as time series from a monitoring network. The extension PostGIS (http://postgis.refractions.net/) enables PostgreSQL to deal with geographical data in vector format implementing the OpenGIS Simple Feature Specification for SQL (OGC, 2005b). Relevant geographic data in the AMIS context are for instance, point data (climate stations), line data (channel network), and polygon data (catchment borders). Via look-up tables environmental time series data can spatially linked to their location in the real world and thus, easily accessed by the GIS interface. The database can be installed on a web-server allowing the user to access data via the Internet from any location, providing all users with the same datasets. Sharing data with colleagues is much easier this way, and if time series are updated centrally, everyone has automatically access to the same new datasets. Furthermore, the database provides functions to analyze time series data as well as spatial data.

2.1.3 GIS-DB interface

The interface between GIS and database is implemented in the GIS environment and its functions manifests in the menu Database (see Figure 2 below), which is not available in the common version of SAGA GIS. It provides comprehensive functions to access data in a PostgreSQL database as well as to analyze and query the data using database functions. SAGA can import geodata in the common ESRI Shapefile format and the interface provides functions to export them to the database as OGC conform Simple Features. Any SQL command, depending on the user's permissions, can be executed in the database via the interface and the results can be visualized in the GIS. The strength of SAGA is originally on grid analysis. Using the spatial capabilities of PostGIS, the database interface extends the GIS towards advanced vector functionality.

Additional AMIS components are functions that where tailored for specific purposes, such as the soil salinity monitoring and assessment (described in the NeWater deliverable 1.6.5b), the rainfall-runoff models, and tools to develop the rainfall-runoff-database (described in section 6 of this document). All additional components are integrated in the GIS-DB interface.

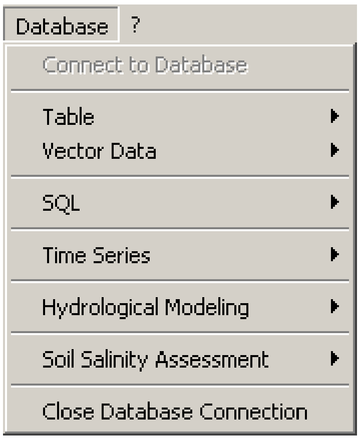

Figure 2. Menu *Database*

3 The case study

3.1 The Ukrainian part of the Tisza river basin

The catchment of the upper Tisza River is situated in the geographical centre of Europe. The river basin is strongly affected by floods that are mostly generated in the Ukrainian part of the Carpathian Mountains in spring time. Natural extreme events like floods and droughts can occur almost simultaneously during one year. From the northwest to the southeast the river basin is surrounded by the Carpathian Mountains with elevations up to 2500 meters MASL. Precipitation patterns are closely related to the altitudes with annual ranges from over 1700 mm in mountainous areas to below 500 mm in the lowlands (Jolánkai & Pataki, 2005). Dangerous floods can be triggered by abrupt snowmelt processes due to fast temperature increases or heavy rainfall events on the snow cover or the still frozen surface in mountainous areas. The regions mostly affected by floods in the Tisza river basin are the lowland areas in the Ukraine and Hungary. High water levels in the rivers draining the study area of the upper Tisza (~12,500 km2), the Carpathian Mountains, can occur four to five times per year. The frequency is strongly related to the extent to which soils are saturated with water (ZFMP, 2006).

Despite the fact, that the catchment is equipped with a number of automated climate stations, it can be considered as data poor. Data measured at these stations are precipitation, air temperature, discharge or water level, and water temperature.

3.2 Current deficiencies in the flood risk assessment and forecasting strategy

According to the opinions of Ukrainian hydrologists and water managers, current deficiencies in flood risk management and flood forecasting are related to data scarcity and data quality. From a modeller’s point of view, available time series are usually too short and data quality is sometimes too low to calibrate the models in a sufficient way. Historical time series exists, but not always in digital format, or if in digital format, not in the necessary frequency, for instance, monthly means instead of daily values. At several gauges water levels instead of discharge are measured, where water level data can only be used to calibrate hydrologic models if they are transformed to discharge via Q-h-relations. The rating curves used to convert water levels to discharge are sometimes old and thus are not representing the data properly. The hydrodynamic model currently used for flood forecasting requires a lot of measured cross sections, that are not always available, as well as proper discharge time series. Hence, the model results can be considered as highly uncertain.

From our point of view the main deficiencies of the current modelling approach are the discrepancies between data availability and data requirements of the used hydrodynamic model. Hence, the modelling strategy is not adapted to the current data situation. In order to improve this, or at least to harmonize the application of tools and their requirements with data availability we propose the usage of parsimonious hydrological models.

Moreover, a conceptual rainfall-runoff model was used to develop a rainfall-runoff database as an important tool to support flood risk management.

Please note: SINCE THE UKRAINIAN PARTNERS DID NOT PROVIDE RAINFALL AND STREAMFLOW DATA UP TO NOW, BOTH THE PROPOSED MODELLING

APPROACH AND THE DEVELOPMENT OF THE RAINFALL-RUNOFF DATABASE WAS ALTERNATIVELY TESTED IN A GERMAN RIVER BASIN.

3.3 Proposed strategy to adapt the current system

Step 1

As a complement to the current flood risk assessment and forecasting strategy, beside the currently applied hydrodynamic model, we propose the usage of parsimonious conceptual rainfall-runoff models which require only data that are currently available (precipitation and temperature). It should be highlighted here that the alternative modelling approach is not proposed in order to substitute the existing strategy, but to provide information about flood risk and streamflow forecasts based on a different modelling approach. The application of an alternative modelling approach can be considered as the first step in adapting the current flood risk assessment and forecasting strategy to the current (data) situation. The proposed rainfall-runoff models are described in section 5.

Step 2

In a second step a parsimonious rainfall-runoff model is used to develop a comprehensive rainfall-runoff database as a useful tool to support water managers in flood risk assessment. The rainfall-runoff database, presented in section 6, can be used here as an effective tool to easily assess possible streamflow situations assuming different amounts of rainfall during the previous and following days. For this purpose a database query must be performed to select all streamflow scenarios where the rainfall patterns or volumes during the initialization period are similar to the real rainfall patterns observed during the previous days. The next step is scenario-based. The user selects all simulations where the rainfall storm event is in a certain range (rainfall depth in mm) according to the weather forecast. 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. The benefits of this approach are: (1) the minimal time required by the database queries to achieve the desired results; (2) the usability of the database without hydrologic modelling skills; (3) the parsimonious approach to data requirements that enables the user to apply the database to many catchments, including data-poor regions.

Moreover, the rainfall-runoff database can be used to study general catchment response to various rainfall scenarios. An important topic in this context is the investigation of the impact of different catchment pre-conditions (extremely dry, dry, medium, wet, and extremely wet) on flood extents, caused by rainfall volumes (storm events) in a certain range. The database can be used to identify critical rainfall volumes for each catchment pre-condition.

4 Alternative study site (Mulde catchment in Central Germany)

The Mulde river basin in Central Germany is one of the major tributaries to the Elbe River with an area of approximately 5,400 km^2 (at gauge Golzern). It 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. Altitudes in the basin range from 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 (17%), urban areas (10%), pasture (10%), and 3% for others. Due to an increasing number of catastrophic floods during the past decades, several flood protection measures have been implemented in the basin. The recurrence interval of the last flood in the year 2002 has been estimated to be 500 to 1000 years at some gauges (Becker and Gruenwald, 2003).

The argument to choose the Mulde catchment as alternative study site to the upper Tisza river basin was data availability, the occurence of spring floods or high flow conditions due to snow melt, and climatic and orographic similarities. The Area of the Mulde catchment is with 5400 km^2 smaller than the upper Tisza catchment (ca. 12,500km^2), but both catchments represent the meso scale. Altitudes in the Mulde catchment reach up to 1200 m.a.s.l. and in the Tisza river basin up to 2500 m.a.s.l.

5 Rainfall-runoff modelling

Based on a literature review two parsimonious rainfall-runoff models where selected, the model GR4J [Modèle du **G**énie **R**ural à **4** paramètres **J**ournalier] (Perrin et al. 2003) and IHACRES [**I**dentification of unit **H**ydrographs **a**nd **C**omponent flows from **R**ainfall, **E**vaporation and **S**treamflow data] (Jakeman et al., 1990; Jakeman and Hornberger, 1993). Due to their minimal data requirements, the models can be applied to many catchments without spending a lot of time on preparing the necessary input data. The models merely require time series of precipitation and temperature/evapotranspiration (optional) to simulate catchment runoff. Observed streamflow data are used for calibration. In order to better represent snow melt processes a simple snow module, based on the degree-day method, has been implemented into both rainfall-runoff models. This is an important prerequisite to model streamflow in snow affected catchments like the upper Tisza. As mentioned above, the models have been tested in a German catchment which is also affected by snow melt during spring time.

Both models have been implemented as modules in the Advanced Monitoring and Information System (AMIS), see section 2.

5.1 The rainfall-runoff model GR4J

The model GR4J belongs to the family of soil moisture accounting models, using only four calibration parameters (Perrin et al., 2003). The disadvantage is that it requires a time series of potential evapotranspiration instead of temperature. The probability, that potential evapotranspiration is available in a data poor region is quite low. For this reason a simple method (Hamon, 1961) was implemented, converting a temperature time series to evapotranspiration using only the latitude of the climate station in degrees as additional parameter. Accordingly, temperature or evapotranspiration values can be used to simulate streamflow with GR4J. Thus, the required model input is a daily time series of precipitation (P), potential evapotranspiration (ET_p), and measured discharge to calibrate the model. The first step is the determination of net rainfall (P_n) and potential evapotranspiration. This is done by subtraction of ET_p from P. If P_n is greater zero, a part of it (P_s) fills the production store that is important for low flow conditions. The other part of P_n (P_n-P_s) plus the water that is percolation leakage ($Perc$) from the production store is divided into two components. 90% of P_r (P_n-P_s + $Perc$) is routed by a unit hydrograph before it feeds a non-linear routing store. The remaining 10% of P_r are routed by a single unit hydrograph. The outflow of the routing store and the unit hydrograph, modified by a groundwater exchange function, are finally summarized to the simulated discharge. For a detailed model description see Perrin (2003).

5.2 The rainfall-runoff model IHACRES

The IHACRES metric conceptual rainfall-runoff model has a parsimonious approach to model parameterisation. IHACRES has been applied to catchments with a wide range of climatologies and sizes (Croke et al., 2004a). 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).

As illustrated in Figure 3, a rainfall (r_k) time series is converted into effective rainfall (u_k) in the non-linear loss module. 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 into streamflow (x_k). We used a storage configuration of two parallel storage components, a quick (x^q) and a slow component (x^s). The parameters (a_q, a_s) are the recession rates for the quick and slow storage component, whereas parameters (β_q, β_s) are representing the fractions of effective rainfall (u_k) for peak response.

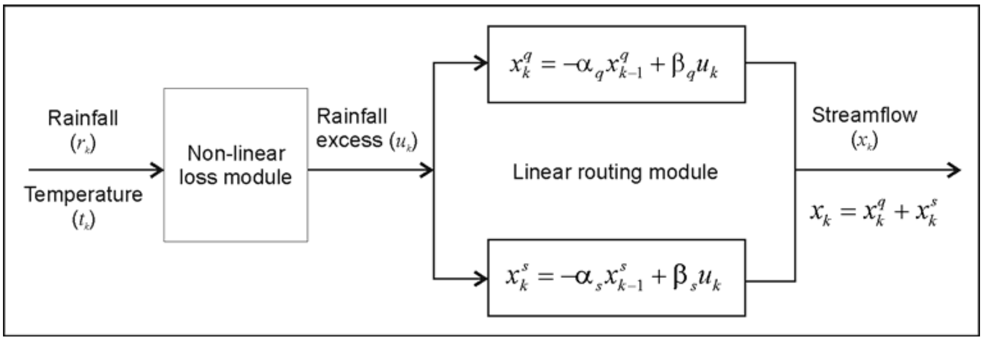

Figure 3. IHACRES model (after Jakeman and Hornberger, 1993; Croke et al., 2004)

Several versions of the non-linear loss module have been developed in the last years. We used the classic redesign (Croke et al., 2005) version in this study.

5.2.1 Model calibration and validation

The rainfall-runoff models GR4J and the IHACRES were calibrated at gauge Golzern with a catchment size of 5,400 km2. Arithmetic mean time series of all available precipitation and temperature gauges in the catchment served as model inputs. The period 1998 to 2003 was chosen to calibrate the model, because it includes the extreme flood event of August 2002, and consists of a variety of hydrologic conditions: wet, dry, and normal years (see Table 1). For model validation, the period 1983 - 1994 was selected. The performance of the model calibration was measured on a daily time step using two objective functions: Nash-Sutcliffe efficiency (NSE) and the PBIAS (percent bias). Table 1 shows the simulation results of the two models.

Table 1. Model performance

Year	**IHACRES**		**GR4J**	
	NSE	**PBIAS**	**NSE**	**PBIAS**
Calibration				
1998	0.77	-2.94	0.79	11.13
1999	0.84	-3.49	0.83	-10.07
2000	0.88	18.32	0.93	6.52
2001	0.60	7.72	0.76	16.30
2002	0.93	-6.27	0.95	-0.34
2003	0.86	7.38	0.87	-7.97
Mean	0.81	7.69	0.85	8.72
Validation				
1992	0.67	13.25	0.36	13.45
1993	0.54	9.45	0.57	10.36

1994	0.80	11.14	0.76	19.13
1995	0.79	3.89	0.73	13.62
1996	0.59	-14.07	0.21	-22.25
1997	0.52	-5.46	0.83	-1.38
Mean	0.65	9.54	0.57	13.36

Both models obtain good to reasonable model performance for every year of the calibration period. In terms of Nash-Sutcliffe efficiency the GR4J model performs slightly better than the IHACRES model during the calibration period. During the validation period it is the other way round. In terms of volumetric differences between observed and simulated annual streamflow volumes the IHACRES model performs in both periods slightly better than the GR4J model.

According to the obtained results shown in Table 1, both models are able to adequately simulate streamflow in the Mulde catchment. The implementation of the snow melt module was considerably increasing the model performance in snow affected seasons.

5.2.2 Model validation for high flow events

In regard to the objective of our study, it was important to analyze the model performance of the parsimonious rainfall-runoff models for flood and high flow events. Here we achieved very different results. Where some events were captured adequately others were under- or overestimated by the models. Figure 4 shows high flow situations where the models underestimate streamflow (a); overestimate streamflow (b); and adequately represent high flow conditions (c) and (d).

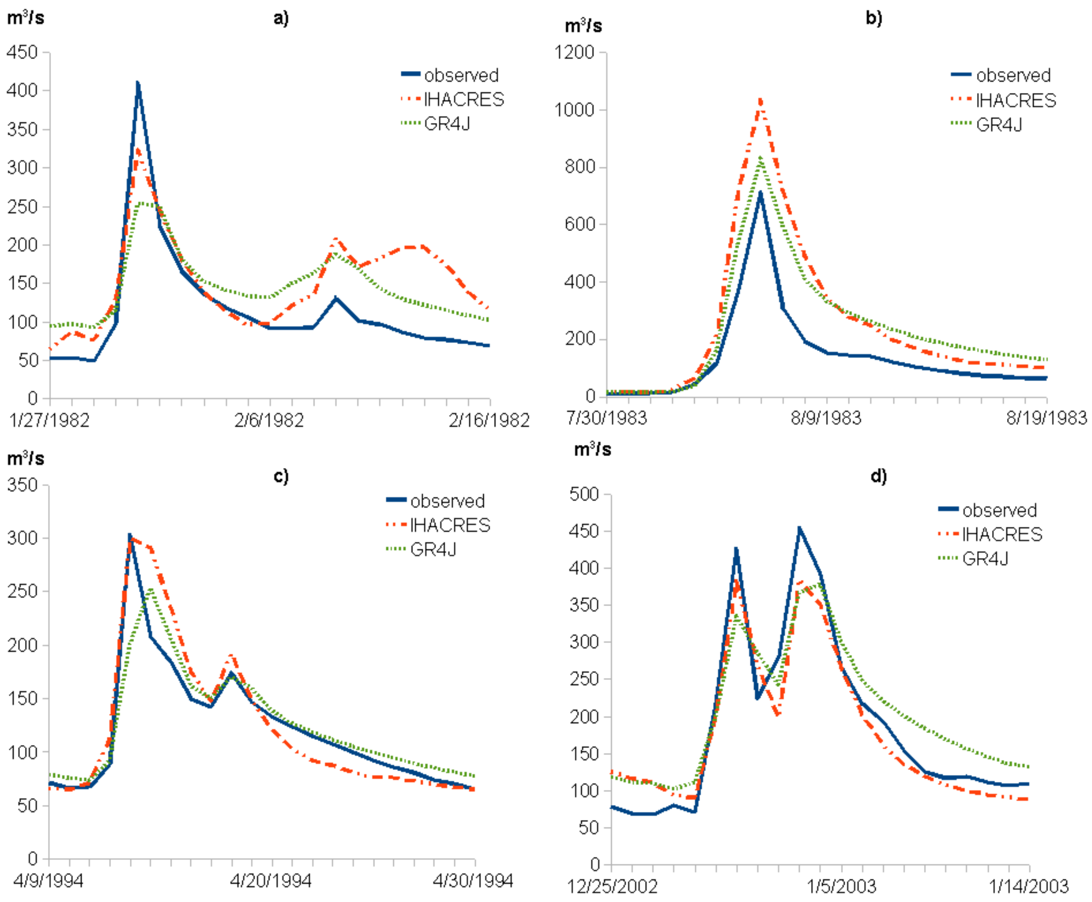

Figure 4. Model performance for high flow conditions

Although both models are not always representing flood and high flow events perfectly we assume that they can be used as valuable tools in the field of flood risk management.

5.2.3 Dynamic response characteristics

The model parameters of the calibrated IHACRES model can be used to derive dynamic response characteristics (DRCs) of the catchment. The DRCs contribute to the understanding of hydrological characteristics of the river basin. Moreover, the IHACRES model estimates for each time step a catchment wetness index, representing actual saturation of the catchment. The catchment saturation plays a fundamental role in flood risk assessment. Continuous streamflow simulation using the IHACRES model could thus provide valuable information for flood managers.

The parameter settings used to simulate runoff as well as the DRCs are shown in Table 2 below. According to the model parameter settings of the linear module, DRCs can be derived where τ_q and τ_s are the recession time constants for the quick and slow flow component (τ_q = -1/ln(α_q) and $\tau_s = 1 - \tau_q$), and υ_q and υ_s the proportion of quick and slow flow to total flow $\upsilon_q = \beta_q/(1+\alpha_q)$ and $\upsilon_s = 1 - \upsilon_q$). Post and Jakeman (1996) state that the relative volume of water passing through the slow storage component (υ_s) can be considered to be similar to the base flow index.

Table 2. Parameter settings and DRCs

Model parameters							
$1/c$	f	τ_w	l	p	α_q	α_s	β_q
101.4	1.8	4.8	0.37	0.89	-0.62	-0.97	0.157

Dynamic Response Characteristics				
υ_q	υ_s	τ_q (days)	τ_s (days)	Rainfall-Runoff coeff.
0.4	0.6	2.1	31.8	41.2

6 Rainfall-runoff database

Flood risk assessment and flood management require appropriate tools to study catchment response to a variety of rainfall events characterized by different volumes and intensities. In this section we present the development of a comprehensive rainfall-runoff database as a valuable tool to support flood risk management. The database can be easily applied by users without hydrologic modelling skills, because the modelling step has already been accomplished and is integrated into the database. Moreover, due to the parsimonious approach to data requirements (only daily rainfall and streamflow data for calibration are used) it can be applied to many catchments, even to data-poor regions. The IHACRES metric conceptual rainfall-runoff model was used to simulate runoff on the basis of a large number of randomly produced rainfall events. The resulting rainfall-runoff database can be used as an effective tool to easily assess possible streamflow situations assuming different rainfall volumes for the previous and the following days.

In the following we give an overview about the various components used to develop the rainfall-runoff database. After that we show an example application of the database in the Mulde catchment in Central Germany.

6.1 Software components

The operational system of the rainfall-runoff database consists of various software components: (1) the AMIS (components of the AMIS are described in section 2 above; (2) the IHACRES model implemented as SAGA module; (3) and a rainfall generator. Freely available and open source software was used in all of this.

The rainfall generator was developed in order to generate user-defined rainfall scenarios that were directly exported to the database. The IHACRES model, on the other hand, was implemented as a module for SAGA-GIS. It has been equipped with a calibration tool based on the Monte Carlo approach which is appropriate to calibrate six to eight free parameters in a short period of time. The GIS-database interface (AMIS component) provides functions to pre-process relevant data for rainfall-runoff modelling, and for enabling the IHACRES model to access rainfall-scenarios in the database, and, finally, to enter streamflow scenarios directly into the database.

It should be mentioned here that all software components, described above, are necessary to develop the rainfall-runoff database. Hydrological modelling skills are required for this, of course. The final product is a PostgreSQL database which can be exported to any computer. Our main objective while developing the rainfall-runoff database was to support applied flood risk management and to study general catchment behaviour by providing a large set of 20-day rainfall-runoff simulations. The latter can capture a variety of different rainfall scenarios and corresponding runoff simulations. We thus produced 2.2 million rainfall-runoff scenarios, based on 10,000 rainfall scenarios and 220 different model initialization states (combinations of parameters WI0 and Q0).

Once, the rainfall-runoff database has been developed for a certain streamflow gauge in a river basin, it can be applied by users without hydrologic modelling skills. In the current version it is necessary to translate rainfall conditions into SQL statements (Structured Query Language, ISO/IEC 9075) in order to receive the desired runoff result-set from the database. In the future it is planned to develop a graphical user interface that supports the user to systematically analyse and produce the desired runoff result-sets more intuitively.

6.2 Rainfall scenario generator

The development of the rainfall-runoff database for flood events is based on a large number of randomly generated rainfall scenarios. We chose the duration of 20 days for each scenario because this is a reasonable length to study single flood events. Hlavcova et al. (2005) state that there is, for the time being, no real preference for a certain method to estimate design rainfall events. Furthermore, the rainfall-runoff model used in our study requires only average catchment time series of precipitation and temperature (optional) to simulate streamflow. It was thus not necessary to apply sophisticated methods to generate distributed rainfall events as, for example, practiced by Gabellani et al. (2007).

Although, the rainfall scenarios used in our study were produced randomly, we tried to influence rainfall generation towards reasonable representation of natural variability and typical catchment characteristics. But in order to account for unpredictable changes in rainfall patterns due to climate change, we knowingly abandon the option of generating rainfall scenarios completely rule-based. Therefore, the rainfall scenarios are divided into three periods that are illustrated in Figure 6. The first period is an initialization period, the second period represents a storm event, and the last period is used to study streamflow recession behaviour. The length of these periods and the rainfall volumes, respectively, can be defined by the user. In order to assign reasonable values of duration and volumes, it was necessary to study measured rainfall records in the catchment. Hence, characteristics of rainfall patterns before extreme events, the patterns and extents of extreme events, and the characteristics of rainfall after extreme events were analysed. In order to account for extreme events not included in the rainfall records, the values used to define maximum rainfall volumes were chosen a little bit higher than observed volumes. Due to the large number of generated rainfall scenarios, a variety of artificial (or not yet occurred) as well as real rainfall events are captured, representing a large spectrum of rainfall patterns with different volumes and intensities. Figure 5 shows an example of the observed rainfall event during the flood of August 2002. In addition it displays two randomly generated rainfall scenarios from the database which capture the pattern of the observed event.

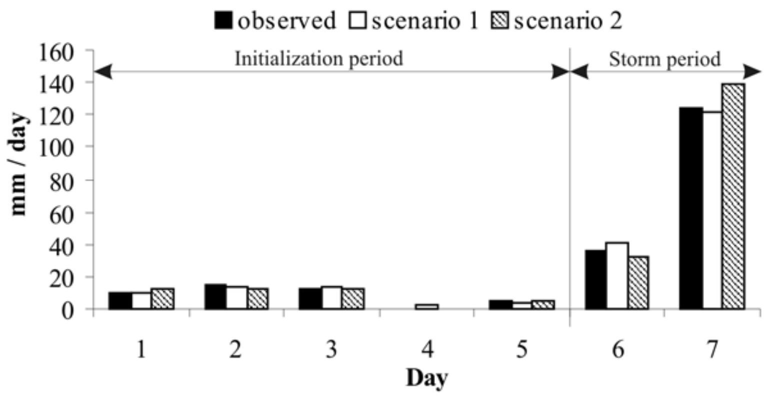

Figure 5. Randomly generated rainfall scenarios capturing the observed rainfall event of August 2002 in the Mulde catchment

We chose a length of five days for the initialization period and allowed rainfall volumes in the range of 0 and 80 mm. These are representative values in the area under study before an extreme event. The random generator first produces a rainfall depth value in the user-defined range (in our case between 0 and 80 mm) for each scenario during the initialization period. It randomly distributes this value over a five-day period. Please note that the aim of the rainfall initialization period is not to initialize the rainfall-runoff model, as described in the following sub-section, but to capture uncertainties in rainfall patterns and measurements. Following the initialization period, a two day storm event is generated randomly based on the same approach. An analysis of the rainfall time series in the Mulde catchment shows that the duration of two days for the storm event is adequately representing natural conditions. We defined possible rainfall depth for the storm event in the range of 40 to 180 mm to be distributed over two days.

In order to study streamflow recession behaviour, a third period with the duration of 13 days was introduced. This latter was characterized by low rainfall events (0 to 20 mm). The method used to generate this period was similar to the approach described above.

Altogether, 10,000 rainfall scenarios with the duration of 20 days were produced and directly entered into the relational database management system.

6.3 Runoff simulations

The IHACRES model was used to simulate streamflow scenarios on the basis of 20-day rainfall scenarios.

Usually, rainfall-runoff models require rather long “warm-up” or initialization periods, respectively, before they provide reasonable results. In order to avoid this, the streamflow simulations based on each rainfall scenario are calculated starting with different initial model states. These states represent a variety of possible catchment saturation pre-conditions (wet to dry) at time step zero (t0). The parameters required for model initializations are the wetness index (WI0) and the streamflow (Q0). Initial combinations of these parameters are stored in a table in the database. This table could show, for instance, that the first combination is Q0 = 10 m3/s and WI0 = 5, that the second combination is Q0 = 10 m3/s and WI0 = 10, and so on. We used 220 pre-condition combinations in our study. Thus, for each rainfall scenario 220 streamflow simulations were performed. Please note that the model initialization should not be mixed up with the initialization period of the rainfall scenarios as described in the previous sub-section.

The final result is a PostgreSQL database containing 10,000 randomly produced rainfall scenarios and 2.2 million streamflow scenarios. How the database can be used is explained in the following section.

7 Rainfall-runoff database results

Generally the rainfall-runoff database can be used for two different purposes (1) for flood risk assessment and flood forecasting, and (2) to study catchment response to different rainfall events under different catchment saturation preconditions. In the following we show results of the application of the database in the Mulde catchment in Central Germany.

7.1 Flood risk assessment and forecasting

In case the rainfall-runoff database is used to assess possible streamflow situations for the following days, i.e. in order to decide whether predicted short-term climate scenarios might lead to dangerous flooding, information on past and on future events is required (see Figure 4).

Information about the past is determined by the range of streamflow Q_0, the range of WI_0, and by the rainfall volumes of previous days (during the initialization period). In order to account for uncertainties in streamflow measurements at time step t_0, we use a range of initial Q_0 values instead of the measured value itself. For example, if $Q_{obs(t0)}$ = 20 m^3/s, then the lower and higher initial Q_0 value available in the WI_0/Q_0 combination table will be selected: 10 m^3/s <= Q_0 <= 30 m^3/s. The range of initial WI_0 values is determined by using continuous model results or on the basis of rainfall conditions before time step t_0. Here we distinguish between five possible states (extremely dry, dry, medium, wet, and extremely wet). Each category represents a range of catchment wetness conditions obtained by an analysis of model results during the calibration period.

The measured rainfall volume of the previous days is used in order to select rainfall scenarios with similar volumes during the initialization period. As illustrated in Figure 6, we select simulations starting with a small range of initial conditions at t_0. Due to different rainfall patterns of the scenarios during the initialization period we end up with a larger range (compared to time step t_0) of possible current conditions at time step t_{today}. The time step “today” corresponds to the last time step in the initialization period, i.e. one day before the storm event. The range of possible states represents uncertainties of rainfall measurement, catchment saturation, and streamflow observations before the expected storm event.

Information about the future is determined by the weather forecast representing a range of expected rainfall volumes. Additionally, a recession period, characterized by low rainfall volumes following the storm event, is used to study streamflow recession behaviour after the flood. Both rainfall observations for the previous days and the weather forecast are used to select streamflow scenarios from the database, simulated on the basis of conditions comparable to the real conditions that occurred during the previous days and the expected rainfall volumes.

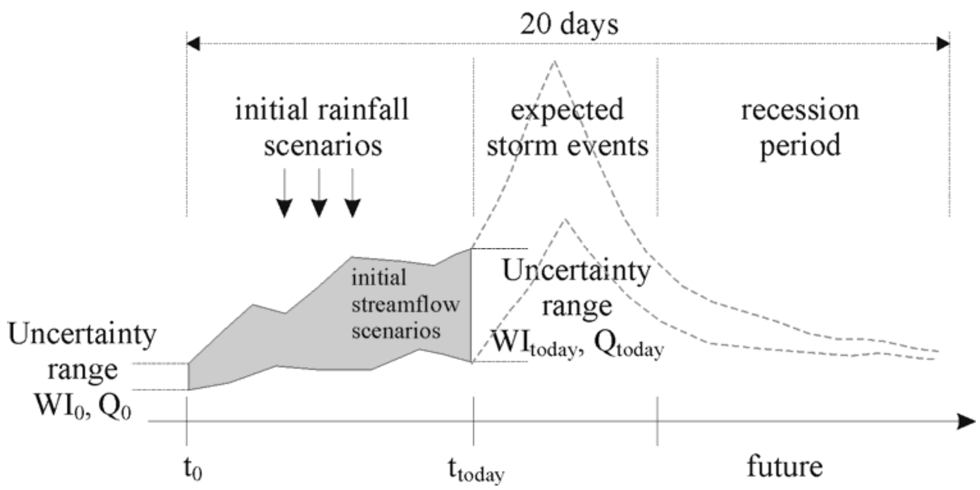

Figure 6. Time scale structure of rainfall-runoff scenarios

In order to test the database performance, we checked whether the three flood events of the years 1983, 1995, and 2002 are captured. Therefore, it was necessary to create SQL queries for each event according to the climatic conditions before and during the flood event. In the year 1983 for example, 105 mm rainfall were measured during the two-day storm event (time steps 6 and 7), and an amount of 70 mm during the five days before the storm event (time steps 1 to 5; initialization period). The catchment pre-conditions at time step t_0 were: observed discharge (Q_0) = 10.1 m^3/s, and simulated wetness index (WI_0) = 4.7. Consequently, the SQL query was formulated as following:

SELECT	*all simulations*
FROM	*runoff simulation table*
WHERE	*rainfall volume in the initialization period is* > 65 and < 75
AND	*rainfall volume in the storm period is* > 100 and < 110
AND	*initial streamflow is* <= 20 m^3/s
AND	*initial wetness index is* <= 10

Figure 7 shows the runoff result-set for the SQL query above. Only runoff simulations based on rainfall scenarios that are comparable to the real rainfall event of 1983 are displayed.

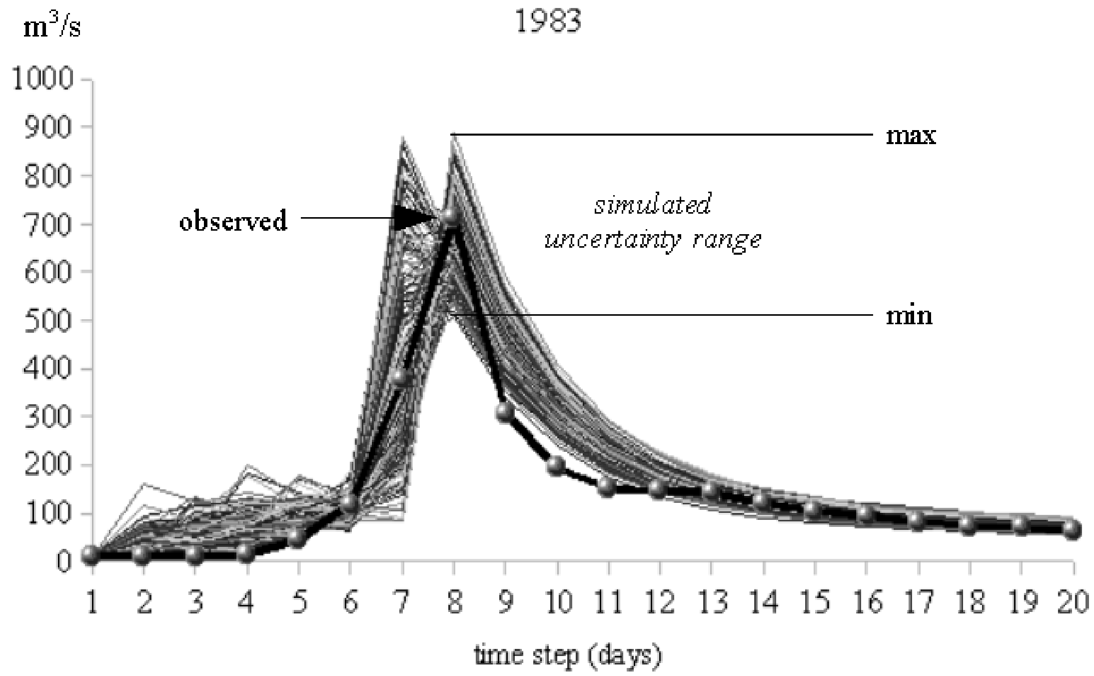

Figure 7. Database result-set capturing the 1983 flood event

The example shows that the runoff simulation result-set captures the 1983 flood event. However, some of the simulations are underestimating, others overestimating the flood peak. The difference between the lowest and the highest simulated flood peak can be considered as the uncertainty range. Due to the fact that a storm period of two days was applied, the result-set contains two flood peaks. In some rainfall scenarios, the major share of the rainfall volume was allocated to the first day, in other scenarios to the second day. Similar results were achieved for the flood events of the years 1995 and 2002, which are not illustrated here.

As shown in Figure 7, the uncertainty range is still rather broad. It ranges from 600 - 900 m^3/s. The objective for applied flood risk assessment is to keep the uncertainty range as small as possible, without failing the aim to capture the real event. In order to reduce the uncertainty range, the parameter ranges in the SQL query need to be limited. This, in turn, should only be done by experienced users with good knowledge about catchment response behaviour. An alternative to refine the results would be to increase the number of runoff simulations in the database by increasing the number of Q_0 and WI_0 combinations in the pre-condition table. This would lead to smaller uncertainty ranges at time step t_0 and "today", as illustrated in Figure 6 above.

7.2 Catchment response analysis

Beside flood risk assessment and forecasting the rainfall-runoff database can be used to study general catchment response to various rainfall scenarios. An important topic in this context is the investigation of the impact of different catchment pre-conditions (extremely dry, dry, medium, wet, and extremely wet) on flood extents, caused by rainfall volumes (storm events) in a certain range. The database can be used to identify critical rainfall volumes for each catchment pre-condition. In the study area we assume streamflow values exceeding a threshold of 500 m^3/s as critical.

In the following we describe how the database is used to estimate critical rainfall volumes for each catchment pre-condition category (*CPC*). As explained previously, catchment pre-conditions at time step t_0 $CPC(t_0)$ are determined by observed streamflow (Q_0) and simulated wetness index (WI_0). The conditions at time step t_{today} $CPC(t_{today})$ are determined by $CPC(t_0)$ and observed rainfall volumes during the initialization period $Rain_{init}$ (see Figure 6). According to the catchments characteristics, parameter ranges are assigned to each category, as shown in Table 3 below.

Table 3. Classifications of pre-conditions

Category	**Value**	Q_0 **[m³/s]**	WI_0	$Rain_{init}$ **[mm]**
extremely dry	1	<= 10	<= 10	<= 1
dry	2	> 10 <= 20	> 10 <= 20	> 1 <= 5
medium	3	> 20 <= 50	> 20 <= 50	> 5 <= 15
wet	4	> 50 <= 150	> 50 <= 100	> 15 <= 25
extremely wet	5	> 150	> 100	> 25

Each pre-condition category has a value, e.g. extremely dry = 1, and extremely wet = 5. These values are used to estimate $CPC(t_0)$ using the simple algorithm:

$$CPC(t_0) = (C[Q_0]\omega_Q + C[WI_0]\omega_{WI}) / \sum \omega \qquad (1)$$

where $C[Q_0]$and $C[WI_0]$ are the pre-condition category values, and parameters ω_Q and ω_{WI} are the weighting factors. The result is shown in the cross-classified table below.

Table 4. Pre-conditions at time step t_0 $CPC(t_0)$

	Q_0 **[m³/s]**				
WI_0	<= 10	> 10 <= 20	> 20 <= 50	> 50 <= 150	> 150
<= 10	1	2	3	3	4
> 10 <= 20	1	2	3	4	4
> 20 <= 50	2	2	3	4	5
> 50 <= 100	2	3	3	4	5
> 100	2	3	4	4	5

Weights: $\omega_Q = 3$; $\omega_{WI} = 1$

1 = extremely dry, 2 = dry, 3 = medium, 4 = wet, and 5 = extremely wet

In order to create a cross-classified table for the pre-conditions $CPC(t_{today})$ from $CPC(t_0)$ and $Rain_{init}$, the following equation was used:

$$CPC(t_{today}) = (C[CPC(t_0)]\omega_{CPC(t_0)} + C[Rain_{init}]\omega_{Rain_{init}}) / \sum \omega \qquad (2)$$

where $C[CPC(t_0)]$ and $C[Rain_{init}]$ are the category values and $\omega_{CPC(t_0)}$ and $\omega_{Rain_{init}}$ are the weighting factors. The results of the calculations of equation 5 are shown in Table 5 below.

Table 5. Pre-conditions at time step t_{today} $CPC(t_{today})$

$CPC(t_0)$	$Rain_{init}$ [mm] <= 1	> 1 <= 5	> 5 <= 15	> 15 <= 25	> 25
extremely dry	1	2	2	3	3
dry	2	2	3	3	4
medium	2	3	3	4	4
wet	3	3	4	4	5
extremely wet	3	4	4	5	5

Weights: $\omega PC(t_0) = 1$; $\omega Rain_{init} = 1$

1 = extremely dry, 2 = dry, 3 = medium, 4 = wet, and 5 = extremely wet

After the definition of parameter settings for each pre-condition category, the database was used to analyse the effects of catchment pre-conditions and rainfall volumes on flood peak extents. In other words: Which rainfall storm event in combination with which pre-condition can lead to peak flows exceeding the critical value of 500 m^3/s?

We assumed four different storm events (40, 80, 120, and 160 mm during two days) and analysed the runoff result-set for each pre-condition category $CPC(t_{today})$. Therefore, it was necessary to create one ore more SQL queries for each pre-condition category and storm event. In order to get the result set for a storm event with a volume of about 80 mm and *extremely dry* pre-conditions, the following SQL statement was formulated:

SELECT	*all simulations*
FROM	*runoff simulation table*
WHERE	*rainfall volume in the initialization period is* <= 1
AND	*rainfall volume in the storm period is* > 75 and < 85
AND	*initial streamflow is* <= 10 m^3/s
AND	*initial wetness index is* <= 20

For the pre-condition $CPC(t_{today})$ = *medium*, the SQL statements is much more complex, because $CPC(t_{today})$ = *medium* occurs nine times in the cross-classified table (Table 5).

For each pre-condition category the mean maximum peak flow of the result-set(s) was calculated. Figure 6 shows the mean maximum peak flows of each pre-condition result-set plotted over the rainfall storm events. The dashed line highlights the critical threshold of 500 m^3/s.

Based on this analysis we formulate the following statements for the Mulde catchment in Central Germany: (1) A storm event with a total volume < 40 mm can be considered as not critical whatever catchment pre-condition; (2) storm events with a volume > 120 mm are always critical whatever catchment pre-condition; (3) rainfall volumes > 45 mm are critical for *extremely wet* pre-conditions; (4) rainfall volumes > 85 mm are critical for *wet* pre-conditions; (5) rainfall volumes > 105 mm are critical for *medium* pre-conditions; (6) rainfall volumes > 110 mm are critical for *dry* pre-conditions.

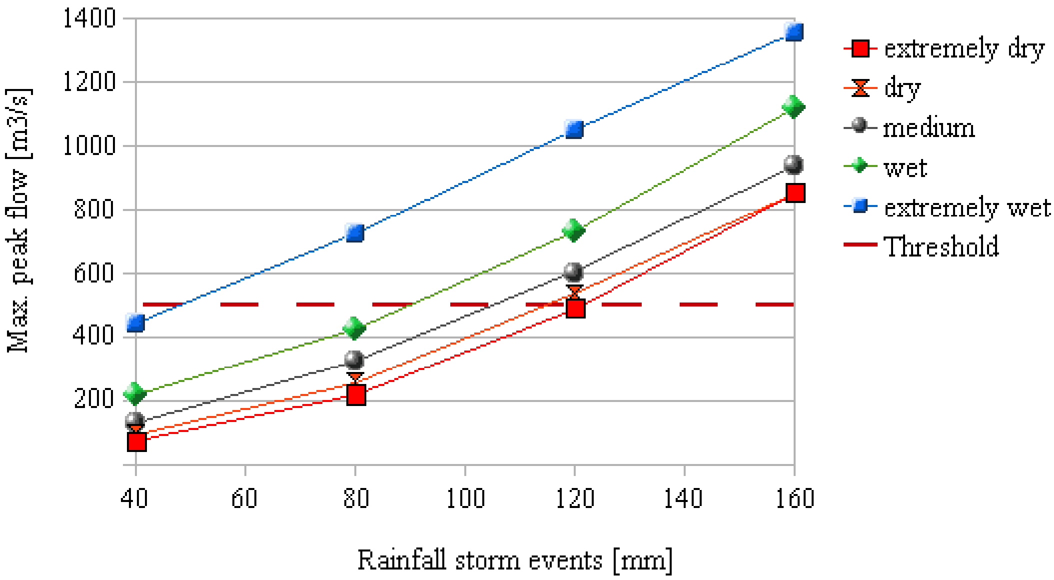

Figure 8. Correlation between storm event, pre-condition, and maximum peak flow

7.3 Transferability of the method

The proposed method to develop a rainfall-runoff database can be applied to any catchment where good performance of streamflow simulations can be achieved with the IHACRES model. Due to the parsimonious parameterization of the model and its minimal data requirements, runoff simulations can be performed very quickly on a standard PC. These are optimal conditions to realize thousands of simulations within a short period of time.

Steps to transfer the method: (1) Create rainfall scenarios by adapting the duration and rainfall volume ranges for each period (initialization, storm, and recession) to the characteristics of the catchment; (2) calibrate the IHACRES model; (3) define reasonable ranges and combinations of WI_0 and Q_0 values according to observed streamflow data and simulated WI ranges; (4) simulate runoff on the basis of rainfall scenarios using the IHACRES model.

8 Conclusion

Unfortunately, we cannot draw a conclusion concerning the applicability of the proposed methods in the Tisza case study. But due to similarities between the alternative catchment (Mulde) and the upper Tisza river basin, and the transferability of the method, we assume that particularly the development of rainfall-runoff databases for streamflow gauges in the upper Tisza catchment could be a valuable enrichment for flood risk management. Sources of uncertainty in the flood forecasting process are manifold, starting from uncertainties in precipitation measurements, followed by the uncertainty attributable to the internal states of hydrological and hydrodynamic models, initial conditions, and relevant process parameterizations (Arduino et al., 2005). With the development of the rainfall-runoff database we were able to show the uncertainties related to precipitation measurements and forecasts as well as uncertainties related to internal model states and 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.

The benefits of the database approach are: (1) the database can be developed rather quickly – if necessary data are readily available during one day; (2) the database can be used to assess possible streamflow situations for the following days or to generally study catchment response to different rainfall scenarios without requiring hydrologic modelling skills; but for the database development, modelling skills are required, of course; (3) on the basis of the performance of the database, results can be provided in a very short period of time; (4) due to the parsimonious approach to data requirements the database can be applied in many data-poor catchments; (5) information provided by the database result-set takes into account uncertainties in rainfall measurement and forecasting as well as uncertainties relating to model predictions.

By using database queries, a water manager is able to produce flood risk scenarios, depending on short-term rainfall forecasts. The database can be used by persons who are not familiar with hydrological modelling, because the modelling step has already been accomplished. By linking the simulation results (minimum and maximum peak flow) with a hydrodynamic model, a water manager is able to delineate flood inundation areas. Deficiencies of the rainfall-runoff database are: (1) a re-calibration of the rainfall-runoff model is necessary, if boundary conditions change dramatically in the catchment, such as land use; (2) the developed rainfall generator is suitable for a daily time step only; in order to generate hourly-based scenarios, a rule-based approach would be required.

Both parsimonious rainfall-runoff models (GR4J and IHACRES) have been successfully applied by many hydrologists to a variety of catchments characterized by different climatologies. The establishment of these models in the upper Tisza river basin to complement the current flood forecasting strategy would - in any case - be useful.

9 References

Arduino, G., Reggiani, P. and Todini, E., 2005. Recent advances in flood forecasting and flood risk assessment. Hydrology and Earth System Sciences 9(4). 280-284.

Becker, A. and Gruenwald, U., 2003. Disaster Management: Flood Risk in Central Europe. Science 300(5622). 1099.

Cofino, W.P., 1995. Quality management of monitoring programs. In: Adriaanse M., J van der Kraats; P.G. Stocks, and R.C. Wards (eds). Proceeding of the international workshop on monitoring and assessment in water management; Monitoring Tailor-Made, 20-23 September 1994, Beekbergen, The Netherlands.

Croke, B. F. W., Andrews, F., Jakeman, A. J., Cuddy, S. and Luddy, A., 2005 c. Redesign of the IHACRES rainfall-runoff model. In: 29th Hydrology and Water Resources Symposium, Water Capital, Engineers Australia, 21-23 February.

Croke, B. F. W., Merritt, W. S. and Jakeman, A. J., 2004. A dynamic model for predicting hydrologic response to land cover changes in gauged and ungauged catchments. Journal Of Hydrology 291(1). 115-131.

Fazey, I., Fazey, J. and Fazey, D., 2005. Learning More Effectively from Experience. Ecology and Society (10).

Gabellani, S., Boni, G., Ferraris, L., von Hardenberg. J. and Provenzale, A., 2007. Propagation of uncertainty from rainfall to runoff: A case study with a stochastic rainfall generator. Advances in Water Resources 30(10). 2061-2071.

Hamon, W. R., 1961. Estimating potential evapotranspiration. 107-120.

Hlavcova, H., Kohnova, S., Kubes, R., Szolgay, J. and Zvolensky, M., 2005. An empirical method for estimating future flood risks for flood warnings. Hydrology and Earth System Sciences 9(4). 431-448.

ISO/IEC 9075, 2008. Information technology – Database languages – SQL – Part 1: Framework (SQL/Framework). International Organization for Standardization.

Jakeman, A. J. and Hornberger, G. M., 1993. How Much Complexity Is Warranted in a Rainfall-Runoff Model?. Water Resources Research 29(8). 2637-2649.

Jakeman, A. J., Littlewood, I. G. and Whitehead, P. G., 1990. Computation of the instantaneous unit hydrograph and identifiable component flows with application to two small upland catchments. Journal of Hydrology 117(1-4). 275-300.

Jolánkai, G. and Pataki, B., 2005. The Tisza River Project. Real-life scale integrated catchment models for supporting water- and environmental management decisions. Description of the "Tisza River Project" and its main results.

Kokkonen, T. S. and Jakeman, A. J., 2002. Structural Effects of Landscape and Land Use on Streamflow Response. In: Environmental Foresight and Models: A Manifesto. (). 303-321.

Kokkonen, T. S., Jakeman, A. J., Young, P. C. and Koivusalo, H. J., 2003. Predicting daily flows in ungauged catchments: model regionalization from catchment descriptors at the Coweeta Hydrologic Laboratory, North Carolina. Hydrological Processes 17(11). 2219-2238.

OGC (2005a). OpenGIS Consortium, Inc. OpenGIS Implementation Specification for Geographic information - Simple feature access - Part 1: Common architecture Open Geospatial Consortium Inc.

OGC (2005b). OpenGIS Consortium, Inc. OpenGIS Implementation Specification for Geographic information - Simple feature access - Part 2: SQL option Open Geospatial Consortium Inc.

Perrin, C., Michel, C. and Andreassian, V., 2003. Improvement of a parsimonious model for streamflow simulation. Journal of Hydrology 279(). 275-289.

Post, D. A. and Jakeman, A. J., 1999. Predicting the daily streamflow of ungauged catchments in S.E. Australia by regionalising the parameters of a lumped conceptual rainfall-runoff model. Ecological Modelling 123(2-3). 91-104.

Post, D. A. and Jakeman, A. J., 1996. Relationships Between Catchment Attributes and Hydrological Response Characteristics in Small Australian Mountain Ash Catchments. Hydrological Processes 10(6). 877-892.

Post, D. A., Jones, J. A. and Grant, G. E., 1998. An improved methodology for predicting the daily hydrologic response of ungauged catchments. Environmental Modelling and Software 13(3-4). 395-403.

Sefton, C. E. M. and Howarth, S. M., 1998. Relationships between dynamic response characteristics and physical descriptors of catchments in England and Wales. Journal of Hydrology 211(1-4). 1-16.

Timmerman, J.G., Ottens, J.J. and Ward, R.C., 2000. The information cycle as a framework for defining information goals for water-quality monitoring. Environmental Management 25(3): 229-239.

Walker, B. H., L. H. Gunderson, A. P. Kinzig, C. Folke, S. R. Carpenter, and L. Schultz. 2006. A handful of heuristics and some propositions for understanding resilience in social-ecological systems. Ecology and Society 11(1): 13. [online] URL: http://www.ecologyandsociety.org/vol11/iss1/art13/

ZFMP, Z. F. M. P., 2006. Flood Management in Zakarpattia Region. The European Union's TACIS Programme for Ukraine.